A Comparison of Haar Wavelets and Kekre's Wavelets for Storing Colour Information in a Greyscale Image

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ABSTRACT
The technique to store colour information within a greyscale image has been proposed previously using various colour spaces, such as the YCbCr, LUV, YCgCb, YUV, and YIQ colour spaces, and using the Haar wavelet transform. One such study is described in [1]. This research paper extends the study to another wavelet transform – Kekre's wavelet transform (abbreviated as KWT). The embedding of the colour information into the greyscale image leads to the formation of a slightly distorted greyscale image known as a "matted greyscale" image. This matted greyscale image is used to reconstruct the colour image.

Keywords – Colouring, Colour to Grey, Matted Greyscale, Grey to Colour, Colour Space, YCbCr, LUV, YCgCb, YIQ, YUV, Haar Wavelets, Kekre's Wavelet Transform.

I. INTRODUCTION
Embedding colour information in a greyscale image has many advantages, not least of which is the fact that the colour image can be generated from just the greyscale image. This would simplify transmission of images as only one plane needs to be sent (i.e. the greyscale or luminance plane) instead of three planes, one each for red (R), green (G), and blue (B).

One technique for achieving this is by transforming the colour image from the RGB colour space to a colour space that is based on luminance and chrominance components such as the YCbCr or LUV colour spaces. The luminance component is then taken to create the greyscale image which is transformed using some appropriate image transform such as the Discrete Wavelet Transform (DWT) or the Haar Transform. The chrominance components are then scaled down and are used to replace the lesser significant portions of the transformed matrix. This matrix is then inverse transformed back into a greyscale image, thus embedding colour information in the greyscale image.

This technique has been described in [1] using the YCbCr, LUV, YCgCb, YUV, and YIQ colour spaces and the Haar transform. The technique itself is based on a technique proposed in [2] which used just the YCbCr colour space and the Discrete Wavelet Transform (abbreviated as DWT). This paper extends the study of the same technique by using a new transform – Kekre's Wavelet Transform (abbreviated as KWT) – and compares the results obtained using the Haar Transform and KWT across the same colour spaces.

The following sections describe the various colour spaces used, followed by details on the two transformations used (the Haar Transform and Kekre's Wavelet Transform). Subsequent sections provide a detailed description of the technique used to embed the colour information in the greyscale image, and finally the results of applying the technique using the different transforms and the different colour spaces. Hence a thorough comparison of the performance of this technique using the Haar Transform and Kekre's Wavelet Transform is obtained across various colour spaces.

II. YCbCr COLOUR SPACE
The YCbCr model defines a colour space in terms of one luminance (brightness) and two chrominance (colour) components. It is one of the most extensively used colour spaces and has been considered for many applications such as those described in [2], [3], and [4]. In the YCbCr colour space, the Y component gives luminance and the Cb and Cr components give the chromaticity values of the colour image. To get the YCbCr components, the conversion of the RGB components to YCbCr components must be known. The RGB to YCbCr conversion matrix is given below.

$$\begin{bmatrix} Y \\ Cb \\ Cr \end{bmatrix} = \begin{bmatrix} 0.2989 & 0.5866 & 0.1145 \\ -0.1688 & -0.3312 & 0.5 \\ 0.5 & -0.4184 & -0.0816 \end{bmatrix} . \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad (1)$$

To get the RGB values from the YCbCr components, the following conversion matrix can be used.

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1 & -0.001 & 1.402 \\ 1 & -0.3441 & -0.714 \\ 1 & 1.7718 & 0.001 \end{bmatrix} . \begin{bmatrix} Y \\ Cb \\ Cr \end{bmatrix} \quad (2)$$

III. LUV COLOUR SPACE
The LUV colour space is a colour space generally used in techniques involving the colourization of images such as those described in [5], [6], [7], and [8]. In the LUV colour space, the L component provides the luminance, while the U and V components contain the colour information. The RGB to LUV conversion matrix is given below.

$$\begin{bmatrix} L \\ U \\ V \end{bmatrix} = \begin{bmatrix} 0.33333 & 0.33333 & 0.33333 \\ -0.3333 & 0.16667 & 0.16667 \\ 0 & -0.5 & 0.5 \end{bmatrix} . \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad (3)$$

To get the RGB values from the LUV components, the following conversion matrix can be used.

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1 & -2 & 0 \\ 1 & 1 & -1 \\ 1 & 1 & 1 \end{bmatrix} . \begin{bmatrix} L \\ U \\ V \end{bmatrix} \quad (4)$$

A negative value for the U component in the LUV colour space indicates prominence of the red component in the colour image. Similarly, a negative value for the V component indicates prominence of the green component over the blue component in the colour image.

IV. YCgCb COLOUR SPACE

The YCgCb colour model is a newly proposed colour space similar to the LUV colour space described in the previous section. Since it is newer than the LUV colour space, it has not yet been used extensively. One application not directly related to the technique under discussion is described in [9].

In the YCgCb colour space, the Y component provides the luminance, while the Cg and Cb components contain the chromaticity values. The RGB to YCgCb conversion matrix is given below.

$$\begin{bmatrix} Y \\ Cg \\ Cb \end{bmatrix} = \begin{bmatrix} 0.33333 & 0.33333 & 0.33333 \\ 0.33333 & -0.3333 & 0 \\ 0.33333 & 0 & -0.3333 \end{bmatrix} . \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad (5)$$

To get the RGB values from the YCgCb components, the following conversion matrix can be used.

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & -2 & 1 \\ 1 & 1 & -2 \end{bmatrix} . \begin{bmatrix} Y \\ Cg \\ Cb \end{bmatrix} \quad (6)$$

A negative value for the Cg component in the YCgCb colour space indicates prominence of the green component over the red component in the colour image. Similarly, a negative value for the Cb component indicates prominence of the blue component over the red component.

V. YIQ COLOUR SPACE

YIQ is the colour space used by the NTSC colour TV system, employed mainly in North and Central America. ‘I’ stands for “in phase” and ‘Q’ stands for “quadrature,” referring to the components used in quadrature amplitude modulation.

As in the YCbCr colour space, the Y component gives luminance and the I and Q components give the chromaticity values of the colour image. To get the YIQ components, the conversion of the RGB components to the YIQ components is defined by the following conversion matrix.

$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ 0.596 & -0.275 & -0.321 \\ 0.212 & -0.523 & 0.311 \end{bmatrix} . \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad (7)$$

To get the RGB values from the YIQ components, the following conversion matrix can be used.

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1 & 0.956 & 0.621 \\ 1 & -0.272 & -0.647 \\ 1 & -1.107 & 1.704 \end{bmatrix} . \begin{bmatrix} Y \\ I \\ Q \end{bmatrix} \quad (8)$$

VI. YUV COLOUR SPACE

YUV is a colour space that encodes a colour image or video taking human perception into account, allowing reduced bandwidth for chrominance, thereby typically enabling transmission errors or compression artefacts to be more efficiently masked by human perception than using a direct RGB representation.

Similar to the other colour spaces discussed previously, the Y component gives luminance, and the U and V components provide the chrominance values. The RGB to YUV conversion matrix is shown below.

$$\begin{bmatrix} Y \\ U \\ V \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ -0.1471 & -0.2889 & 0.436 \\ 0.615 & -0.5149 & 0.10001 \end{bmatrix} . \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad (9)$$

To get the RGB values from the YUV components, the following conversion matrix can be used.

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 0.74952 & -0.509 & 1.1398 \\ 1.0836 & -0.2247 & -0.5806 \\ 0.97086 & 1.9729 & 0.00001467 \end{bmatrix} . \begin{bmatrix} Y \\ U \\ V \end{bmatrix} \quad (10)$$

VII. HAAR TRANSFORM

The Haar functions were proposed as a sequence in 1909 by Alfréd Haar [10]. Haar used these functions to give an example of a countable orthonormal system for the space of square-integrable functions on the real line. The study of wavelets, and even the term "wavelet", did not come until much later [11]. The Haar wavelet is also the simplest possible wavelet. As the Haar wavelet is not continuous, it is also not differentiable. This is a technical disadvantage of Haar wavelets.

The Haar wavelet's mother wavelet function ψ(t) can be described as follows.

$$\psi(t) = \begin{cases} 1, & 0 < t \le \frac{1}{2} \\ -1, & \frac{1}{2} < t \le 1 \\ 0, & otherwise \end{cases} \quad (11)$$

VIII. KEKRE’S WAVELET TRANSFORM

The KWT matrix is a generic version of the LUV colour space matrix. Unlike most other transforms (wavelet or otherwise), the size of the KWT matrix need not be a power of two which is definitely an advantage of this transform.

The general form of an N x N KWT matrix is as follows.

$$\begin{bmatrix} 1 & 1 & 1 & \cdots & 1 & 1 \\ -N+1 & 1 & 1 & \cdots & 1 & 1 \\ 0 & -N+2 & 1 & \cdots & 1 & 1 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 1 & 1 \\ 0 & 0 & 0 & \cdots & -N+(N-1) & 1 \end{bmatrix}$$

Figure 1 – General N x N KWT matrix

As can be seen in figure 1 above, in the KWT matrix, all values above the diagonal are one (including the diagonal itself). The diagonal just below the primary diagonal has specific values, and all remaining values in the matrix are zeroes. In general, the value of K_{xy} in the KWT matrix, where ‘x’ is the row number starting from 1 and ‘y’ is the column number also starting from one, is given by the following equation.

$$K_{xy} = \begin{cases} 1, & x \le y \\ -N + (x-1), & x = y + 1 \\ 0, & otherwise \end{cases} \quad (12)$$

The inverse KWT matrix is nothing but the transpose of the above general matrix as the KWT is orthogonal. Normalization is required to get back the identity matrix.

IX. COLOUR TO MATTED GREY CONVERSION

The most trivial way to convert a colour image to greyscale for printing is to retain and use the luminance component of the colour image. The problem with this approach is that regions that have contrasting colours with similar luminance components would be assigned the same output luminance level and would, therefore, look the same.

The other option is to map colours to textures [2]. One can control halftone dots or patterns as a function of the colours, for example, as a function of hue and saturation. Hence, regions of different colours with similar luminance will look different after mapping because they would have different textures [12]. The

procedure proposed in [2] produces a continuum of textures using the DWT that naturally switch between patterns without causing visual artefacts. The DWT decomposes an image into several sub-bands [13] each representing different spatial frequency contents.
In this paper, as explained previously, is an extension of [1] and is a more detailed study of a technique based on the one described in [2]. Here, the wavelet transforms used are the basic Haar transform and the KWT. Five different colour spaces are considered – LUV, YCbCr, YCgCb, YIQ, and YUV. The greyscale image obtained by following the procedure outlined below is known as the matted greyscale image and it contains the colour information about the image embedded within its transform.

As various colour spaces are used, the procedure is outlined for a general colour space 'ABC' where 'A' is the luminance component, and 'B' and 'C' are the chromaticity components. As two different transforms are used, even the transforms are generalized as just 'the transform.' The following procedure has been taken from [1].

The steps involved to create the matted greyscale image are as follows.

1. The original colour image is converted from the RGB colour space into the ABC colour space using the appropriate conversion matrix, that is, using equations (1), (3), (5), (7), or (9) for the YCbCr, LUV, YCgCb, YIQ, and YUV colour spaces respectively. The 'A' component is the luminance and is considered as the "original greyscale" image.
2. The 'A' component is transformed using the transform into the transform domain. Let this transformed image be known as T_o.
3. T_o can be divided into 4 regions as shown in figure 1 below.

LL	LH
HL	HH

Figure 2 – Structure of T_o

4. Most of the information in the image is found in the LL region of T_o which corresponds to the low frequency components of the image. This region is left untouched. The LH and HL regions of T_o are replaced by scaled down versions of the 'B' and 'C' components respectively. Thus we now have a modified transformed image that contains scaled down versions of the chromaticity components of the colour space being used. Let this be known as T_m.
5. The inverse transform is now applied to T_m to get a new greyscale image in the spatial domain. This greyscale image now contains colour information hidden within its transform and is known as the matted greyscale image.

X. COLOUR EXTRACTION FROM MATTED GREY

Since the matted greyscale image already contains the colour information hidden within its transform, extracting the colour image from the matted greyscale image is a straightforward procedure. It consists of the following steps.

1. The matted greyscale image is read or scanned.
2. Once available in digital form, the matted greyscale image is transformed using the transform into the transform domain. The transformed image obtained will be T_m.
3. T_m can be represented as shown in figure 2 below.

LL	B'
C'	HH

Figure 3 – Structure of T_m

4. The B' and C' regions of T_m are the scaled down versions of the 'B' and 'C' components of the original colour image. Thus by extracting these two regions from T_m and scaling them up back to their original size we get B_{approx} and C_{approx} which are approximations of the original 'B' and 'C' components of the original colour image.
5. To retrieve an approximation for the 'A' component, we replace regions B' and C' in T_m by zeroes and perform an inverse transformation. The image obtained in the spatial domain is an approximation of the original 'A' component of the image, A_{approx}.

Now the approximations for the ABC components are used to convert the image back to the RGB colour space using the appropriate conversion matrices, that is, equations (2), (4), (6), (8), and (10) for the YCbCr, LUV, YCgCb, YIQ, and YUV colour spaces respectively.

XI. IMPLEMENTATION AND RESULTS

The implementation of the technique described in the previous section was an extension of the implementation described in [1]. The technique was broadened to include the KWT and the results obtained using the KWT were also added. The technique was applied to a large number of images. All the images were of the size 256 x 256 pixels, and belonged to various categories such as people, objects, vehicles, animals, cartoons, and nature.

On applying the technique proposed, the following set of images was derived from the each original image – original colour, original greyscale, matted greyscale, and reconstructed colour.

Performance was measured by calculating the mean square error (MSE) between the original greyscale image and the matted greyscale image as well as between the original colour image and the reconstructed colour image. The MSE is the mean of the square of the Euclidean distances between each pixel value. The Euclidean distance 'd' between two images I_m and I_o is defined as follows.

$$d = \sqrt{\sum (z_m - z_o)^2} \qquad (13)$$

Where, z_m is the value of the pixel in I_m, z_o is the value of the corresponding pixel in I_o and the summation is over all pixels in the images.

It must be noted that for a colour image, each pixel will have 3 values, one for the red (R) plane, one for the green (G) plane, and one for the blue (B) plane. The MSE thus provides an objective criterion that can be used as a measure of the degree of similarity between two given images. The greater the similarity between the two images at the pixel level, the lower the MSE.

The table 1 given below shows the MSE values between the matted greyscale images and the original greyscale images averaged across all images for each of the five colour spaces and both transforms.

	MSE (Haar)	MSE (KWT)
YCbCr	411.221335	401.618715
LUV	341.32406	335.38614
YCgCb	317.00611	309.915005
YIQ	432.70043	423.13666
YUV	643.38025	603.0701

Table 1 – Greyscale MSE across all images

Figure 4 illustrates the results graphically.

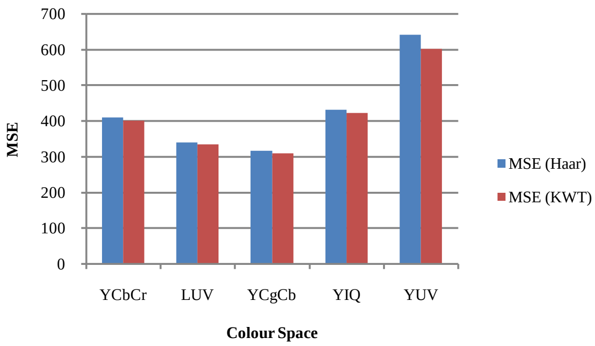

Figure 4 – Greyscale MSE across all images

As can be clearly seen from the figure above, the YCgCb colour space provided the best results in terms of the MSE across all images for the matted greyscale image. Also, the KWT consistently outperformed the Haar transform across all colour spaces, but not by an extremely significant amount.

The results for the reconstructed colour images, however, were slightly different. The table below shows the MSE values between the reconstructed colour images and the original colour images.

	MSE (Haar)	MSE (KWT)
YCbCr	245.36608	268.69903
LUV	233.00122	249.32088
YCgCb	245.31157	263.90563
YIQ	249.90365	265.723
YUV	417.922255	498.013915

Table 2 – Colour MSE across all images

Figure 5 illustrates the results graphically.

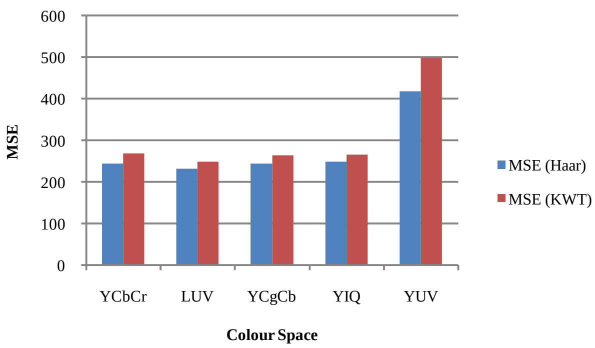

Figure 5 – Colour MSE across all images

It can be noticed that in the case of the reconstructed colour images, there is no clear winner across four colour spaces when the MSE is averaged across all images: YCbCr, LUV, YCgCb, and YIQ. The YUV colour space clearly underperforms using this technique for both greyscale and colour images and hence is not recommended. The colour space that performs the best is the LUV colour space, but not by a large amount. The YCgCb colour space, the YIQ colour space, and the YCbCr colour space give almost identical performance results based on the MSE.

When considering the transforms, on the other hand, here the roles are reversed. The Haar transform now appears to perform consistently better than the KWT. Once again, as the case was with the greyscale MSE, the difference in performance between the two transforms is now extremely significant.

Some of the images used when implementing this procedure are shown below.

Figure 6a, b – Original Colour, Original Greyscale

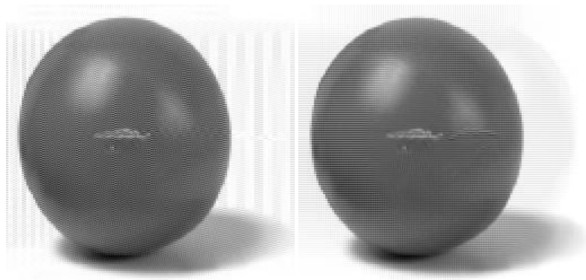

Figure 6c, d – Matted Greyscales (Haar, KWT)

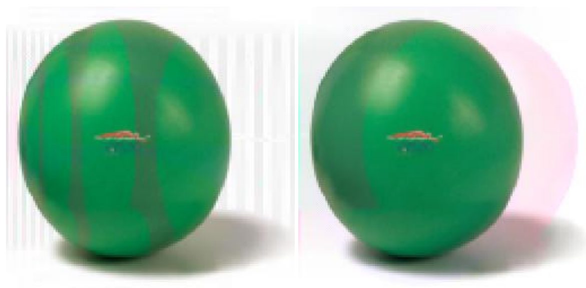

Figure 6e, f – Reconstructed Colour (Haar, KWT)

Figure 6 shows an image of a green ball. This is a simple image with a plain white background. The only object in the image is the ball itself. It can be seen that in the case of the matted greyscale image generated using the KWT, there appears to be an extra shadow behind the ball itself. While this shadow effect does not seem to unduly mar the quality of the matted greyscale image, the reconstructed colour image gets adversely affected.

Considering the Haar transform, the reconstructed colour image does not have the shadow effect behind the ball, however the ball itself is more discoloured than in the case of the KWT. There are at least three prominent discolourations on the green surface.

Figure 7a, b – Original Colour, Original Greyscale

Figure 7c, d – Matted Greyscales (Haar, KWT)

Figure 7e, f – Reconstructed Colour (Haar, KWT)

Figure 7 shows the image of a red car. Once again this is a relatively simple image with all details concentrated solely in the foreground. This image is more complex than that of the ball shown in figure 6. For this image, the matted greyscales look acceptable for both transforms, however a subjective evaluation of the quality of the reconstructed colour images shows the image created using the KWT to be of superior quality. The discolourations in the reconstructed colour image obtained using the Haar transform are very prominent.

Figure 8a, b – Original Colour, Original Greyscale

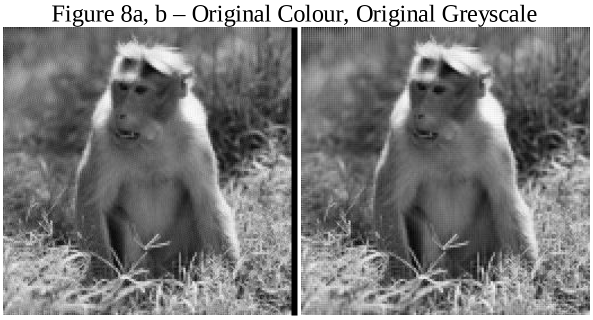

Figure 8c, d – Matted Greyscales (Haar, KWT)

Figure 8e, f – Reconstructed Colour (Haar, KWT)

Figure 8 shows a more complex image than the ones seen till now. This image has both foreground and background detail. The results obtained, using either transform, for this image are similar. Both performed exceedingly well and neither resulted in any extreme discolourations in the reconstructed colour images. The matted greyscale images were also highly acceptable with minimal distortions.

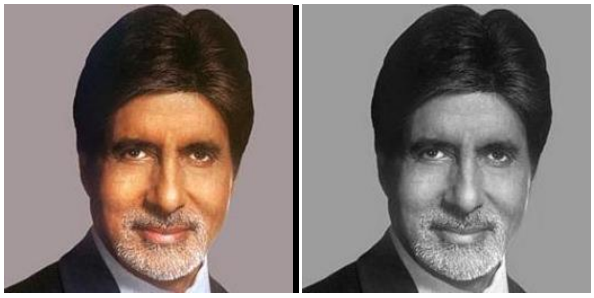

Figure 9a, b – Original Colour, Original Greyscale

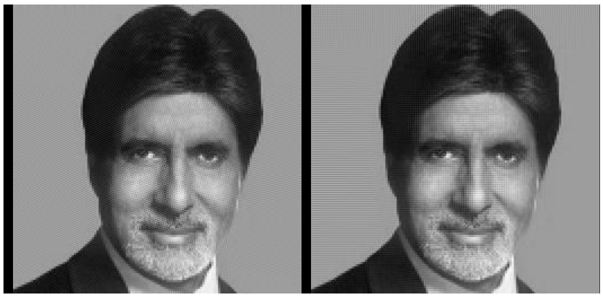

Figure 9c, d – Matted Greyscales (Haar, KWT)

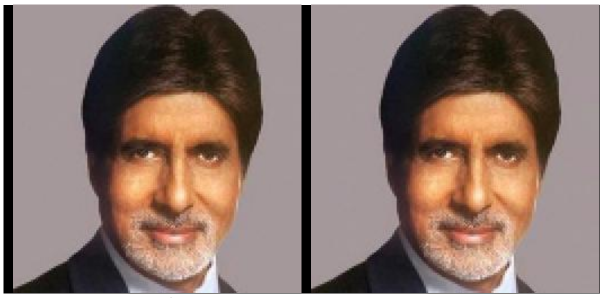

Figure 9e, f – Reconstructed Colour (Haar, KWT)

Finally, figure 9 shows a face. It should be noted that both matted greyscale images have a black strip of pixels on the left which is absent in the original greyscale image, and that this strip of pixels persist even in the reconstructed colour images. Both reconstructed colour images are of similar quality and are acceptable.

The MSE for both the matted greyscale images and the reconstructed colour images using both transforms for the images shown in figures 6 to 9 are given in table 3 and table 4 respectively. Figures 10 and 11 illustrate the same results graphically.

	MSE (Haar)	MSE (KWT)
Ball	368.8388	359.4922
Car	764.5332	741.3582
Monkey	274.749	274.4384
Face	228.1034	228.375

Table 3 – Greyscale MSE

	MSE (Haar)	MSE (KWT)
Ball	173.84852	196.052
Car	497.4836	561.1308
Monkey	158.2638	158.675
Face	45.67854	45.83958

Table 4 – Colour MSE

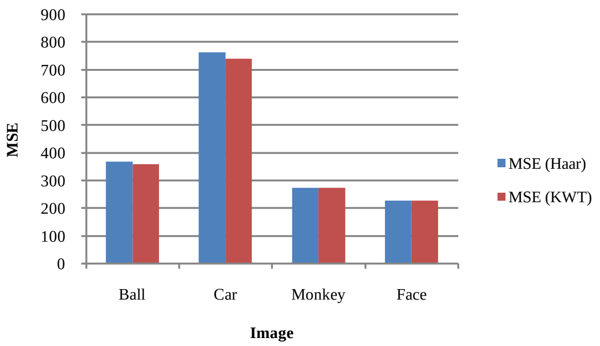

Figure 10 – Graphical Representation of Greyscale MSE

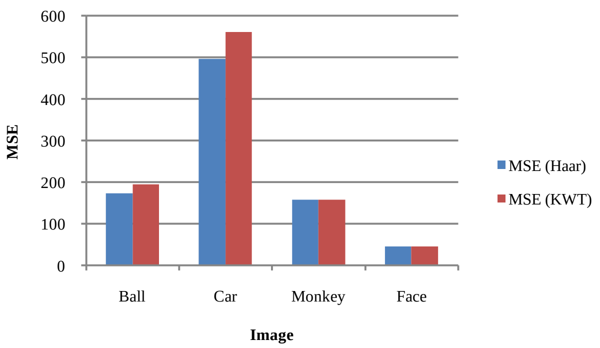

Figure 11 – Graphical Representation of Colour MSE

XII. CONCLUSION

In conclusion, it can be said that the performance of both the Haar wavelet transform and the KWT using this technique to embed colour information inside a greyscale image is similar when compared objectively using the MSE. However, when the images are subjectively compared, the discolourations caused when the Haar transform is used are more prominent and distracting than when the KWT is used. Thus, the KWT is a good choice for the wavelet transform to be used when implementing this technique, especially with its added advantage of working on all image sizes and not just those images whose sizes are a power of two.

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