Performance Evaluation of JPEG, JPEG2000 and New CSI-JPEG Algorithms by Incorporating Different Color Spaces

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Abstract

In the current work, seven different color spaces were investigated including sRGB, YCbCr, YCoCg-R, RDgDb, CIELAB, IPT, and CAM02-UCS by incorporating into JPEG1992, JPEG2000 and new JPEG. The prime objective of this work was to compare the performance of CSI-JPEG with that of JPEG1992 and JPEG2000. Psychophysical experiments were also performed to examine visual appearance of the compressed and decompressed images. Compression performance was examined for different color spaces by using measures like SNR, PSNR, MSE, CIEDELAB and CIEDE2000. The results showed that CSI-JPEG algorithm provided about 20-30% more compression rate compared to JPEG1992 algorithm for same color difference. Moreover, CAM02-UCS was found to perform best in terms of compression rate and image quality for all three algorithms. The CAM02-UCS was found significantly better compared with linear color spaces but CIELAB, CIELUV, and IPT were insignificantly better. This also implies that it is visually more uniform than CIE uniform color spaces. Results also showed that performance difference of CSI-JPEG and JPEG2000 was not significant but both performed significantly better compared with JPEG1992.

Introduction

Researchers have been working on image compression for last few decades [1-8]. The most commonly used industrial standard for image compression is JPEG 1992 standard, an algorithm proposed by joint photographic experts group (JPEG) [1]. JPEG is a low loss compression algorithm which can achieve desired degree of compression by allowing a selectable tradeoff between compression rate and quality of the compressed image. For fast and less expensive storage/transmission of photographic images, JPEG has become the most widely used format. For typical web usage, storage size of image data is very important and for such applications JPEG is very popular. It performs its best when used for photographs with smooth variations of tone and color. A more advanced version of JPEG is JPEG2000 [2] which has been developed for particular interests and improvements including better compressibility, color accuracy, tile structure support resolution accuracy, high dynamic range support, flexibility of file format, lossless, near lossless or lossy compression etc.

It has become crucial to investigate that which color space has more compressibility and better visual performance. Moroney *et. al* [3], investigated six different color spaces to propose the best one to improve compression performance of JPEG [3]. They found that CIE uniform color spaces CIELAB and CIELUV performed best and similar but performance of CIELUV was inconsistent. Zhu and Luo [4], investigated different models and found that non-linear models perform better comparing with linear models. Malvar [5], reviewed some reversible color spaces for image compression and found that a reversible variant of YCoCg called YCoCg-R can perform better. Starosolski [6], recently have investigated a number of commonly used color spaces in compression algorithms and tested by incorporating into significantly different algorithms including JPEG-LS, JPEG2000, and JPEG-XR. He found that RDgDb performed best on average for JPEG-LS and JPEG2000, while its variant mRDgDb performed best for JPEG-XR. In our last year's research [7], we investigated six different color spaces (sRGB, XYZ, YIQ, CIELAB, CIELUV, and CAM02-UCS) by incorporating them into JPEG1992 and newly developed CSI-JPEG algorithms. We concluded that proposed CSI-JPEG performed significantly better compared with JPEG1992 and CAM02-UCS outperformed other five color spaces tested.

Some newly developed uniform color spaces like IPT and CAM02-UCS, and some newly proposed linear color space such as YCoCg-R and RDgDb, need to be comprehensively investigated for their compression performance [9-10]. It is believed that a more uniform color space close to visual perception should give better performance in image compression i.e. equal amount of compression in different color regions to give same amount of perceived color differences. Based on previous investigations and in order to comprehensively study newly developed uniform color spaces, a set of seven color spaces was selected for the current study. The present work was conducted to study different color spaces and algorithms more comprehensively. So, more color spaces (YCbCr, YCoCg-R, RDgDb, and IPT) were selected and those from the previous set [7] which had good and/or consistent performance were also included in the current set.

Seven widely used and popular color spaces were investigated including standard display device space sRGB, YCbCr used in JPEG and JPEG2000, YCoCg-R supported by video compression codecs, RDgDb best among linear models according to resent investigations of Starosolski [6], CIE uniform color space CIELAB, IPT which has better hue uniformity, and a CIECAM02 based color space CAM02-UCS. These were incorporated into standard JPEG, proposed CSI-JPEG, and JPEG2000 algorithms. The CIEDE2000 color difference formula was used for performance analysis [11]. Note that both CAM02-UCS [10] and CIEDE2000 [11] were derived to fit same reliable color-difference datasets. They have very similar performance. However the later does not have a color space on which the performance of image compression can be based.

Compression Algorithms

The JPEG, CSI-JPEG, and JPEG2000 algorithms have been investigated in this work for color image compression. Conventionally in JPEG normally the chrominance components of the image are down-sampled and up-sampled before and after using standard baseline JPEG algorithm, which is the first algorithm investigated here. Secondly, the new CSI-JPEG algorithm which is amalgamation of cubic spline interpolation and standard baseline JPEG algorithm [8], and the advanced version of JPEG that is JPEG2000 [2] were compared with JPEG.

In JPEG algorithm, image is down-sampled after color space transformation and standard JPEG encoder is then applied. Output of the JPEG encoder is the compressed image data which can be saved or transmitted over the network. To restore the compressed image, reverse process is done, which includes standard JPEG decoder, up-sampling and reverse color space transformation. JPEG encoder and decoder consist of three steps each, applied on 8x8 blocks of pixels for each channel. In JPEG encoder, 8x8 blocks of image are first transformed from spatial representation to frequency representation and are then quantized systematically. The quantized data is encoded using statistical encoding. These steps are repeated for each block of the entire image. At this point, the image can be stored or transmitted. While decoding the stored image, statistical decoding, de-quantization and frequency to spatial domain transformation are performed. For decompression, the basic computational unit is again 8x8 pixels per block. Steps of spatial to frequency transformation and statistical encoding are same for all three channels of color image, but quantization matrices are different for luminance and chrominance channels. The flow diagram of JPEG is shown in **Fig. 1**.

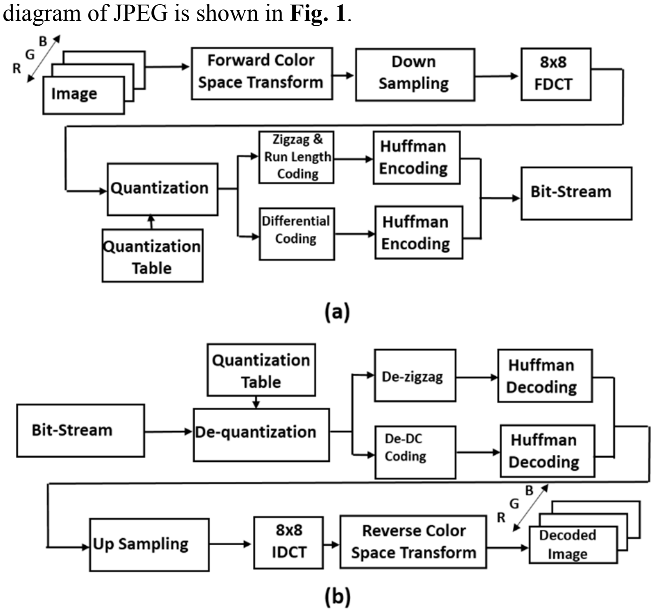

Figure 1. Block diagram of JPEG; a) Encoder, and b) Decoder.

In JPEG2000 discrete wavelet transform (DWT) is used instead of discrete cosine transformation (DCT). Before DWT, each image channel is partitioned into several tiles to make JPEG2000 enable for the application of region of interest (ROI). Lossless or lossy JPEG2000 quantization is then applied followed by entropy encoding. Entropy encoding is divided into two steps i.e., Tier-1 and Tier-2. The Tier-1 encoder is composed of three parts: bit-plan conversion, context formation, and the arithmetic coding. After entropy encoding by Tier-1, the function of Tier-2 is to package the output data into the final bit stream. And it also controls resolution scalability, the size of the image, the region of interest, etc. The block diagrams of JPEG2000 encoder and decoder are shown in **Fig. 2**. Image resolution can be reduced by using multiple levels of wavelet transformation which increases the compression rate at the cost of image quality. Hence in JPEG2000, images are not necessarily down-sampled to achieve high compression rate. The second level DWT was used in this work.

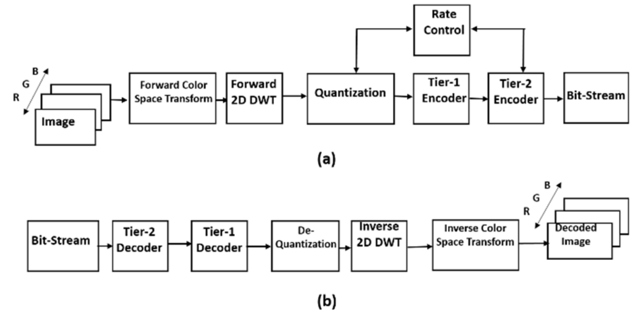

Figure 2. Block diagram of JPEG2000; a) Encoder, and b) Decoder.

The new compression algorithm CSI-JPEG is different than JPEG at the sampling stage. Where, forward cubic spline interpolation has been incorporated instead of using down-sampling and inverse cubic spline interpolation instead of up-sampling in the compression and decompression, respectively. To obtain maximum smoothness and to avoid distortions at the edges, the constraint of continuity of first two derivatives was employed on cubic spline interpolation. And smoothness at the edges is highly desired to avoid distortions, while sub-sampling the image data [8]. The CSI was employed in such a way that the image size reduced to 9/64 of the original. While in the case of down sampling the image size is reduced to 16/64 of the original image. That is why it increases the compression rate of JPEG by about 20-30%. Compression rate can be improved and the restored image will be more close to the original image if this algorithm is applied. After sampling stage, baseline JPEG algorithm has been used in the same way as described above.

Experimental Color Spaces

As mentioned earlier, seven different color spaces sRGB, YCbCr, YCoCg-R, RDgDb, CIELAB, IPT, and CAM02-UCS were tested in this work. The sRGB and YCbCr color spaces were selected because sRGB space is standard system used for display and YCbCr is used in compression algorithms as its dynamic range matches with device space range and it well minimizes inter-component correlation, which results in good ratios and image quality. And YCbCr variants have been used by many algorithms including JPEG1992/2000. Three visually uniform color spaces CIELAB, IPT and CAM02-UCS were also included. The CIELAB is CIE 1964 uniform color space, IPT is another color model which is more uniform in hue direction, and CAM02-UCS is a CIECAM02 based uniform color space. The CIELUV model was not included as it has almost similar performance as CIELAB but not very consistent [3, 7]. A strictly (integer) reversible color space YCoCg-R, which is used in JPEG XR for integrated lossless and lossy compression, was also investigated. Another worth investigating color space RDgDb was also included, which was developed for lossless image compression and gave best compression ratios for JPEG2000 and JPEG-XR according to a recent research [6].

Luminance signal is represented by Y in YCbCr, and YCoCg-R, by L^* in CIELAB, and by J' in CAM02-UCS color space, while the other two channels in these color spaces are chrominance channels. The sRGB space is the only color space in which there is no single channel that represents only luminance or chrominance.

Luminance and chrominance quantization tables were used for luminance and chrominance channels, respectively. But only Luminance quantization table was applied to all three channels of sRGB color space. Note that the display used here was calibrated to a sRGB display.

The sRGB color space can be linearly transformed to XYZ. The sRGB matrix was defined under CIE D65 and 1931standard colorimetric observer. In YCbCr color space, Y represents luminance, and Cb, and Cr represent chrominance channels. There are many variants of transformation matrix used for RGB to YCbCr conversion, we used the same as given in [6].

For conversion back to sRGB, inverse matrices were used. Three visually uniform color spaces selected were CIELAB, IPT and CAM02-UCS. The CIELAB space is intended to use for the surface colors. The second uniform color space is IPT that accurately models constant perceived hue and does not affect other color appearance attributes while predicting hue. The luminance component I, and chrominance components P, and T can be calculated from XYZ [9]. The XYZ color space can be transformed to CAM02-UCS components using CIECAM02 and transformation given in [10]. The reversible color space YCoCg-R is a variant of irreversible model YCoCg used in JPEG-XR [6]. In RDgDb, R is the R component of RGB space and Dg, and Db are differences of primary colors [6].

Experimental Color Spaces

All three compression algorithms with each of seven color models using MATLAB were implemented. Twelve different test images were selected from an image set including over 100 test images. The selection criteria was based on including images with contents of natural objects, human faces, animals, indoor and outdoor environment, and natural scenes like green grass, water, clouds, and blue sky. All images are shown in **Fig. 3** with same aspect ratios. Adapting field luminance (La) and background luminance factor (Yb) were set at 127.4cd/m2 and 20, respectively and 'average' surround conditions were used for CIECAM02. Six measures for quantifying the performance of compressibility including compression rate (CR), signal to noise ratio (SNR), peak signal to noise ratio (PSNR), mean squared error (MSE), CIELAB color difference measure (ΔE^*_{ab}) and CIEDE2000 color difference formula (ΔE_{00}), were used to examine the overall performance.

Figure 3. Selected test images.

Two tests were performed for performance comparison of each of the seven models for all three algorithms. In first test, ΔE_{00} value was fixed to 5. And in the second test, compression rate (CR) was fixed to 14. To obtain reliable results in both tests, the threshold values of ΔE_{00} and CR were chosen to meet the criteria of acceptability and perceptibility with tolerance values found by Song *et. al* [12]. These tests were designed to verify the methods' performance in order to find how much compression rate each model can give to achieve equal color difference, and how much color difference can be reached by adapting same compression rate, respectively.

The results of the first test were averaged over twelve images and are summarized in Tables 1-3, for JPEG, CSI-JPEG, and JPEG2000, respectively. From these results, the seven color spaces according to their compressibility performance were ranked because all the color space models have same average color difference in terms of ΔE_{00}. Table 1 shows that for conventional JPEG algorithm, CAM02-UCS performed the best, followed by IPT and CIELAB. The RDgDb and YCoCg-R outperformed YCbCr as well as sRGB which stood the worst. Almost same ranking of the seven color spaces can be observed for CSI-JPEG and JPEG2000 algorithms, as shown in Tables 2 and 3 compared with Table 1. However CSI-JPEG gave almost 20-30% extra compression rate as compared to JPEG algorithm and JPEG2000 outperformed both JPEG and CSI-JPEG as expected. From numerical results, it can be seen that in the first test, CSI-JPEG algorithm with superior CAM02-UCS model outperformed all other models in terms of compressibility.

Table.1: Test results of JPEG, for ΔE_{00}=5

Color Spaces	CR	SNR	PSNR	MSE	ΔE^*_{ab}
sRGB	9.4	41.1	46.5	11.6	6.5
YCbCr	11.8	40.3	48.7	11.6	5.7
YCoCg-R	12.4	40.3	50.8	10.6	6.4
RDgDb	12.8	37.2	47.7	10.2	5.9
CIELAB	14.7	38.5	47.7	11.1	6.2
IPT	17.0	37.6	47.6	10.8	6.3
CAM02-UCS	17.9	40.7	50.7	11.3	6.0

Table.2: Test results of CSI-JPEG, for ΔE_{00}=5

Color Spaces	CR	SNR	PSNR	MSE	ΔE^*_{ab}
sRGB	12.0	40.4	44.3	11.6	6.7
YCbCr	13.7	38.7	46.4	10.7	6.2
YCoCg-R	16.1	41.5	48.7	12.9	6.0
RDgDb	16.8	40.3	42.9	11.5	5.9
CIELAB	18.7	41.4	46.5	11.8	6.6
IPT	21.7	45.3	52.3	11.2	6.1
CAM02-UCS	22.9	40.4	48.5	11.7	6.1

Table.3: Test results of JPEG2000, for ΔE_{00}=5

Color Spaces	CR	SNR	PSNR	MSE	ΔE^*_{ab}
sRGB	12.3	43.0	46.7	11.3	6.6
YCbCr	15.8	41.3	46.6	10.8	6.0
YCoCg-R	16.5	44.5	50.6	10.4	5.5
RDgDb	17.7	41.9	46.6	11.6	6.3
CIELAB	19.3	40.1	48.1	12.2	5.8
IPT	22.4	45.5	47.2	10.2	6.2
CAM02-UCS	23.6	41.6	48.0	12.2	6.1

In the second test, compression rate was fixed (CR=14) and all other measures were computed for three algorithms. The results of JPEG, CSI-JPEG, and JPEG2000 are summarized in Tables 4 to 6, respectively. These results verify that CAM02-UCS color space is best among seven selected color models for image compression. The JPEG2000 remained best and performance of CSI-JPEG algorithm is better than JPEG in terms of color difference and signal to noise ratio when the compression rate is same. The performance of uniform color spaces IPT and CAM02-UCS was better compared with CIELAB in all three algorithms.

Table.4: Test results of JPEG, for CR=14

Color Spaces	SNR	PSNR	MSE	ΔE^*_{ab}	ΔE_{00}
sRGB	29.4	35.3	12.1	7.1	6.0
YCbCr	34.4	43.9	10.5	6.3	5.1
YCoCg-R	40.6	51.8	9.5	5.2	4.7
RDgDb	36.5	48.1	10.3	6.0	4.6
CIELAB	40.7	52.5	9.5	5.3	4.3
IPT	42.4	54.8	8.2	4.6	3.9
CAM02-UCS	42.5	56.7	8.0	4.3	3.7

Table.5: Simulations results of CSI-JPEG, for CR=14

Color Spaces	SNR	PSNR	MSE	ΔE^*_{ab}	ΔE_{00}
sRGB	34.5	43.7	10.1	7.3	5.1
YCbCr	41.4	49.1	8.3	6.2	4.4
YCoCg-R	44.8	54.8	7.7	5.4	4.1
RDgDb	40.7	49.0	8.4	6.3	4.0
CIELAB	44.0	55.8	7.6	5.3	3.7
IPT	47.8	57.9	7.0	5.0	3.1
CAM02-UCS	49.6	58.6	6.8	4.9	2.9

Table.6: Simulations results of JPEG2000, for CR=14

Color Spaces	SNR	PSNR	MSE	ΔE^*_{ab}	ΔE_{00}
sRGB	34.3	40.1	10.4	7.0	4.8
YCbCr	39.6	45.5	8.2	6.3	4.1
YCoCg-R	45.5	48.4	7.1	5.4	4.0
RDgDb	41.9	46.6	8.1	6.1	3.8
CIELAB	46.6	50.4	7.2	5.3	3.6
IPT	48.4	54.3	6.7	4.6	3.1
CAM02-UCS	48.8	56.1	6.5	4.4	2.8

Statistical significance test was also performed for the results of both tests. Significance of the difference of compression ratio and ΔE_{00} was calculated for the results of the first and second tests, respectively. Pair comparison was done using two-tailed t-test. Firstly, it was tested that whether the performance of color spaces is significantly different as compared to each other. Over all analysis of variance (ANOVA) showed that performance of all models for both tests was significantly different. Subsequently, the models were compared pair wise for the two algorithms in both tests. The results showed that uniform color space CIELAB performed insignificantly better compared with linear color spaces. While the performance of IPT and CAM02-UCS was significantly better comparing with linear color spaces and insignificantly better in comparison with CIELAB. Moreover, linear model RDgDb outperformed YCoCg-R and YCbCr as well as sRGB. Secondly, the three algorithms were compared and results proved that CSI-JPEG and JPEG2000 performed significantly better comparing with conventional JPEG algorithm in both tests while JPEG2000 was insignificantly better comparing with CSI-JPEG.

Psychophysical Experiment

Psychophysical experiment was also performed to quantify the quantitative results from the second test. A calibrated wide-gamut Eizo ColourEdgeCG243W display was adopted. The peak white of the monitor was set at 6500K with a luminance value of 100cd/m^2. The grey background with L^*=50 was set to display images. Ten normal color vision observers participated in the experiment. The observers were seated 3*ft* away in front of the display in a darkened room. **Fig. 4** illustrates the viewing conditions used for the psychophysical experiment.

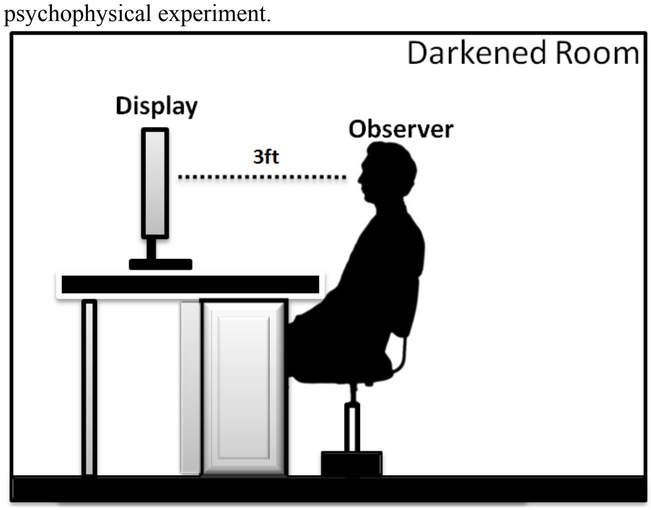

Figure 4. Experimental viewing conditions in a darkened room.

Twelve original images and their corresponding restored images from each of the 21 models (7 for each of JPEG, CSI-JPEG, and JPEG2000) were processed for the experiment. The restored images from different models were compared pair wise. Each pair of restored images was randomly displayed along with the corresponding original image and keeping the original image in the middle. The observers were then asked to judge that which (left or right) image out of a pair is visually more close to the original one (middle). There were 25200 ((21 x 20) / 2) x 12 x 10) numbers of assessments in total. Each observer participated in two sessions and each session took about 75 minutes.

The data were presented in Z-score to represent how close the result of each model is to the original image. The raw data given by observers to each model were sorted out and then transformed to Z-score for the models studied (see **Fig. 5**). The 95% confidence interval was also calculated that indicates the reliability of the estimate and is shown in **Fig. 5**. Because of meeting the criteria of perceptibility and acceptability while designing tests, better visual performance of all the models was observed and experimental results validated the test results. The ranking of the models in the visual performance evaluation was almost similar to the test results.

The correlation coefficients between Z-score and the other five measures, were computed. The results are given in Table 7 in terms of correlation coefficient. It can be seen that color difference formula CIEDE2000 gave the best correlation with the visual results (Z-score). This was followed by ΔE^*_{ab} *and* MSE, which have almost equal correlation and ranked second. The CIEDE2000 was significantly better compared with SNR and PSNR but insignificantly better comparing with MSE and ΔE^*_{ab}. This implies that a more robust model such as CIEDE2000 can be reliably used to predict color difference for complex images.

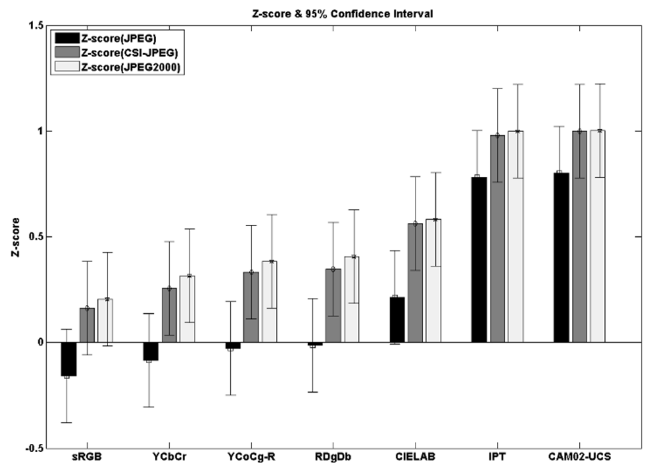

Figure 5.Results of psychophysical experiment given in terms of Z-score and 95% confidence interval.

Conclusions

A new image compression algorithm CSI-JPEG was developed. It was tested together with JPEG1992 and JPEG2000 algorithms by incorporating seven different color spaces. Two different tests were conducted by fixing ΔE_{00} and CR. The results clearly showed that CSI-JPEG provided about 20-30% higher performance than JPEG1992. JPEG2000 outperformed JPEG1992 significantly but performed insignificantly better compared to CSI-JPEG. And it was also concluded that compressibility of CAM02-UCS color space is best among the color spaces tested. The visually uniform color spaces overall performed better than linear models. The RDgDb stood best among linear models. The performance of IPT and CAM02-UCS was proved significantly better compared with linear color models and their performance difference with CIELAB was insignificant.

A psychophysical experiment was also carried out using 3 algorithms, 7 color models and 12 test images. Experimental results were consistent with the present second test results. The results confirmed that CSI-JPEG and JPEG2000 gave smaller visual difference compared with JPEG between the compressed and the original images, when the compression rate is same, for all three algorithms. Out of the five measures used, ΔE_{00} best correlated with the Z-Score of the models. The overall conclusion is that when JPEG1992 incorporates cubic spline interpolation, its performance increases and with the use of a more uniform color space such as CAM02-UCS or IPT, the performance of JPEG, CSI-JPEG and JPEG2000 can even be improved.

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