Secure and Robust Image Watermarking Scheme Using Homomorphic Transform, SVD and Arnold Transform in RDWT Domain

Priyank KHARE, Vinay Kumar SRIVASTAVA

Electronics & Communication Engineering Department, Motilal Nehru National Institute of Technology, Teliarganj, 211004 Allahabad, India

rel1606@mnnit.ac.in, vinay@mnnit.ac.in

DOI: 10.15598/aeee.v17i3.3154

Abstract. *The main objective for a watermarking technique is to attain imperceptibility, robustness and security against various malicious attacks applied by illicit users. To fulfil these basic requirements for a scheme is a big issue of concern. So, in this paper, a new image watermarking method is proposed which utilizes properties of homomorphic transform, Redundant Discrete Wavelet Transform (RDWT), Arnold Transform (AT) along with Singular Value Decomposition (SVD) to attain these required properties. RDWT is performed on host image to achieve LL subband. This LL subband image is further decomposed into illumination and reflectance components by homomorphic transform. In order to strengthen security of proposed scheme, AT is used to scramble watermark. This scrambled watermark is embedded with Singular Values (SVs) of reflectance component which are obtained by applying SVD to it. Since reflectance component contains important features of image, therefore, embedding of watermark in this part provides excellent imperceptibility. Proposed scheme is comprehensively examined against different attacks like scaling, shearing etc. for its robustness. Comparative study with other prevailing algorithms clearly reveals superiority of proposed scheme in terms of robustness and imperceptibility.*

Keywords

Arnold transform, homomorphic transform, RDWT, SVD, watermarking.

1. Introduction

In recent times, forgery related to various digital multimedia such as images, video etc. is easily carried out by illegitimate attackers. So, in order to provide secure transmission of information among users, there must be a technique developed which easily resolves these challenges. Image watermarking is one of the methods which provides possible solution to this problem. In image watermarking, secret information which is generally in form of image is concealed inside host image such that it becomes imperceptible to users.

The key features for a watermarking [1] algorithm are robustness, imperceptibility, security and capacity. Robustness measures efficacy of algorithm towards various unintentional attacks, whereas imperceptibility signifies both images should be visually similar. Capacity defines data payload. Lastly, security secures algorithm against unauthorized users. Depending on working domain, watermarking schemes are classified into two parts (i) spatial domain [2] and (ii) transform domain. Since transform domain [3] provides good robustness in comparison with spatial domain, hence, they are preferred. Depending on information needed at receiver side, the watermarking techniques are categorised as non-blind, semi-blind and blind. In non-blind method, both original image and watermark are essential, whereas in semi-blind, partial information of watermark is needed. In blind schemes, there is no requirement of original and watermark images. To improve these properties, simultaneously fusion of various transforms such as Discrete Cosine Transform (DCT) [4] and [5], Discrete Wavelet Transform (DWT) [6], [7] and [8] along with SVD are used.

Authors in [9] reported a method in which directly watermark is embedded into SVs of cover image. Researchers suggested a method [10] in which cover image is decomposed in various frequency subbands using RDWT, afterwards SVD is performed on all subbands. SVs of watermark are embedded into SVs of subbands. However, this method results in non-blind technique. In [11], authors investigated a method which is similar to [10], the only key difference is that directly watermark is embedded into SVs of subbands by which scheme become blind. A new homomorphic-based method is developed in [12] where researcher uses homomorphic transform along with SVD. Firstly, reflectance component is obtained with help of homomorphic transform of cover image and then, SVs of reflectance component are directly embedded with watermark. This approach is also extended to block level, where reflectance component is segmented into blocks and embedding of watermark is performed at block level. In [13], it is analysed that technique developed in [12] suffers from False Positive Problem (FPP) due to which invalid watermark can be easily extracted by the illicit attacker with aid of singular vectors of original watermark. So, technique described in [12] is not so much reliable due to FPP. Khare et al. [14] investigated method using DWT and chaotic mapping, in which watermark is randomized with help of logistic mapping, in order to boost security. Finally, this encrypted watermark is embedded with wavelet coefficients of cover image.

In [15], authors reported method using Finite Radon Transform (FRAT) in which FRAT is applied on host image, subsequently DWT is applied yielding various subbands followed by SVD. SVs of watermark are embedded with SVs of transformed host image, although this method results in weak robustness. Guo et al. [16] developed method which provides solution to FPP by embedding of watermark with help of its principal components. In [17], authors suggested method using DWT and SVD where SVs of LL subband of host image are directly embedded with watermark. For robustness analysis embedding of watermark is done with different values of scaling factor.

The main emphasis of this work is to propose a watermarking technique which provides robustness, imperceptibility and security simultaneously. Since reflectance component is varying rapidly, therefore better imperceptibility is attained by embedding of watermark as it will be difficult to perceive it visually whereas selection of LL subband increases robustness against attacks such as scaling, rotation etc. AT enhances the security of scheme by scrambling watermark and thereby reducing FPP. Direct insertion of watermark makes scheme blind. So, combining all these properties helps in developing an effective watermarking algorithm.

Remaining part of this paper is organised as follows: Sec. 2. discusses about background of homomorphic transform, RDWT, SVD and AT whereas watermark embedding and extraction procedure are elaborated in Sec. 3. . Analysis of simulation results are mentioned in Sec. 4. . Section 5. concludes this proposed scheme.

2. Background

A brief overview of homomorphic transform, RDWT, SVD and AT are presented in this section.

2.1. Homomorphic Transform

Image $a\ (m_1, m_2)$ is considered as product of two components i.e. illumination $i\ (m_1, m_2)$ and reflectance $r\ (m_1, m_2)$ [18], where (m_1, m_2) denotes spatial coordinates.

$$a(m_1, m_2) = i(m_1, m_2) \cdot r(m_1, m_2). \tag{1}$$

Both components present in Eq. (1) are made separable using natural logarithm.

$$\ln(a(m_1, m_2)) = \ln(i(m_1, m_2)) + \ln(r(m_1, m_2)). \tag{2}$$

Fast Fourier Transform (FFT) is performed on both sides in Eq. (2).

$$A(u, v) = A_i(u, v) + A_r(u, v). \tag{3}$$

Afterwards, frequency domain output $A(u, v)$ is passed through High Pass Filter (HPF) $H(u, v)$.

$$F(u, v) = A_i(u, v) \cdot H(u, v) + A_r(u, v) \cdot H(u, v), \tag{4}$$

where $F(u, v)$ denotes output obtained from HPF. Inverse FFT is performed on Eq. (4).

$$f(m_1, m_2) = \Im^{-1}(F(u, v)), \tag{5}$$

where $f\ (m_1, m_2)$ is output in logarithmic domain. Filtered output image $g\ (m_1, m_2)$ is computed as:

$$g(m_1, m_2) = \exp(f(m_1, m_2)). \tag{6}$$

Figure 1 depicts schematic diagram for homomorphic transform.

2.2. Redundant Discrete Wavelet Transform

Though DWT provides excellent multiresolution analysis of signal by decomposing the image into four frequency subbands, i.e. LL, HL, LH and HH, major concern in implementation of DWT is shift variance. DWT employs down samplers in filtering process due to which shift variance arises. In order to remove this problem, down-sampling process is completely eliminated and shift invariance is attained. This process results in RDWT [19]. The size of each subband remains same after applying RDWT. Therefore, RDWT provides better imperceptibility by embedding watermark in desired frequency subband. Robustness of scheme is also enhanced due to its shift invariance property. Figure 2 shows RDWT decomposition of "Cameraman" image.

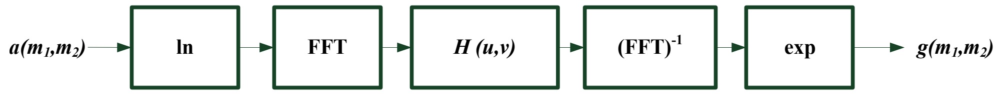


Fig. 1: Block diagram of homomorphic transform.

Fig. 2: RDWT decomposition of 'Cameraman' image.

2.3. Singular Value Decomposition

SVD decomposes a given image '**B**' of size $M \times N$ into three matrices '**U**', '**V**' and '**S**', where **U** and **V** are orthogonal matrices [20], [21] and [22]. '**S**' is a diagonal matrix which consists of SVs which are arranged in decreasing order.

$$\mathbf{B} = \mathbf{U}\mathbf{S}\mathbf{V}^T. \quad (7)$$

SVD is a popular analysis performed on image because it provides excellent stability as SVs do not change on slight modifications performed on image such as translation, shearing etc. which enhances robustness of algorithm.

2.4. Arnold Transform

In order to enhance security of images while transmission over channel, generally they are scrambled using various techniques. Arnold transform is one method employed for scrambling of image. Mathematically it is given as:

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} 1 & 1 \\ 1 & 2 \end{pmatrix} \cdot \begin{pmatrix} x \\ y \end{pmatrix} \bmod N, \quad (8)$$

where $\begin{pmatrix} x' \\ y' \end{pmatrix}$ and $\begin{pmatrix} x \\ y \end{pmatrix}$ denotes pixel values of image after and before scrambling. 'N' defines size of image.

This mapping is periodic with period 'T'. So, after fixed number of iterations, original image is recovered back [23], [24] and [25]. Figure 3(a) shows original image whereas Fig. 3(b) represents one-time AT of 'Lena' image.

(a) (b)

Fig. 3: (a) Original image and (b) 'Lena' image after one-time AT.

3. Proposed Algorithm

Proposed watermark embedding and extraction algorithms are elaborated in this section. Fusion of homomorphic transform, RDWT, SVD along with AT are used in proposed algorithm. Reflectance component of LL subband of cover image is selected for embedding of watermark. Since reflectance component contains major image information, so a high degree of imperceptibility is achieved by embedding watermark into this component, whereas use of RDWT and SVD strengthens robustness of algorithm. Arnold transform enhances security of proposed algorithm. 2-D Gaussian Low Pass Filter (LPF) and HPF are employed in homomorphic transform.

$$H_{LPF}(u,v) = e^{\frac{-((u-\mu_u)^2 + (v-\mu_v)^2}{2R^2}}, \quad (9)$$

where 'H_{LPF}' denotes transfer function of LPF as presented in Eq. (9) and corresponding transfer function for HPF 'H_{HPF}' is given below:

$$H_{HPF}(u,v) = 1 - H_{LPF}(u,v). \quad (10)$$

Illumination 'I' and reflectance 'R' components are separated with help of these filters. This work mainly focuses to develop an imperceptible, robust and secure watermarking technique. Figure 4 and Fig. 5 show embedding and extraction algorithms block diagram.

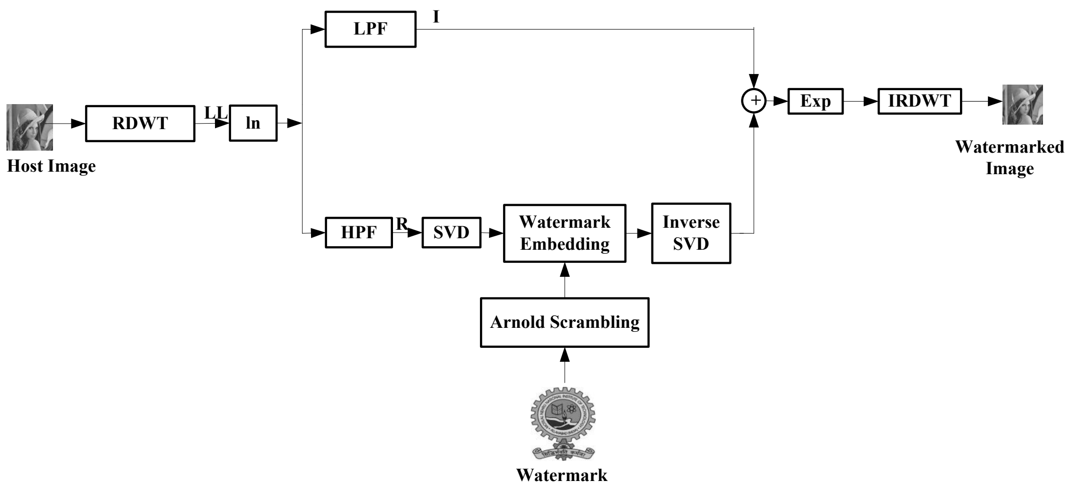


Fig. 4: Schematic diagram for proposed watermark embedding algorithm.

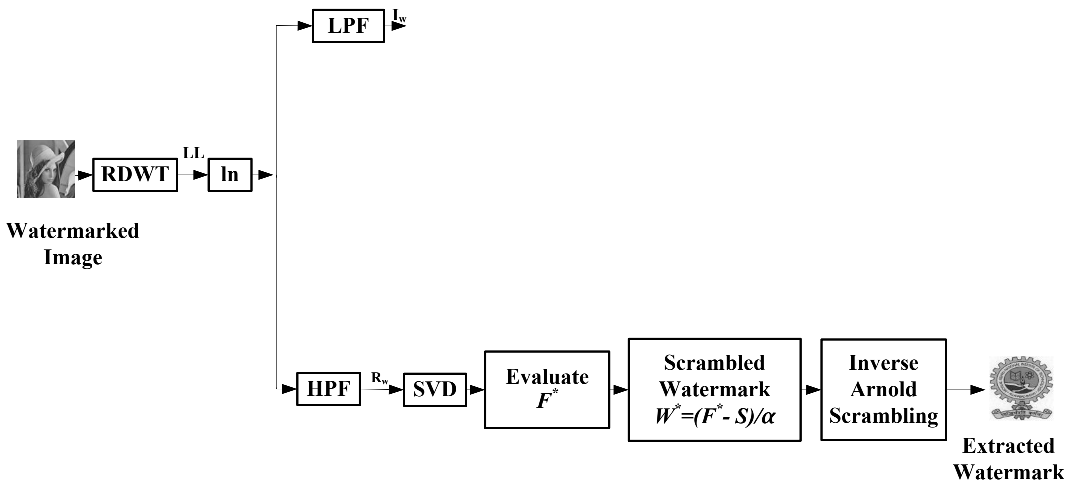


Fig. 5: Schematic diagram for proposed watermark extraction algorithm.

3.1. Embedding Algorithm

- First level RDWT is performed on host image '$\mathbf{A}$' which decomposes it into four subbands, i.e. LL, HL, LH and HH.
- Homomorphic transform is performed to LL subband to separate out illumination '$\mathbf{I}$' and reflectance '$\mathbf{R}$' components.
- Further SVD is performed on reflectance matrix for obtaining SVs.

$$\mathbf{SVD}(\mathbf{LL}_R) = \mathbf{USV}^T. \tag{11}$$

- Now, AT is performed on watermark '$\mathbf{W}$'.
- Scrambled watermark '$\mathbf{W}$' is embedded into SVs of '$\mathbf{LL}_R$'.

$$\mathbf{A}^{new} = \mathbf{S} + \alpha^* \mathbf{W}, \tag{12}$$

where $\alpha = 0.005$.

- SVD is applied on '$\mathbf{A}^{new}$'.

$$\mathbf{A}^{new} = \mathbf{U}_W \mathbf{S}_W \mathbf{V}_W^T. \tag{13}$$

- New modified reflectance matrix '$\mathbf{R}^{\text{mod}}$' is computed as:

$$\mathbf{R}^{\text{mod}} = \mathbf{US}_W \mathbf{V}^T. \tag{14}$$

- Inverse homomorphic transform is performed on '$\mathbf{R}^{\text{mod}}$' according to Eq. (15) and Eq. (16):

$$\mathbf{Z}^{new} = \mathbf{R}^{\text{mod}} + \mathbf{I}, \tag{15}$$

$$\mathbf{C} = \exp(\mathbf{Z}^{new}) - 1. \tag{16}$$

- Watermarked image '$\mathbf{A}_w$' is obtained by taking inverse RDWT of '$\mathbf{C}$' with other unaltered wavelet coefficients.

3.2. Extraction Algorithm

- One level RDWT is performed on watermarked image '$\mathbf{A}_w$' to obtain four subbands LL, HL, LH and HH.
- Homomorphic transform is applied to LL subband using similar LPF and HPF as used in embedding

method to separate out illumination '$\mathbf{I}_w$' and reflectance '$\mathbf{R}_w$' components.

- Now *SVs* of '$\mathbf{R}_w$' are obtained using *SVD*.

$$\mathbf{SVD}(\mathbf{LL}_{R_W}) = \mathbf{U}^*\mathbf{S}^*\mathbf{V}^{*T}. \tag{17}$$

- Matrix '$\mathbf{F}^*$' which contains watermark is evaluated as:

$$\mathbf{F}^* = \mathbf{U}_W\mathbf{S}^*\mathbf{V}_W^T. \tag{18}$$

- Scrambled watermark '$\mathbf{W}^*$' is extracted according to Eq. (19).

$$\mathbf{W}^* = \frac{(\mathbf{F}^* - \mathbf{S})}{\alpha}. \tag{19}$$

- Original watermark is recovered by applying inverse AT to '$\mathbf{W}^*$'.

4. Simulation Results

To evaluate performance of proposed scheme, it is tested on various standard images which are chosen as 'Lena', 'Bridge', 'House', 'Boat', and 'Man' of size 512×512 as depicted in Fig. 6(a), Fig. 6(b), Fig. 6(c), Fig. 6(d) and Fig. 6(e). 'MNNIT' logo is taken as watermark of size 512×512 as presented in Fig. 6(f), whereas Fig. 7(a), Fig. 7(b), Fig. 7(c), Fig. 7(d) and Fig. 7(e) represents the watermarked images and extracted watermark is presented in Fig. 7(f). MATLAB R2015a is used for implementation of proposed algorithm.

(a) (b) (c) (d) (e) (f)

Fig. 6: Original images (a) Lena, (b) Bridge, (c) House, (d) Boat, (e) Man and (f) Watermark 'MNNIT' logo.

(a) (b) (c) (d) (e) (f)

Fig. 7: Various watermarked images (a) Lena, (b) Bridge, (c) House, (d) Boat, (e) Man and (f) Extracted watermark 'MNNIT' logo.

Various performance parameters are evaluated to measure imperceptibility and robustness of proposed technique. Peak Signal to Noise Ratio ($PSNR$) and Structural Similarity Index ($SSIM$) metrics are used to evaluate imperceptibility of proposed technique. Mathematically $PSNR$ is given as:

$$PSNR = 10\log_{10}\left(\frac{255^2}{MSE}\right), \tag{20}$$

where MSE is mean square error computed between original '$\mathbf{X}$' image and watermarked '$\mathbf{Y}$' image.

$$MSE = \frac{1}{N^2}\sum_{a=0}^{N-1}\sum_{b=0}^{N-1}[\mathbf{X}(a,b) - \mathbf{Y}(a,b)]^2. \tag{21}$$

Another parameter used is $SSIM$ [26] which evaluates structural similarity between original and watermarked images. Eq. (22) presents its mathematical description.

$$SSIM(x,y) = \frac{(2\mu_x\mu_y + c_1)\cdot(2\sigma_{xy} + c_2)}{(\mu_x^2 + \mu_y^2 + c_1)\cdot(\sigma_x^2 + \sigma_y^2 + c_2)}, \tag{22}$$

where μ_x, μ_y are mean of x and y. σ_x, σ_y are standard deviations of x and y, whereas σ_{xy} is covariance between x and y, respectively.

Robustness of proposed algorithm is measured under various attacks using Normalized Coefficient Correlation (NCC), mathematically defined in Eq. (23) which computes similarity between original and extracted watermark images.

$$NCC = \frac{\sum_{i=1}^{p}\sum_{j=1}^{q}[\mathbf{W}(i,j)\cdot\mathbf{W}^*(i,j)]}{\sqrt{\sum_{i=1}^{p}\sum_{j=1}^{q}[\mathbf{W}(i,j)]^2}\sqrt{\sum_{i=1}^{p}\sum_{j=1}^{q}[\mathbf{W}^*(i,j)]^2}}, \tag{23}$$

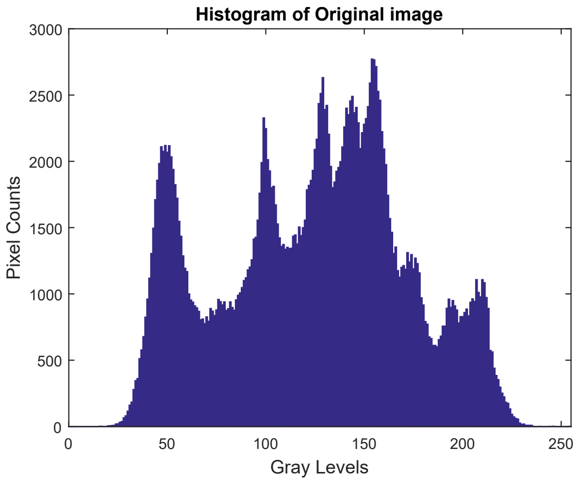
where $\mathbf{W}(i,j)$ is watermark image and $\mathbf{W}^*(i,j)$ is extracted watermark.

Figure 8(a) and Fig. 8(b) show histograms for original and watermarked 'Lena' images from which it can be easily inferred that proposed scheme offers good imperceptibility. Table 1 tabulates values of various performance parameters under no attacks for different watermarked images.

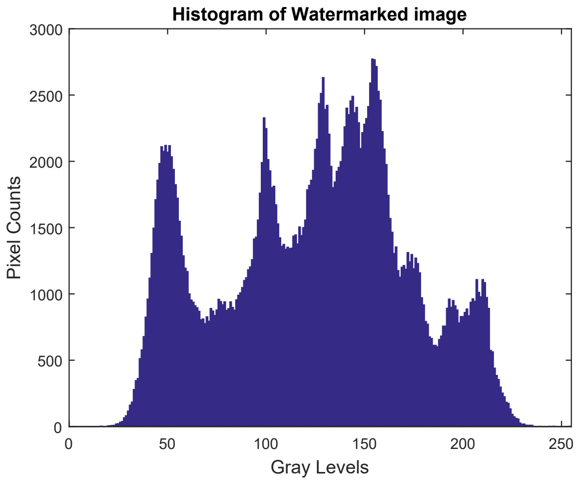
Tab. 1: Performance metrics for proposed scheme under no attacks.

Image	$PSNR$ (dB)	NCC	$SSIM$
Lena	68.5287	1.00	1.00
Bridge	72.1434	1.00	1.00
House	65.1710	1.00	0.9999
Boat	65.9651	1.00	0.9999
Man	66.0615	1.00	0.9999

Figure 9 given below demonstrates watermarked 'Lena' image subjected to various attacks such as salt & pepper noise (0.001), Gaussian filtering (3×3), histogram equalization and rotation ($20°$) whereas Fig. 10 shows corresponding extracted watermark images.



(a) Original image.

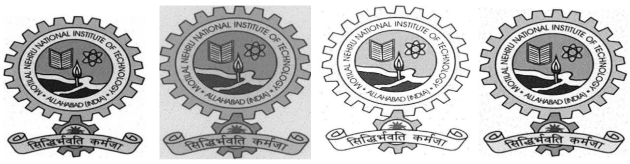


(b) Watermarked image.

Fig. 8: Histograms.

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

Fig. 9: Attacks applied on watermarked image (a) salt & pepper, noise (0.001), (b) Gaussian filtering, (c) histogram, equalization and (d) rotation (20°).



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

Fig. 10: Extracted watermark image (a) salt & pepper, noise (0.001), (b) Gaussian filtering, (c) histogram, equalization and (d) rotation (20°).

Robustness analysis is presented in Tab. 2 where NCC values for extracted watermark are computed under varieties of attacks applied on different watermarked images. By observing Tab. 2, it can be easily inferred that proposed approach exhibits good robustness as NCC values are lying in proximity of +1 which signifies its efficacy. Highest NCC of 1.00 is attained for several watermarked images under numerous attacks.

Figure 11 represents $PSNR$ values for various watermarked images under varieties of attacks. Higher values of $PSNR$ are attained by proposed algorithm which clearly signifies its high imperceptibility. Highest $PSNR$ of 53.6790 dB for Gaussian filtering attack is attained whereas $PSNR$ of 7.1367 dB for rotation (20°) attack is obtained. It is clearly illustrated in Fig. 11 that proposed approach attains $PSNR$ well above 25 dB for most of the attacks.

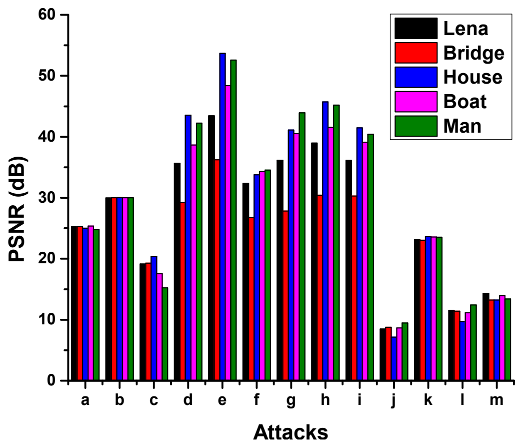


Fig. 11: Imperceptibility analysis for various watermarked images under different attacks: (a) salt & pepper, noise (0.01), (b) Gaussian noise (0, 0.001), (c) histogram, equalization, (d) sharpening, (e) Gaussian filter (3×3), (f) averaging filter (3×3), (g) median filter (3×3), (h) Wiener filter (3×3), (i) JPEG compression (Q=40), (j) rotation (20°), (k) gamma correction (0.8), (l) shearing (0.1, 0.1) and (m) translation [10 10].

Table 3 clearly states superiority of our scheme by comparing it with other prevailing schemes such as [9], [11], [12] and [12][a] where [12][a] denotes block-based technique used in [12] present in the literature. From comparative analysis depicted in Tab. 3 it is quite obvious that developed method delivers better NCC values which clearly signifies high robustness of the proposed technique. Higher values of NCC are reported for same attacks as applied to existing methods which signifies efficacy of our method. '-' stands for not reported in Tab. 3.

Tab. 2: NCC values evaluated under different attacks.

Attacks	Lena	Bridge	House	Boat	Man
Salt & pepper noise (0.01)	0.9933	0.9997	0.9495	0.9588	0.9277
Gaussian noise (0, 0.001)	0.9981	1.00	0.9812	0.9839	0.9651
Histogram equalization	0.9972	0.9975	0.9968	1.00	0.9873
Sharpening	1.00	0.9999	1.00	1.00	1.00
Gaussian filter (3×3)	0.9996	0.9997	0.9997	0.9998	0.9999
Averaging filter (3×3)	0.9983	0.9982	0.9988	0.9991	0.9975
Median filter (3×3)	0.9997	0.9997	0.9997	1.00	1.00
Wiener filter (3×3)	0.9995	0.9995	0.9991	0.9998	0.9997
JPEG compression ($Q = 40$)	0.9993	0.9998	1.00	1.00	1.00
Rotation (20°)	0.9990	0.9880	0.9950	0.9941	0.9869
Gamma correction (0.8)	0.9995	0.9985	0.9984	0.9998	0.9992
Shearing (0.1, 0.1)	0.9993	0.9982	1.00	1.00	0.9967
Translation [10 10]	0.9430	0.9642	0.9206	0.9449	0.9709

Tab. 3: Comparative analysis of our proposed scheme with other existing schemes.

Attacks	[9]	[11]	[12]	[12][a]	Our scheme
Salt & pepper noise (0.001)	–	0.9940	–	–	1.00
Gaussian noise (0, 0.15)	0.3120	0.5780	0.6190	0.8920	0.9651
Scaling (0.5, 2)	0.6120	0.9480	0.6615	0.9530	0.9982
JPEG compression ($Q = 60$)	0.6160	0.9920	0.6950	0.9640	1.00
Median filter (3×3)	–	0.9820	–	–	0.9997
Cropping	0.5480	0.7170	0.7634	0.9410	0.9584
Rotation (-3°)	0.2310	0.3560	0.6654	0.9470	0.9999

5. Conclusion

In this paper, a novel image watermarking technique is developed which uses homomorphic transform, RDWT, SVD and AT. Embedding of watermark in reflectance component obtained by homomorphic transform of RDWT transformed host image results in excellent imperceptibility, whereas RDWT and SVD improve robustness of the scheme. The proposed scheme is fast and reliable as it does not require original host image for extraction and reliability is enhanced by scrambling of watermark. LL subband demonstrates good robustness towards various attacks like histogram equalization, scaling, rotation etc. The proposed algorithm is highly imperceptible and robust as indicated by higher values of performances metrics. Further superiority of proposed scheme is exhibited by comparing it with other existing schemes such as [9], [11], [12] and [12][a]. This work can be extended for improving imperceptibility and robustness such that trade-off between them is maintained and further investigations will be performed for developing a watermarking technique free from FPP.

References

[1] COX, I., M. MILLER, J. BLOOM, J. FRIDRICH and T. KALKER. *Digital watermarking and steganography*. 2nd. ed. Boston: Morgan Kaufmann, 2008. ISBN 978-0-1237-2585-1.

[2] NIKOLAIDIS, N. and I. PITAS. Robust image watermarking in the spatial domain. *Signal processing*. 1998, vol. 66, iss. 3, pp. 385–403. ISSN 0165-1684. DOI: 10.1016/s0165-1684(98)00017-6.

[3] EJIMA, M. and A. MIYAZAKI. On the evaluation of performance of digital watermarking in the frequency domain. *Electronics and Communications in Japan (Part III: Fundamental Electronic Science)*. 2003, vol. 86, no. 4, pp. 38–47. ISSN 1042-0967. DOI: 10.1002/ecjc.10013.

[4] ALI, M., C. W. AHN and M. PANT. A robust image watermarking technique using SVD and differential evolution in DCT domain. *Optik*. 2014, vol. 125, iss. 1, pp. 428–434. ISSN 0030-4026. DOI: 10.1016/j.ijleo.2013.06.082.

[5] SVERDLOV, A., S. DEXTER and A. M. ESKICIOGLU. Robust DCT-SVD domain image watermarking for copyright protection: embedding data in all frequencies. In: *2005 13th European Signal Processing Conference*. Antalya: IEEE, 2005, pp. 1–4. ISBN 978-160-4238-21-1.

[6] AL-HAJ, A. Combined DWT-DCT digital image watermarking. *Journal of computer science*.

2007, vol. 3, iss. 9, pp. 740–746. ISSN 1552-6607. DOI: 10.3844/jcssp.2007.740.746

[7] LAI, C. C. and C. C. TSAI. Digital image watermarking using discrete wavelet transform and singular value decomposition. *IEEE Transactions on instrumentation and measurement*. 2010, vol. 59, iss. 11, pp. 3060–3063. ISSN 1557-9662. DOI: 10.1109/tim.2010.2066770.

[8] BHATNAGAR, G. and B. RAMAN. A new robust reference watermarking scheme based on DWT-SVD. *Computer Standards & Interfaces*. 2009, vol. 31, iss. 5, pp. 1002–1013. ISSN 0920-5489. DOI: 10.1016/j.csi.2008.09.031.

[9] LIU, R. and T. TAN. An SVD-based watermarking scheme for protecting rightful ownership. *IEEE transactions on multimedia*. 2002, vol. 4, iss. 1, pp. 121–128. ISSN 1941-0077. DOI: 10.1109/6046.985560.

[10] LAGZIAN, S., M. SORYANI and M. FATHY. Robust watermarking scheme based on RDWT-SVD: Embedding Data in All subbands. In: *2011 International Symposium on Artificial Intelligence and Signal Processing (AISP)*. Tehran: IEEE, 2011, pp. 48–52. ISBN 978-1-4244-9834-5. DOI: 10.1109/AISP.2011.5960985.

[11] MAKBOL, N. M. and B. E. KHOO. Robust blind image watermarking scheme based on redundant discrete wavelet transform and singular value decomposition. *AEU-International Journal of Electronics and Communications*. 2013, vol. 67, iss. 2, pp. 102–112. ISSN 1434-8411. DOI: 10.1016/j.aeue.2012.06.008.

[12] ABDALLAH, H. A., R. A. GHAZY, H. KASBAN, O. S. FARAGALLAH, A. A. SHAALAN, M. M. HADHOUD, M. I. DESSOUKY, N. A. EL-FISHAWY, S. A. ALSHEBEILI and F. E. A. EL-SAMIE. Homomorphic image watermarking with a singular value decomposition algorithm. *Information Processing & Management*. 2014, vol. 50, iss. 6, pp. 909–923. ISSN 0306-4573. DOI: 10.1016/j.ipm.2014.07.001.

[13] LOUKHAOUKHA, K., A. REFAEY and K. ZEBBICHE. Comments on "Homomorphic image watermarking with a singular value decomposition algorithm". *Information Processing & Management*. 2016, vol. 52, iss. 4, pp. 644–645. ISSN 0306-4573. DOI: 10.1016/j.ipm.2015.12.009.

[14] KHARE, P., A. K. VERMA and V. K. SRIVASTAVA. Digital image watermarking scheme in wavelet domain using chaotic encryption. In: *2014 Students Conference on Engineering and Systems*. Allahabad: IEEE, 2014, pp. 1–4. ISBN 978-1-4799-4939-7. DOI: 10.1109/SCES.2014.6880072.

[15] RASTEGAR, S., F. NAMAZI, K. YAGHMAIE and A. ALIABADIAN. Hybrid watermarking algorithm based on singular value decomposition and radon transform. *AEU-International Journal of Electronics and Communications*. 2011, vol. 65, iss. 7, pp. 658–663. ISSN 1434-8411. DOI: 10.1016/j.aeue.2010.09.008.

[16] GUO, J. M. and H. PRASETYO. False-positive-free SVD-based image watermarking. *Journal of Visual Communication and Image Representation*. 2014, vol. 25, iss. 5, pp. 1149–1163. ISSN 1047-3203. DOI: 10.1016/j.jvcir.2014.03.012.

[17] JANE, O., E. ELBASI and H. G. ILK. Hybrid non-blind watermarking based on DWT and SVD. *Journal of applied research and technology*. 2014, vol. 12, no. 4, pp. 750–761. ISSN 1665-6423. DOI: 10.1016/S1665-6423(14)70091-4

[18] GONZALEZ, R. C. and R. E. WOODS. *Digital image processing*. 2nd. ed. New Jersey: Prentice Hall, 2002. ISBN 978-0130946508.

[19] FOWLER, J. E. The redundant discrete wavelet transform and additive noise. *IEEE Signal Processing Letters*. 2005, vol. 12, iss. 9, pp. 629–632. ISSN 1558-2361. DOI: 10.1109/LSP.2005.853048.

[20] CHANDRA, D. S. Digital image watermarking using singular value decomposition. In: *The 2002 45th Midwest Symposium on Circuits and Systems, 2002. MWSCAS-2002*. Tulsa: IEEE, 2002, pp. 264–267. ISBN 0-7803-7523-8. DOI: 10.1109/MWSCAS.2002.1187023.

[21] RYKACZEWSKI, R. Comments on "An SVD-based watermarking scheme for protecting rightful ownership". *IEEE Transactions on Multimedia*. 2007, vol. 9, iss. 2, pp. 421–423. ISSN 1941-0077. DOI: 10.1109/TMM.2006.886297.

[22] ZHANG, X. P. and K. LI. Comments on "An SVD-based watermarking scheme for protecting rightful Ownership". *IEEE Transactions on Multimedia*. 2005, vol. 7, iss. 3, pp. 593–594. ISSN 1941-0077. DOI: 10.1109/TMM.2005.843357.

[23] LIU, Z., M. GONG, Y. DOU, F. LIU, S. LIN, M. A. AHMAD, J. DAI and S. LIU. Double image encryption by using Arnold transform and discrete fractional angular transform. *Optics and Lasers in Engineering*. 2012, vol. 50, iss. 2, pp. 248–255. ISSN 0143-8166. DOI: 10.1016/j.optlaseng.2011.08.006.

[24] VAISH, A. and M. KUMAR. Color image encryption using MSVD, DWT and Arnold transform in fractional Fourier domain. *Optik*. 2017, vol. 145, iss. 1, pp. 273–283. ISSN 0030-4026. DOI: 10.1016/j.ijleo.2017.07.041.

[25] MAKBOL, N. M. and B. E. KHOO. A hybrid robust image watermarking scheme using integer wavelet transform, singular value decomposition and arnold transform. In: *International Visual Informatics Conference*. Selangor: Springer, 2013, pp. 36–47. ISBN 978-3-319-02958-0. DOI: 10.1007/978-3-319-02958-0_4.

[26] WANG, Z., A. C. BOVIK, H. R. SHEIKH and E. P. SIMONCELLI. Image quality assessment: from error visibility to structural similarity. *IEEE transactions on image processing*. 2004, vol. 13, iss. 4, pp. 600–612. ISSN 1941-0042. DOI: 10.1109/TIP.2003.819861.

About Authors

Priyank KHARE received his B.Tech. degree in Electronics & Communication Engineering from Uttar Pradesh Technical University in 2009 and M.Tech. in Digital Systems from Motilal Nehru National Institute of Technology, Allahabad, India in 2014. He is presently pursuing Ph.D. degree in Electronics & Communication Engineering from Motilal Nehru National Institute of Technology, Allahabad, India. His research interests include digital image processing, digital image watermarking.

Vinay Kumar SRIVASTAVA received his B.E.degree in Electronics & Telecommunication from GEC Rewa in 1989, M.Tech. in Communication from I.I.T BHU, Varanasi, India, in 1991 and Ph.D. in Electrical Engineering from I.I.T. Kanpur, India, in 2001. He is presently working as Professor in the Department of ECE at MNNIT Allahabad, India. His research interests include image compression, post-processing, digital watermarking, image denoising, design and analysis of IDMA systems, genomic signal processing. He has authored and co-authored several reputed journal publications.