



Robust Watermarking in Mid-Frequency Band in Transform Domain using Different Transforms with Full, Row and Column Version and Varying Embedding Energy

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Abstract: This paper proposes a watermarking technique using sinusoidal orthogonal transforms DCT, DST, Real Fourier transform and Sine-cosine transform and non-sinusoidal orthogonal transforms Walsh and Haar. These transforms are used in full, column and row version to embed the watermark and their performance is compared. Also using energy conservation property of transforms, different percentage of host image energy like 60%, 100% and 140% is maintained after embedding the watermark to observe the effect on robustness of proposed watermarking technique. Though for different types of attacks, different transforms are proved robust, Haar column transform followed by Haar row transform are observed to be best in terms of robustness. These are followed by Walsh column/row transform and DCT column and row transform.

Keywords: Watermarking; DCT; DST; Real Fourier Transform; Sine-Cosine transform; Walsh; Haar

I. Introduction

Networked communication systems have become very popular for data exchange, especially for multimedia data. Though distribution of multimedia data has become easier due to advanced technology, many times creators of data or owners of data are not willing to distribute their data to avoid copyright violation. Distribution of multimedia contents without violating its copyright is possible through digital watermarking. Contents like audio, video, images can be secured from unauthorized copying or distribution by hiding the certain information in it such that it remains unperceivable to Human Visual System (HVS). Other applications of digital watermarking include fingerprinting, broadcast monitoring, owner identification, indexing etc. [1].

Various watermarking techniques which have been proposed till now can be classified into two groups: those which hide the information in spatial domain i.e. in pixel values of an image and those which hide the information in frequency domain [2]. Depending upon need of various applications, watermarking can also be classified as robust, fragile, semi-fragile, visible and invisible watermarking [1].

Selection of appropriate domain (spatial or frequency domain) depends on required robustness of watermarking scheme with respect to specific alterations introduced in data. Spatial domain watermarking is robust against geometric attacks however; its poor capacity of embedding data may violate the imperceptibility characteristic. Transform based or frequency domain watermarking techniques are more robust and also provide better imperceptibility. This is due to fact that when watermark is embedded in transform domain of host image, its effect gets scattered all over the image in spatial domain rather than concentrating in a specific pixel area. Combinations of one or more transforms are also found to be more robust than using one single transform. Wavelet transforms are popular transforms used in frequency domain watermarking.

In this paper various orthogonal transforms are explored for watermarking under various attacks. In addition, these transforms are applied in different forms like full transform; column transform and row transform to study their effect when various attacks are performed on watermarked images. By using energy conservation property of transforms, watermark is embedded in such a way that it contributes to 60%, 100% and 140% energy of the host image region chosen for embedding the watermark. Appropriate scaling factors are used to make the energy level of watermark up to the desired level of energy of host image region.

Remaining paper is organized as follows. Section 2 gives review of existing watermarking techniques. Section 3 gives brief idea of Real Fourier transform and Sine-cosine transform. Section 4 describes proposed method. Section 5 focuses on results and discussions related to proposed method. Section 6 gives conclusion of the work presented in paper.

II. Review of Literature

Ample of transform based watermarking techniques have been proposed in literature. Among them DCT and its combination with Discrete Wavelet Transforms (DWT) are very popular. Barni et.al proposed a DCT based watermarking scheme for copyright protection of multimedia data. A pseudo-random sequence of real numbers is embedded in a selected set of DCT coefficients [2]. Jiansheng, Sukang and Xiaomei proposed such DCT-

DWT based invisible and robust watermarking scheme in which Discrete Cosine transformed watermark is inserted into three level wavelet transformed host image [3]. Surya Pratap Singh, Paresch Rawat, Sudhir Agrawal also proposed a DCT-DWT based watermarking technique in which scrambled watermark using Arnold transform is subjected to DCT and inserted into HH3 band of host image [4]. Yet another joint DCT-DWT based watermarking scheme [5] is proposed by Saeed K. Amirgholipour and Ahmad R. Naghsh-Nilchi. Another combined DWT-DCT based watermarking with low frequency watermarking and weighted correction is proposed by Kaushik Deb, Md. Sajib Al-Seraj, Md. Moshikul Hoque and Md. Iqbal Hasan Sarkar in [6]. In their proposed method, watermark bits are embedded in the low frequency band of each DCT block of selected DWT sub-band. The weighted correction is also used to improve the imperceptibility. In [7], Zhen Li, Kim-Hui Yap and Bai-Ying Lei proposed a DCT and SVD based watermarking scheme in which SVD is applied to cover image. By selecting first singular values macro block is formed on which DCT is applied. Watermark is embedded in high frequency band of SVD-DCT block by imposing particular relationship between some pseudo randomly selected pairs of the DCT coefficients. H. B. Kekre, Tanuja Sarode, Shachi Natu presented a DWT-DCT-SVD based hybrid watermarking method for color images in [8]. In their method, robustness is achieved by applying DCT to specific wavelet sub-bands and then factorizing each quadrant of frequency sub-band using singular value decomposition. Watermark is embedded in host image by modifying singular values of host image. Performance of this technique is then compared by replacing DCT by Walsh in above combination. Walsh results in computationally faster method and acceptable performance. Imperceptibility of method is tested by embedding watermark in HL2, HH2 and HH1 frequency sub-bands. Embedding watermark in HH1 proves to be more robust and imperceptible than using HL2 and HH2 sub-bands. In [9] and [10] Kekre, Sarode, and Natu presented DCT wavelet and Walsh wavelet based watermarking techniques. In [9], DCT wavelet transform of size 256×256 is generated using existing well known orthogonal transform DCT of dimension 128×128 and 2×2 . This DCT Wavelet transform is used in combination with the orthogonal transform DCT and SVD to increase the robustness of watermarking. HL2 sub-band is selected for watermark embedding. Performance of this watermarking scheme is evaluated against various image processing attacks like contrast stretching, image cropping, resizing, histogram equalization and Gaussian noise. DCT wavelet transform performs better than their previous DWT-DCT-SVD based watermarking scheme in [8] where Haar functions are used as basis functions for wavelet transform. In [10] Walsh wavelet transform is used that is derived from orthogonal Walsh transform matrices of different sizes. 256×256 Walsh wavelet is generated using 128×128 and 2×2 Walsh transform matrix and then using 64×64 and 4×4 Walsh matrix which depicts the resolution of host image taken into consideration. It is supported by DCT and SVD to increase the robustness. Walsh wavelet based technique is then compared with DCT wavelet based method given in [9]. Performance of three techniques is compared against various attacks and they are found to be almost equivalent. However, computationally Walsh wavelet was found preferable over DCT wavelet. Also Walsh wavelet obtained by 64×64 and 4×4 is preferable over DCT wavelet and Walsh wavelet obtained from corresponding orthogonal transform matrix of size 128×128 and 2×2 . In [11], other wavelet transforms like Hartley wavelet, Slant wavelet, Real Fourier wavelet and Kekre wavelet were explored by Kekre, Sarode and Shachi Natu. Performance of Slant wavelet and Real Fourier wavelet were proved better for histogram Equalization and Resizing attack than DCT wavelet based watermarking in [9] and Walsh wavelet based watermarking presented in [10]. Kekre *et al.* presented a DCT wavelet transform based watermarking technique [12]. Here DCT wavelet is generated from orthogonal DCT using algorithm of wavelet generation from orthogonal transforms given by Dr. Kekre in [13]. Watermark is compressed before embedding in host image. Various compression ratios are tried for compression of watermark so that watermark image quality is maintained with acceptable loss of information from image. Embedding compressed image also reduces the payload of information embedded in host image and thus causes good imperceptibility of watermarked image. Performance of the technique is evaluated under attacks like binary run length noise, Gaussian distributed run length noise, cropping for various compression ratios used in watermark compression. The work by Kekre *et al.* in [12] was extended for other attacks like resizing and compression in [13]. Also the compressed watermark is obtained using compression ratio 2.67 and strength of compressed normalized watermark is further increased using suitable scaling factor which was not done in [12]. Performance of full, column and row transform using DCT wavelet and DKT_DCT hybrid wavelet against various attacks is explored by Kekre *et al.* in [14] and [15] respectively. Column transform was proved better performance wise as well as computational efficiency wise in both the cases. Further, DKT_DCT column wavelet was observed to be better than DCT column wavelet. Effect of embedding the watermark by maintaining its energy in some proportion of the host energy using wavelet transform is studied in [16] by Kekre *et al.*

III. Real Fourier transform [17] and Sine-Cosine transform [18]

Discrete Fourier Transform (DFT) contains complex exponentials. It contains both cosine and sine functions. It gives complex values in the output of Fourier Transform. To avoid these complex values in the output, complex terms in Fourier Transform are to be eliminated. This can be done by combining elements of Discrete Cosine

Transform (DCT) and Discrete Sine Transform (DST) matrices. If we select odd sequences from DCT matrix and even sequences from DST matrix, it gives sine-cosine transform whereas choosing even sequences from DCT matrix and odd sequences from DST matrix will generate Real Fourier Transform. Real Fourier Transform is nothing but discrete sinusoidal functions in Fourier analysis. Both these versions are real and orthogonal as they have been obtained from real and orthogonal DCT and DST matrices.

IV. Proposed Method

In the proposed method, orthogonal transforms (DCT/DST/ Walsh/ Haar/ Real Fourier transform/Sine cosine transform) are applied to both host image and watermark image. This is done by three different ways by taking full transform, column transform and row transform. Transformed image obtained after applying full transform to it is given by

$$F=T*f*T' \quad (1)$$

Where, T is unitary, orthogonal transform matrix, T' is its transpose, f is image to be transformed and F is transformed image. Original image can be obtained from transformed image as

$$f=T'*F*T \quad (2)$$

For column transform, transformed image is obtained by pre-multiplying image with transform matrix as shown in equation (3) and original image is obtained by pre-multiplying transformed image with transpose of transform matrix as shown in equation (4).

$$F=T*f \quad (3)$$

$$f=T'*F \quad (4)$$

Row transform of an image is given by operating transposed transform matrix on rows of an image and image in spatial domain is obtained by operating transform matrix on rows of transformed image as shown in equation (5) and (6).

$$F=f*T' \quad (5)$$

$$f=F*T \quad (6)$$

One noticeable advantage of applying column or row transform over applying full transform on image from equations (1) to (6) is that it reduces the number of multiplications by 50% making the operation faster.

In a transformed image, low frequency elements correspond to smoothness of an image and high frequency elements are responsible for texture and edges in the image. Smoothness of the image if damaged by any means is easily noticeable to Human Visual System. In contrast, any alterations made to high frequency elements of an image cause the distortion in image texture and image boundaries. Hence hiding the information in terms of watermark in low or high frequency elements of transformed image is not feasible as it will strongly affect imperceptibility. So the suitable candidate for manipulation by information hiding is middle frequency band. In the proposed method also the middle frequency elements are chosen for embedding the watermark. Applying full transform to image leads to generation of HL and LH frequency bands corresponding to middle frequency elements. When column transform is applied to an image, energy concentration is observed to be at the upper side of an image. Hence middle rows of column transformed image correspond to middle frequency elements. When row transform is applied to an image, energy of image gets concentrated towards the left side of image hence middle columns of row transformed image correspond to middle frequency elements.

By knowing these characteristics of full, column and row transform, HL and LH band of full transformed image and middle rows and middle columns of column and row transformed image respectively are selected for embedding the watermark.

Another important property of transforms considered while embedding the watermark is energy conservation property. So when middle frequency elements of transformed image are replaced by transform coefficients of watermark, energy of watermark is made equal (100%) to the energy of middle frequency band of host by using suitable scaling parameter. A study of embedding less energy (60%) and more energy (140%) in middle frequency band is also done.

Following five images (a)-(e) in Fig. 1 are used as host images and Fig. 1(f) is used as watermark.



Figure1 Host images and a watermark image used for experimental work

V. Results of proposed method under various attacks

For various orthogonal transforms used, results of Lena host image after embedding NMIMS watermark with watermark energy matching to the middle frequency band of host selected for embedding are shown. Figure 2 (a) and (b) below show the watermarked Lena image and extracted watermark from it when the watermark is embedded into HL and LH frequency bands of full Haar transformed image. Mean Absolute Error between host

image and watermarked image as well as between embedded and extracted watermark are shown below each corresponding image.

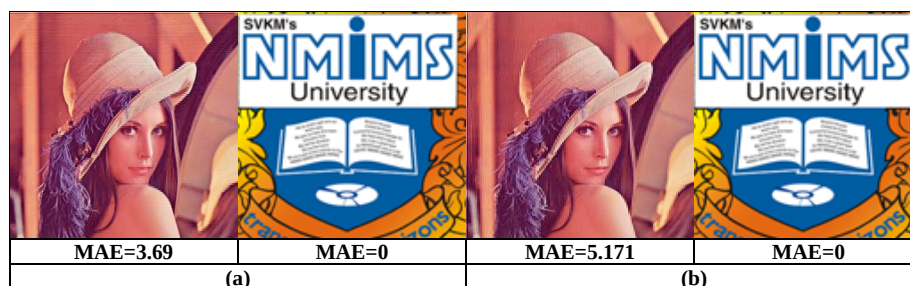


Fig. 2 (a) Watermarked image and extracted watermark using full Haar-HL band (b) Watermarked image and extracted watermark using full Haar-LH band

Fig. 3 (a) and (b) show the watermarked image and extracted watermark from Haar column transformed image and Haar row transformed image.

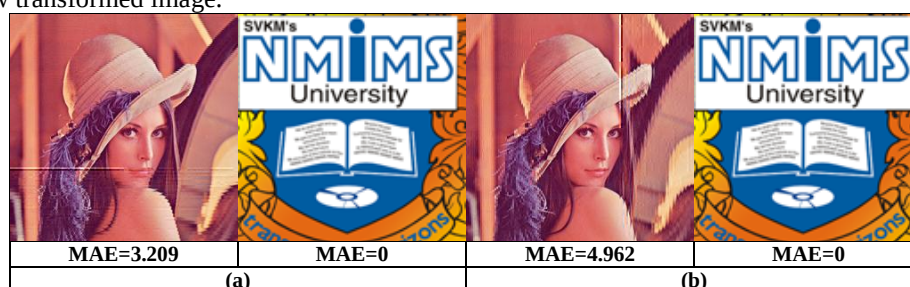


Fig. 3 (a) Watermarked image and extracted watermark using Haar column transform (b) Watermarked image and extracted watermark using Haar row transform

From Fig. 2(a)-(b) and Fig. 3 (a)-(b), it is observed that host image distortion caused by embedding watermark is noticeable in column and row Haar transform though MAE between host and watermarked image is less for them as compared to Full Haar transform-HL and LH frequency band selection for embedding watermark.

A. Performance against various attacks:

Cropping attack: In this type of attack, watermarked image is cropped in three different ways: equally at four corners (16x16size square portion and 32x32size square portion) and at center (32x32 size). Cropped watermark images and watermarks extracted from them when Haar transform is used (full, column and row transform) are shown in Fig. 4(a)-(d).

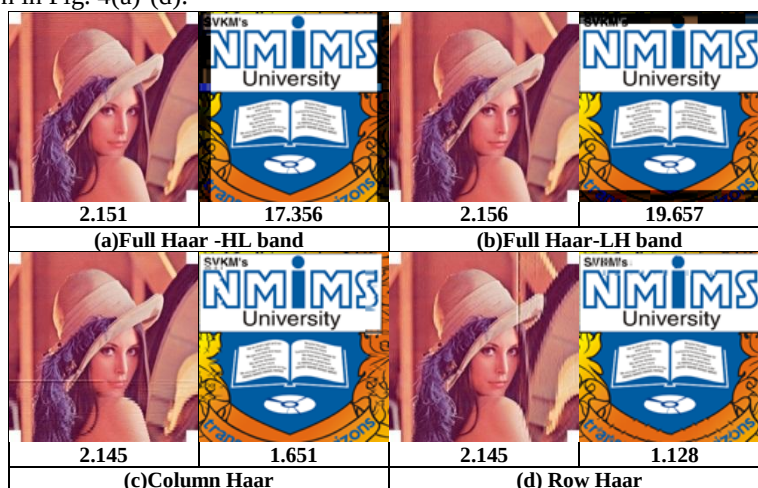


Figure4 (a) cropped watermarked image and watermark extracted from it using full Haar transform and HL band (b) cropped watermarked image and watermark extracted from it using full Haar transform and LH band (c) cropped watermarked image and watermark extracted from it using column Haar transform (d) cropped watermarked image and watermark extracted from it using row Haar transform.

From Fig. 4(a)-(d), it can be seen that for row transform, extracted watermark shows high correlation with the embedded one and is closely followed by column transform. Comparatively, quality of extracted watermark is not good for full transform (both HL and LH band) as it clearly shows the black strips at the borders of extracted watermark.

Compression attack:

Compression is the most common attack that can take place on an image when sent over a network. In the proposed work, compression attack using various orthogonal transforms, JPEG compression and compression

using Vector quantization is performed on watermarked image. Performance of the proposed method against this attack is illustrated in terms of MAE between watermarked image before and after compression and MAE between embedded and extracted watermark from it. Fig. 5(a)-(d) below shows the compressed watermarked image and watermark extracted from it when DCT is used for compression and compression ratio 1.14.

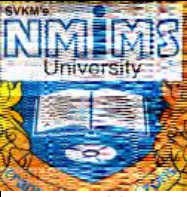
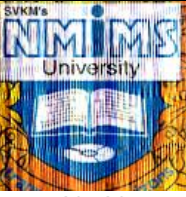
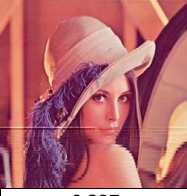
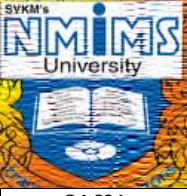
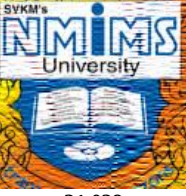
			
1.515	47.539	1.708	39.536
(a) Full Haar -HL band		(b) Full Haar -LH band	
			
0.897	24.684	1.391	31.028
(c) Column Haar		(d) Row Haar	

Fig. 5 (a) DCT Compressed watermarked image and watermark extracted from it using full Haar transform and HL band (b) DCT Compressed watermarked image and watermark extracted from it using full Haar transform and LH band (c) DCT Compressed watermarked image and watermark extracted from it using column Haar transform (d) DCT Compressed watermarked image and watermark extracted from it using row Haar transform.

From Fig. 5(a)-(d), it can be seen that column Haar transform shows better robustness than row and full Haar transform as well as better imperceptibility. For all other compression attacks except compression using vector quantization, column Haar has shown better robustness. Row Haar transform has shown better robustness against VQ based compression attack.

Noise addition attack: In noise addition attack, binary distributed run length noise with different runs and Gaussian distributed run length noise is added to watermarked image. For binary run length noise discrete magnitude level is 0 and 1 whereas Gaussian distributed noise has discrete magnitude between -2 and 2. Fig. 6(a)-(d) shows the results of binary run length noise with run length 10 to 100 and Fig. 7(a)-(d) shows the results of Gaussian distributed run length noise respectively using full, column and row Haar transform.

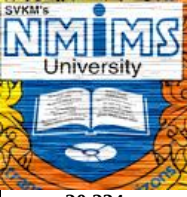
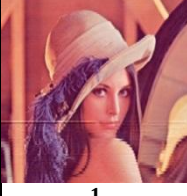
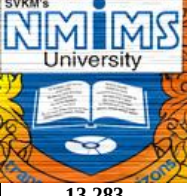
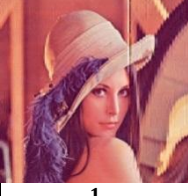
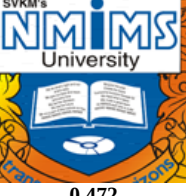
			
1	20.234	1	0
(a) Full Haar -HL band		(b) Full Haar -LH band	
			
1	13.283	1	0.472
(c) Column Haar		(d) Row Haar	

Fig. 6 (a) Binary distributed run length noise added watermarked image and watermark extracted from it using full Haar transform and HL band (b) Binary distributed run length noise added watermarked image and watermark extracted from it using full Haar transform and LH band (c) Binary distributed run length noise added watermarked image and watermark extracted from it using column Haar transform (d) Binary distributed run length noise added watermarked image and watermark extracted from it using row Haar transform.

From Fig. 6(a)-(d), it is observed that embedding watermark in LH band of full transformed host image is strongly robust against specified binary distributed run length noise attack and is closely followed by row transform.

			
0.746	0	0.746	15.144
(a) Full Haar -HL band		(b) Full Haar-LH band	
			
0.746	0.357	0.746	9.088
(c) Column Haar		(d) Row Haar	

Fig. 7 (a) Gaussian distributed run length noise added watermarked image and watermark extracted from it using full Haar transform and HL band (b) Gaussian distributed run length noise added watermarked image and watermark extracted from it using full Haar transform and LH band (c) Gaussian distributed run length noise added watermarked image and watermark extracted from it using column Haar transform (d) Gaussian distributed run length noise added watermarked image and watermark extracted from it using row Haar transform.

As can be seen from Fig. 7, full Haar transform with HL band used for embedding the watermark gives highest robustness against Gaussian distributed run length noise attack and is closely followed by column Haar transform.

Resizing attack: In resizing attack, image is zoomed in using different techniques and watermark is extracted from it after getting back the zoomed image to its original size. Similarly, watermark is also extracted from zoomed image without getting back the zoomed image to its original size. For example, watermarked image of size 256x256 is zoomed to size 512x512 using bicubic interpolation and brought back to size 256x256 to extract the watermark. Another approach followed is transform based image zooming in which Hartley, DFT, DCT, DST and Real Fourier transforms are used to zoom the image as proposed in [19] and zooming using grid based interpolation[20]. This zoomed image is brought back to size 256x256 and then watermark is extracted from it. Similarly, image is zoomed to size 384x384 (1.5 times of the original image) and from this zoomed image watermark is extracted. Fig. 8 shows the results of some representative image resizing attacks using bicubic interpolation, DCT based resizing and Grid interpolation when full Haar, column Haar and row Haar transform is used for watermark embedding.

is used for watermark embedding.

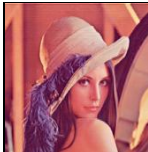
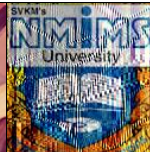
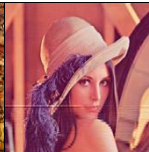
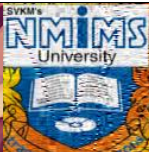
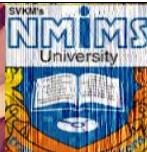
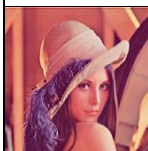
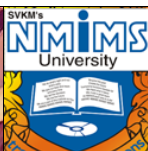
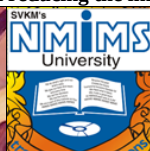
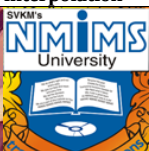
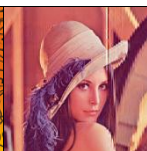
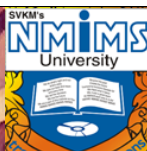
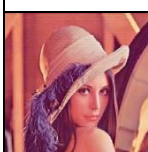
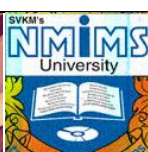
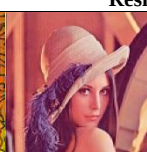
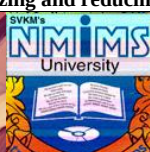
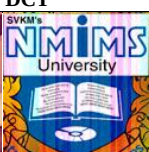
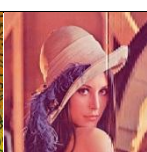
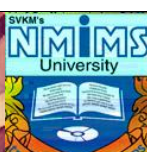
							
1.795	62.318	2.061	58.311	1.38	25.29	1.65	28.90
Full Haar -HL band		Full Haar-LH band		Column Haar		Row Haar	
Resizing and reducing the image using bicubic interpolation							
							
0	0	0	0	0	0	0	0
Full Haar -HL band		Full Haar-LH band		Column Haar		Row Haar	
Resizing and reducing the image using DCT							
							
0.265	10.899	0.298	16.11	0.189	12.50	0.234	17.90
Full Haar -HL band		Full Haar-LH band		Column Haar		Row Haar	
Resized using Grid based resizing technique							

Fig. 8 (a) Resized-reduced watermarked image using bicubic interpolation and watermark extracted from it using full Haar transform and HL band (b) Resized-reduced watermarked image using DCT and watermark extracted from it using full Haar transform and LH band (c) Resized-reduced watermarked image using grid interpolation and watermark extracted from it using column Haar transform (d) Gaussian distributed run length noise added watermarked image and watermark extracted from it using row Haar transform.

From Fig. 8 following observations can be made. For bicubic interpolation based resizing, column Haar transform gives good robustness. For DCT based resizing and all other transform based resizing (i.e. DST, Hartley, Real Fourier Transform and DFT), MAE between embedded and extracted watermark is zero. For resizing using grid based interpolation technique, full Haar transform with HL band used for embedding watermark shows better robustness than column Haar, row Haar and full Haar with LH band.

B. Comparison of various transforms when applied as full (HL and LH), column and row transform

Comparison of various transforms used for embedding the watermark has been done under four categories: full transform HL band used for embedding, full transform LH band used for embedding, column transform and row transform. The case of maintaining 100% embedding energy is considered.

Table 1 below shows the comparison of various transforms used for embedding watermark in the HL band.

Table 1: Comparison of MAE between embedded and extracted watermark using various orthogonal transforms when watermark is embedded in HL band

Attack	Transform used					
	DCT Full HL	DST Full HL	Real Fourier Full HL	Sine-cosine Full HL	Walsh Full HL	Haar Full HL
DCT wavelet compression	20.443	26.948	21.308	27.120	61.952	116.385
DCT compression	3.479	4.286	3.567	4.268	32.565	47.540
DST compression	6.318	3.582	6.220	3.653	32.711	51.454
Walsh compression	51.704	41.742	51.309	42.104	6.298	70.741
Haar compression	84.726	64.234	87.042	65.706	59.434	53.868
JPEG compression	37.261	40.643	38.872	39.890	43.595	45.475
VQ compression	64.754	50.502	64.438	50.665	44.098	43.263
16x16 crop	14.322	14.896	14.101	14.945	2.249	17.356
32x32 crop	31.799	35.040	31.818	35.122	9.216	36.044
32x32 crop at centre	12.342	8.355	11.776	8.912	2.978	0.759
Binary Run Length Noise (1to10)	0.000	0.457	0.000	0.457	0.000	0.000
Binary Run Length Noise (5to50)	31.430	23.096	30.668	23.044	17.732	19.607
Binary Run Length Noise (10 to 100)	30.516	22.822	31.792	22.876	17.043	20.234
Gaussian Distributed run length noise	1.122	0.857	1.138	0.888	0.000	0.000
Bicubic interpolation Resize(4times)-reduce	20.877	20.948	21.177	20.996	37.473	60.837
Bicubic interpolation Resize(2times)-reduce	21.586	21.637	21.893	21.687	38.529	62.318
DFT_resize-reduce	1.998	0.863	1.111	1.454	0.489	9.588
Real FT resize-reduce	0.000	0.000	0.000	0.000	0.000	0.000
Hartley_resize-reduce	0.000	0.000	0.000	0.000	0.000	0.000
DCT resize-reduce	0.000	0.000	0.000	0.000	0.000	0.000
DST resize2	0.000	0.000	0.000	0.000	0.000	0.000
grid resize2	6.639	4.919	6.579	4.921	8.925	10.900
DFT resize1.5 times	89.696	114.346	79.496	115.385	NA	NA
Bicubic interpolation resize1.5 times	62.550	102.951	65.627	103.119	NA	NA
grid based resize 1.5 times	232.301	184.267	215.842	188.541	NA	NA
Histogram equalization	165.551	151.025	166.644	149.988	157.834	139.106

From Table 1 it can be seen that, different transforms prove better for different types of attacks. However from the highlighted cells of the table which correspond to lowest MAE between embedded and extracted watermark, we can say that Haar, Walsh and DCT are performing better than other transforms. For transform based resizing attack, outstanding robustness is shown by all orthogonal transforms used for embedding the watermark with MAE between embedded and extracted watermark zero.

Table 2 shows the performance comparison of various orthogonal transforms used for embedding the watermark in LH band.

Table II: Comparison of MAE between embedded and extracted watermark using various orthogonal transforms when watermark is embedded in LH band

Attack	Transform used					
	DCT Full LH	DST Full LH	Real Fourier Full LH	Sine-cosine Full LH	Walsh Full LH	Haar Full LH
DCT wavelet compression	20.721	25.389	21.637	25.277	66.185	102.888
DCT compression	3.264	3.821	3.308	3.807	32.666	39.537
DST compression	4.442	3.262	4.341	3.412	33.190	42.127
Walsh compression	46.591	44.015	45.818	44.431	5.768	50.598
Haar compression	86.737	74.013	89.504	75.035	62.330	54.236
JPEG compression	34.739	38.278	35.614	37.756	43.558	50.079
VQ compression	46.566	42.901	46.266	43.007	34.469	35.625
16x16 crop	8.456	11.175	8.376	11.216	2.249	19.628
32x32 crop	20.894	27.803	20.679	28.038	9.216	38.421
32x32 crop at centre	9.142	7.304	8.677	7.950	2.978	0.616
Binary Run Length Noise (1to10)	4.811	4.212	5.672	5.213	1.356	2.983
Binary Run Length Noise (5to50)	1.681	1.524	1.658	1.533	0.430	0.939
Binary Run Length Noise (10 to 100)	1.257	1.143	1.341	1.123	0.000	0.000
Gaussian Distributed run length noise	24.375	21.118	24.000	21.401	16.004	15.144
Bicubic interpolation Resize(4times)-reduce	20.939	21.022	21.417	20.952	39.501	56.909
Bicubic interpolation Resize(2times)-reduce	21.648	21.716	22.137	21.644	40.612	58.311
DFT_resize-reduce	2.186	1.006	1.121	1.915	0.472	6.725
Real FT resize-reduce	0.000	0.000	0.000	0.000	0.000	0.000
Hartley_resize-reduce	0.000	0.000	0.000	0.000	0.000	0.000
DCT resize-reduce	0.000	0.000	0.000	0.000	0.000	0.000
DST resize2	0.000	0.000	0.000	0.000	0.000	0.000
grid resize2	4.723	4.193	4.708	4.174	6.122	16.118
DFT resize1.5 times	90.679	96.039	77.384	102.028	NA	NA
Bicubic interpolation resize1.5 times	62.572	91.057	64.972	91.200	NA	NA
grid based resize 1.5 times	217.187	181.693	199.233	188.681	NA	NA
Histogram equalization	162.206	150.612	162.204	150.193	149.343	80.774

Once again from table 2 it can be observed that, different transforms show different degrees of robustness against different attacks. Walsh, Haar and DCT show better performance than other transforms. Walsh performs well for majority of attacks followed by Haar and then DCT.

Table 3 below shows performance comparison of orthogonal column transforms against various attacks.

Table III: Comparison of MAE between embedded and extracted watermark using various orthogonal column transforms

Attack	Transform used					
	DCT Column	DST Column	Real Fourier Column	Sine-cosine Column	Walsh Column	Haar Column
DCT wavelet compression	39.901	47.715	44.457	47.422	71.895	63.734
DCT compression	0.000	0.064	0.049	0.054	7.182	24.685
DST compression	0.223	0.000	0.209	0.057	7.598	26.212
Walsh compression	15.788	12.396	15.634	12.691	0.000	11.720
Haar compression	33.202	30.727	37.628	40.407	11.901	0.000
JPEG compression	28.969	31.591	29.270	31.426	170.211	30.450
VQ compression	47.692	40.766	47.639	41.388	39.719	37.361
16x16 crop	15.491	21.870	16.259	22.664	4.733	1.651
32x32 crop	32.745	42.467	33.024	44.040	17.227	5.728
32x32 crop at centre	13.312	10.437	13.065	10.535	6.900	0.000
Binary Run Length Noise (1to10)	0.000	0.315	0.000	0.342	0.000	0.000
Binary Run Length Noise (5to50)	15.398	11.687	15.524	13.049	12.651	13.358
Binary Run Length Noise (10 to 100)	17.317	13.152	16.066	11.250	12.779	13.284

Gaussian Distributed run length noise	0.770	0.787	0.974	0.724	1.099	0.358
Bicubic interpolation Resize(4times)-reduce	12.059	13.548	12.321	13.737	21.579	24.578
Bicubic interpolation Resize(2times)-reduce	12.498	14.018	12.768	14.212	22.267	25.298
DFT_resize-reduce	0.364	0.349	0.347	0.397	0.241	1.337
Real FT resize-reduce	0.000	0.000	0.000	0.000	0.000	0.000
Hartley_resize-reduce	0.000	0.000	0.000	0.000	0.000	0.000
DCT resize-reduce	0.000	0.000	0.000	0.000	0.000	0.000
DST resize2	0.000	0.000	0.000	0.000	0.000	0.000
grid resize2	4.978	4.278	4.986	4.393	5.929	12.502
DFT resize1.5 times	129.611	139.405	136.072	127.135		
Bicubic interpolation resize1.5 times	124.112	130.534	129.561	121.534		
grid based resize 1.5 times	179.530	162.725	191.747	156.927		
Histogram equalization	169.434	170.085	169.407	171.503	161.122	104.832

Table 3 shows that Haar column transform provides noticeable robustness against various attacks performed on watermarked images. Followed by column Haar is DCT column transform which shows better robustness against bicubic interpolation based resizing, DCT wavelet compression and JPEG compression attack.

Table IV: Comparison of MAE between embedded and extracted watermark using various orthogonal row transforms

Attack	Transform used					
	DCT Row	DST Row	Real Fourier Row	Sine-cosine Row	Walsh Row	Haar Row
DCT wavelet compression	42.617	46.821	45.118	47.016	72.467	70.673
DCT compression	0.000	0.058	0.043	0.044	8.089	31.029
DST compression	0.163	0.000	0.146	0.058	8.312	31.314
Walsh compression	17.776	15.514	17.712	15.666	0.000	11.889
Haar compression	30.536	29.565	34.666	36.577	12.185	0.000
JPEG compression	27.238	28.908	27.834	28.850	25.419	33.579
VQ compression	40.216	37.850	40.090	37.739	33.740	28.905
16x16 crop	10.954	19.150	11.259	19.312	6.571	1.129
32x32 crop	27.507	41.881	27.676	41.523	21.900	6.535
32x32 crop at centre	11.784	10.104	11.492	10.322	5.635	0.000
Binary Run Length Noise (1to10)	3.816	3.215	3.751	4.384	2.919	4.456
Binary Run Length Noise (5to50)	1.875	1.619	1.872	1.696	2.185	1.022
Binary Run Length Noise (10 to 100)	1.087	1.077	1.215	1.034	1.317	0.472
Gaussian Distributed run length noise	13.894	11.765	13.519	12.048	10.139	9.088
Bicubic interpolation Resize(4times)-reduce	12.019	13.232	12.451	13.164	21.628	28.114
Bicubic interpolation Resize(2times)-reduce	12.454	13.695	12.899	13.623	22.313	28.904
FFT_resize-reduce	0.370	0.350	0.343	0.384	0.246	1.370
Real FT resize-reduce	0.000	0.000	0.000	0.000	0.000	0.000
Hartley_resize-reduce	0.000	0.000	0.000	0.000	0.000	0.000
DCT resize-reduce	0.000	0.000	0.000	0.000	0.000	0.000
DST resize2	0.000	0.000	0.000	0.000	0.000	0.000
grid resize2	4.367	4.292	4.438	4.126	5.333	17.907
DFT resize1.5 times	144.271	150.256	145.672	142.358		
Bicubic interpolation resize1.5 times	134.597	138.563	133.834	135.818		
grid based resize 1.5 times	179.770	166.270	186.285	165.164		
Histogram equalization	166.751	163.012	168.509	163.228	164.713	71.624

Table 4 shows that Haar row transform shows highest robustness against maximum number of attacks. Since from Table 1 to Table 4, Haar, Walsh and DCT are prominently seen showing better robustness than other transforms in their full, column and row version, a representative comparison of full, column and row Haar transform is shown in Table 5.

Table V: Comparison of MAE between embedded and extracted watermark using Column, Row and Full Haar transform

Attack	Haar Column Transform	Haar Row Transform	Haar Full Transform HL	Haar Full Transform LH
DCT wavelet compression	74.723	84.251	132.565	119.884
DCT compression	30.121	38.501	55.895	48.312
DST compression	32.101	38.849	59.616	50.927
Walsh compression	12.111	12.369	70.741	50.598
Haar compression	0.000	0.000	53.868	54.236
JPEG compression	31.235	33.412	49.196	50.561
VQ compression	42.831	33.849	52.419	42.511
16x16 crop	1.651	1.129	17.356	19.628
32x32 crop	5.728	6.535	36.044	38.421
32x32 crop at centre	0.000	0.000	0.759	0.616
Binary Run Length Noise (1to10)	0.000	6.313	0.000	6.446
Binary Run Length Noise (5to50)	16.609	1.472	26.385	1.334
Binary distributed run length noise(10 to 100)	16.580	0.487	26.650	0.000
Gaussian Distributed run length noise	0.460	11.679	0.000	19.519
Bicubic interpolation Resize(4times)-reduce	27.853	33.102	68.123	64.747
Bicubic interpolation Resize(2times)-reduce	28.656	34.018	69.783	66.349
FFT_resize-reduce	1.630	1.621	9.588	6.725
Real FT resize-reduce	0.000	0.000	0.000	0.000
Hartley_resize-reduce	0.000	0.000	0.000	0.000
DCT resize-reduce	0.000	0.000	0.000	0.000
DST resize-reduce	0.000	0.000	0.000	0.000
grid resize2	11.215	15.207	11.475	12.324
Histogram Equalization	116.753	88.768	164.577	97.913

In Table 5, cell highlighted with yellow color indicates that for an attack in the corresponding row, transform in corresponding column gives best performance among other similar type of transforms (full/row/column) and green color indicates it is the second best performer. Thus from Table 5, it can be prominently seen that Haar column transform proves to be the best performer against various attacks, closely followed by Haar row transform. When other row and column transforms are compared, Walsh column/row transform is the next best performer followed by DCT column/row transform.

VI. Conclusion

For majority of attacks, Haar transform gives better performance that too when applied column wise or row wise (followed by each other) followed by Walsh transform column wise or row wise. Between column and row transform of Haar / Walsh, column transform gives better performance closely followed by row transform (except VQ based compression and Binary run length noise with run length 5 to 50 and 10 to 100). The overall performance of full, column and row transform can be rated in the following sequence

1. Haar row transform
2. Haar column transform
3. Walsh column/Row transforms
4. DCT Column/ Row transform

For bicubic interpolation based resizing, (4 times and 2 times), Haar is the worst performer. DCT row / column transform is the best in this case followed by Real Fourier row / column transform. For compression attack using DCT wavelet and DCT, DCT column/row/full gives better performance. Among them row transform gives best results. Robustness against attacks improves as the embedding energy is increased. We have studied three cases of varying energy of embedded watermark namely 60%, 100% and 140%. Although the robustness is better for 140% energy, the error in watermarked image is noticeable. Hence the results of 100% are given in the paper.

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