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LOSSLESS AND NEAR-LOSSLESS IMAGE COMPRESSION WITH COLOR TRANSFORMATIONS

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ABSTRACT

A comparison of lossleess compression results is given for RGB, YC_RC_B and reversible JPEG 2000 color space. The paper describes the general conditions that rounding errors of a color transformation do not cumulate in the consecutive cycles of forward and inverse transformation. In particular, rounding errors of the RGB $\rightarrow$ YC_RC_B $\rightarrow$ RGB transformation do not accumulate in the consecutive transformation cycles. Luminance and chrominance representation with two additional bits leads to perfectly reversible color transformation. For such representation compression is slightly better than in RGB but worse as in the JPEG 2000 reversible color space. The paper comprises study on accumulation of errors produced by near-lossless JPEG-LS in the consecutive compression-decompression cycles. Paper proves that alternatively, lossless compression can be performed on luminance and chrominance with reduced representation bit numbers. The advantage is that the errors do not accumulate in the consecutive cycles of compression.

1. INTRODUCTION

The standard approach to lossless and near-lossless compression [1-3] of color or multicomponent images is to process the components independently. Unfortunately the *R*, *G* and *B* components are highly correlated and their straightforward encoding is not efficient. Decorrelation of components improves the results of further compression but optimal adaptive Karhunen-Loéve transformation is rather sophisticated in application. Employment of the Karhunen-Loéve transformation matched to average statistical properties of a whole image mostly leads to poor results [13]. Therefore rough decorrelation of color components is mostly obtained by a linear transformation to the YC_RC_B color space, opponent color space or another similar one. Unfortunately those linear transformations are mostly represented by matrices with noninteger elements and application of such transformations prior to actual compression leads to some rounding errors. The whole cycle of *color transformation – compression – inverse color transformation* is not exactly lossless, i.e. is not exactly reversible. Therefore some reversible color transformations have been proposed [14] and included into the new image compression standard JPEG 2000 [6].

2. LOSSLESS IMAGE COMPRESSION

Contemporary standards for lossless compression of continuous tone images are: JPEG lossless mode [4] and JPEG-LS [5] which is based on the LOCO-I algorithm (*low-complexity context-based lossless image compression*) [11]. Moreover, the new standard JPEG 2000 [6] provides lossy and lossless compression in a single bitstream. Other popular lossless compression techniques are GIF [1] and more efficient PNG [7]. For images with limited graylevel range, application of the binary image compression standard JBIG (ISO/IEC IS 11544) [8] for coding of bitplanes can be advantageous [3]. Nevertheless, for natural images with 8 bits per pixel and component, the JPEG-LS standard outperforms reversible JPEG 2000, lossless mode of JPEG, JBIG on bitplanes as well as PNG[3,12].

Because of its high compression efficiency, the technique know as CALIC (*context-based adaptive lossless/nearly lossless image coding*) [9,10] is considered as a reference technique for research results in lossless image compression. This highly sophisticated algorithm exhibits high computational cost (often four times higher than LOCO-I) but slightly higher compression ratios as compared to LOCO-I (up to 5%). Therefore JPEG-LS (LOCO-I) and CALIC algorithms are chosen for further comparisons in this paper

3. NEAR-LOSSLESS IMAGE COMPRESSION

Besides of the strictly lossless mode, both LOCO-I and CALIC algorithms offer nearly lossless modes of operation that trade off between compression ratio and distortion kept very small. A near-lossless scheme is characterized by the maximum d_{max} of the graylevel or the color component value.

Let us assume a situation where an individual image is transmitted for several times and it is encoded and decoded each time. Near-lossless compression degrades somewhat image quality in each encoding/decoding cycle. Even small and well acceptable distortion caused by a single cycle of compression can be amplified to a very unacceptable distortion even after few transmissions. The user who is not able to perceive the degradation caused by a single coding/decoding cycle is often unaware of coding errors accumulated after several cycles of compression.

For example, application of the near-lossless mode of the LOCO-I (JPEG-LS) algorithm results often in a loss of 10 dB of the peak signal-to-noise ratio after about 10 cycles of encoding and decoding. The experience of authors is that medical histological images exhibited easy to perceive erroneous coloration after already 3 or 4 cycles of encoding/decoding using the LOCO-I (JPEG-LS) algorithm. For example, such a situation is absolutely not acceptable in telepatology where a physician makes vital decisions by considering colors of specific items in a microscopic image. Unfortunately, this problem has not been considered in details hitherto.

4. ROUNDING ERRORS CAUSED BY COLOR TRANSFORMATIONS

It is assumed that an input image is represented by its *R*, *G* and *B* components with integer values. A linear color transformation and the corresponding inverse transformation can be expressed as

$$\begin{bmatrix} D \\ E \\ F \end{bmatrix} = \begin{bmatrix} c_1 \\ c_2 \\ c_3 \end{bmatrix} + \begin{bmatrix} t_{11} & t_{12} & t_{13} \\ t_{21} & t_{22} & t_{23} \\ t_{31} & t_{32} & t_{33} \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}, \quad (1)$$

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} s_{11} & s_{12} & s_{13} \\ s_{21} & s_{22} & s_{23} \\ s_{31} & s_{32} & s_{33} \end{bmatrix} \begin{bmatrix} D-c_1 \\ E-c_2 \\ F-c_3 \end{bmatrix}, \quad (2)$$

where mostly $c_1 = c_2 = c_3 = 0$. For example, in the YC_BC_R color space, there is $D = Y$, $E = C_B$, $F = C_R$ and $c_1 = 16$, $c_2 = c_3 = 128$ in order to match the dynamic range defined by ITU-R [15].

In order to simplify the considerations and without loss of generality, the equations can be simplified to

$$\begin{bmatrix} D \\ E \\ F \end{bmatrix} = \begin{bmatrix} t_{11} & t_{12} & t_{13} \\ t_{21} & t_{22} & t_{23} \\ t_{31} & t_{32} & t_{33} \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}, \quad (3)$$

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} s_{11} & s_{12} & s_{13} \\ s_{21} & s_{22} & s_{23} \\ s_{31} & s_{32} & s_{33} \end{bmatrix} \begin{bmatrix} D \\ E \\ F \end{bmatrix}. \quad (4)$$

The integer *R*, *G* and *B* values are transformed to a *D*, *E*, *F* according to Eq. 3. The obtained values have to be rounded to integers D^{rd}, E^{rd} and F^{rd}. Therefore there is

$$\delta_D = D^{rd} - D \le 0.5, \quad \delta_E = E^{rd} - E \le 0.5, \quad \delta_F = F^{rd} - F \le 0.5.$$

After further lossless encoding and decoding, the values R^d, G^d and B^d are recovered by use of Eq. 4. These samples have to be rounded to integers R^{rd}, G^{rd} and B^{rd}. Let us denote:

$$\delta_R = R^{rd} - R, \quad \delta_G = G^{rd} - G, \quad \delta_B = B^{rd} - B. \quad (5)$$

Therefore δ_R, δ_G, δ_B, denote the differences between the input *R*, *G*, *B* sample values and those R^{rd}, G^{rd}, B^{rd} rounded after decoding and inverse color transformation. The values δ_R, δ_G, δ_B are integer because *R*, *G*, *B* and R^{rd}, G^{rd}, B^{rd} are also integer.

Proposition 1:
Sample errors δ_R, δ_G, δ_B of the *R*,*G* and *B* components in the first cycle of forward and backward transformations are bounded
$|\delta_R| \le L_R, |\delta_G| \le L_G, |\delta_B| \le L_B$, where

$$\begin{aligned} L_R &= round[(|s_{11}| + |s_{12}| + |s_{13}|)/2] \\ L_G &= round[(|s_{21}| + |s_{22}| + |s_{23}|)/2] \\ L_B &= round[(|s_{31}| + |s_{32}| + |s_{33}|)/2] \end{aligned} \quad (6)$$

□

A short proof [16] is based on the observation that the transformations (3) and (4) are mutually inverse and

$$\begin{aligned} |R^d - R| &\le |s_{11} \cdot \delta_D| + |s_{12} \cdot \delta_E| + |s_{13} \cdot \delta_F| \\ |G^d - G| &\le |s_{21} \cdot \delta_D| + |s_{22} \cdot \delta_E| + |s_{23} \cdot \delta_F| \\ |B^d - B| &\le |s_{31} \cdot \delta_D| + |s_{32} \cdot \delta_E| + |s_{33} \cdot \delta_F| \end{aligned}$$

Proposition 2: The conditions:

$$\begin{aligned} (|t_{11}| + |t_{12}| + |t_{13}|) &< 1, \\ (|t_{21}| + |t_{22}| + |t_{23}|) &< 1, \\ (|t_{31}| + |t_{32}| + |t_{33}|) &< 1. \end{aligned} \quad (7)$$

yield the following property:
After the first cycle, all consecutive cycles of forward and backward transformations do not influence the values R^{rd}, G^{rd}, B^{rd} obtained in the first cycle.

□

The proof [16] recognizes that noninteger values $D^{(2)}$, $E^{(2)}$ and $F^{(2)}$ are obtained from the integers in the second cycle of the transformation defined by Eq. 3. The integers R^{rd}, G^{rd}, B^{rd} are already derived by rounding the values R^r, G^r, B^r obtained in the first cycle. There is

$$\Delta_R = R^{rd} - R^r \le 0.5, \quad \Delta_G = G^{rd} - G^r \le 0.5, \quad \Delta_B = B^{rd} - B^r \le 0.5.$$

Let us denote

$$\Delta_D = D^{(2)} - D^{rd}, \quad \Delta_E = E^{(2)} - E^{rd}, \quad \Delta_F = F^{(2)} - F^{rd}.$$

Eq. 3 yields the following linear transformation

$$\begin{bmatrix} R^{rd} \\ G^{rd} \\ B^{rd} \end{bmatrix} = \left(\begin{bmatrix} R^r \\ G^r \\ B^r \end{bmatrix} + \begin{bmatrix} \Delta_R \\ \Delta_G \\ \Delta_B \end{bmatrix} \right) \longrightarrow \begin{bmatrix} D^{(2)} \\ E^{(2)} \\ F^{(2)} \end{bmatrix} = \left(\begin{bmatrix} D^{rd} \\ E^{rd} \\ F^{rd} \end{bmatrix} + \begin{bmatrix} \Delta_D \\ \Delta_E \\ \Delta_F \end{bmatrix} \right)$$

Therefore

$$\begin{aligned} |\Delta_D| &\le |t_{11}\Delta_R| + |t_{12}\Delta_G| + |t_{13}\Delta_B|, \\ |\Delta_E| &\le |t_{21}\Delta_R| + |t_{22}\Delta_G| + |t_{23}\Delta_B|, \\ |\Delta_F| &\le |t_{31}\Delta_R| + |t_{32}\Delta_G| + |t_{33}\Delta_B|. \end{aligned}$$

Proposition 2 is true if the range of integers is unlimited. For a limited range of the values of *R*, *G* and *B* the proof fails on the ends of the interval only.

In particular, let us assume the YC_RC_B color space

$$\begin{bmatrix} Y \\ C_B \\ C_R \end{bmatrix} = \begin{bmatrix} 16 \\ 128 \\ 128 \end{bmatrix} + \frac{1}{256} \begin{bmatrix} 65.738 & 129.057 & 25.064 \\ -37.945 & -74.494 & 112.439 \\ 112.439 & -94.154 & -18.285 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}, \quad (8)$$

where the values of luminance and chrominance are restricted to the interval defined by ITU [15]. Preposition 1 implies that the error bounds for individual components are

$$d_R = d_G = 1 \text{ and } d_B = 2.$$

Proposition 1 implies also that application of 10-bit luminance and chrominance samples yields an entirely lossless color transformation. From the preposition 1 we can deduce that Proposition 2 holds when the range of values is restricted to the interval [1,254]. For the values of 0 and 255 rounding of *R*, *G* and *B* does not fulfill the conditions (5) and slight accumulation of errors occur which is mostly negligible .

5. LOSSLESS COMPRESSION IN SOME COLOR SPACES

Results for lossless compression in various color spaces are given in Table 1 for various 512×512 natural images with 8-bit representations. Reversible JPEG 2000 color space needs 9-bit representation for two components. On the other hand the YC_BC_R color components need 10-bit representations for the transformation to be reversible. The values of PSNR of the RGB-images obtained by use of a color transformation to 8-bit YC_BC_R-samples are given in Table 2.

6. NEAR-LOSSLESS COMPRESSION

Near-lossless mode of JPEG-LS in the RGB color space is compared with lossless compression in the YC_BC_R space with reduced precision of samples (Figs. 1 and 2, Table 3). After 2-3 cycles of compression and decompression the latter approach implies lower errors and higher compression. For near-lossleess compression in the YC_BC_R space the curves are similar in shape but they are shifted towards higher compressions.

Table 1. Compression ratio for lossless compression in various color spaces.

Image	JPEG-LS	CALIC	JPEG-LS	CALIC
	RGB 8-bit representation		JPEG-2000 reversible 8/9-bit representation	
Airplane	2.02	2.06	2.31	2.36
Baboon	1.30	1.33	1.45	1.49
Boats	1.53	1.57	1.73	1.77
Clown	1.68	1.73	1.84	1.88
Lena	2.26	2.33	2.47	2.55
Penguin	1.50	1.62	1.87	2.01
Peppers	1.69	1.73	1.79	1.84
Sailboat	1.53	1.56	1.65	1.69
Average	1.64	1.70	1.89	1.94
	YC_BC_R 8-bit representation		YC_BC_R 10-bit representation	
Airplane	2.74	2.76	2.10	2.05
Baboon	1.56	1.60	1.42	1.40
Boats	1.96	2.01	1.67	1.64
Clown	2.11	2.16	1.77	1.73
Lena	2.98	3.04	2.23	2.17
Penguin	2.04	2.17	1.87	1.75
Peppers	2.01	2.06	1.71	1.67
Sailboat	1.84	1.89	1.61	1.58
Average	2.08	2.13	1.76	1.72

Table 2. PSNR [dB] for the RGB $\rightarrow YC_RC_B \rightarrow$RGB transformation with 8-bit samples.

	Red	Green	Blue
Airplane	52.0	53.9	51.0
Baboon	51.9	53.9	51.0
Boats	52.0	54.0	51.1
Clown	52.1	54.0	51.2
Lena	51.9	53.9	51.0
Penguin	52.0	53.2	52.3
Peppers	51.9	54.0	51.1
Sailboat	51.9	53.9	50.1
Histological images	52.0	53.7	51.0

7. CONCLUSIONS

1. For the YC_RC_B color space and natural images, lossless (JPEG-LS) compression ratio is roughly about 25% higher than for the RGB space and about 10% higher than for the reversible JPEG 2000 color space. The errors due to rounding related to RGB $\rightarrow YC_RC_B$ transformation are above 50 dB (PSNR).
2. The transformation to the YC_RC_B color space with two additional bits is a reversible transformation.
3. For 10-bit samples of Y, C_R, C_B compression ratio of lossless JPEG-LS is between the results for RGB and reversible JPEG 2000 color spaces.
4. Near-lossless JPEG-LS suffers from error accumulation. Large errors occur after only few cycles. The round-off noise reduces the values of the compression ratio in consecutive cycles.
5. The transformation RGB $\rightarrow YC_RC_B$ introduces errors in the first cycle only ($d_R = d_G = 1$, $d_B = 2$). Further cycles do not produce rounding errors apart from few errors for boundary values in the second cycle only.
6. For multiple compression cycles lossless JPEG-LS with reduced sample precision in YC_RC_B is superior to near-lossless JPEG-LS.

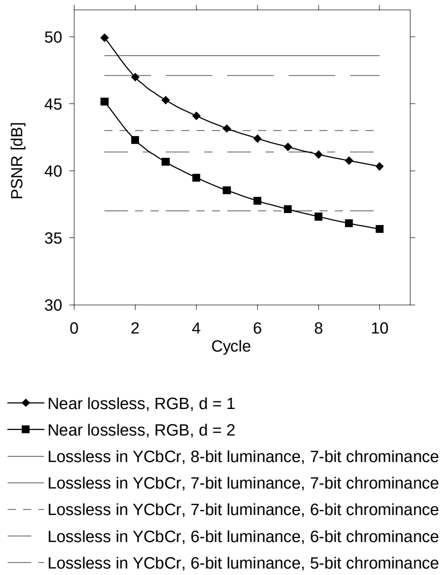

Fig. 1. PSNR[dB] in consecutive cycles of near-lossless LPEG-LS compared to lossless JPEG-LS for he test image *Clown*.

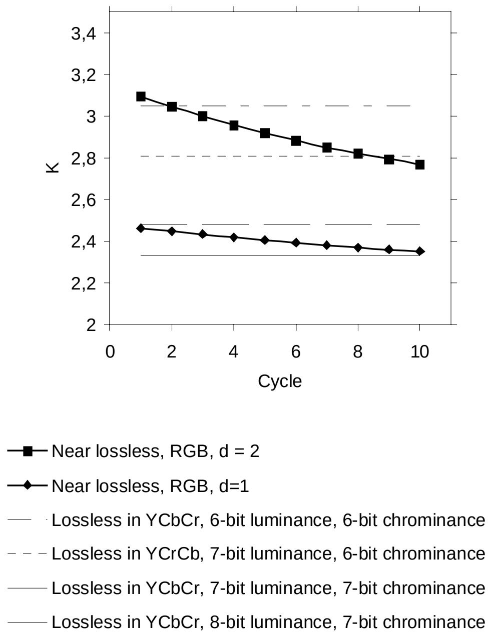

Fig. 2. Compression ratio in consecutive cycles of near-lossless LPEG-LS compared to lossless JPEG-LS for the image *Clown*.

Table 3. Lossless and near-lossless JPEG-LS for still images (8-bit input samples, *Kr*- compression ratio))

Coder	Color Space	Test image *Lena*								Test image *Clown*							
		K_r	d_{max}			PSNR [dB]				K_r	d_{max}			PSNR [dB]			
			R	G	B	R	G	B	Av		R	G	B	R	G	B	Av
Lossless	RGB	2.26	0	0	0	∞	∞	∞	∞	1.68	0	0	0	∞	∞	∞	∞
Lossless	JPEG 2000 reversible	2.47	0	0	0	∞	∞	∞	∞	1.84	0	0	0	∞	∞	∞	∞
Lossless	10 bits luminance 10 bits chrominance YC_BC_R	2.23	0	0	0	∞	∞	∞	∞	1.77	0	0	0	∞	∞	∞	∞
Lossless	8 bits luminance 8 bits chrominance YC_BC_R	2.98	1	1	2	51.9	53.9	51.0	52.3	2.11	1	1	2	52.1	54.0	51.2	52.4
Lossless	8 bits luminance 7 bits chrominance YC_BC_R	3.43	2	2	3	47.9	51.4	46.3	48.5	2.33	2	2	3	47.7	51.5	46.5	48.6
Lossless	7 bits luminance 7 bits chrominance YC_BC_R	3.81	3	2	2	46.7	49.0	45.3	47.0	2.48	3	2	3	46.6	49.1	45.6	47.1
Lossless	6 bits luminance 6 bits chrominance YC_BC_R	4.83	5	5	6	40.9	43.4	39.6	41.3	3.05	6	5	6	40.8	43.3	40.1	41.4
Near-lossless $d_{max}=1$ 1st cycle	RGB	3.79	1	1	1	50.0	50.0	50.0	50.0	2.46	1	1	1	49.9	49.9	50.0	49.9
Near-lossless $d_{max}=1$ 10th cycle	RGB	3.13	10	10	10	40.5	40.4	40.3	40.4	2.35	10	10	10	40.3	40.3	40.4	40.3
Near-lossless $d_{max}=2$ 1st cycle	RGB	5.01	2	2	2	45.5	45.2	45.2	45.3	3.10	2	2	2	45.1	45.2	45.2	45.2
Near-lossless $d_{max}=2$ 10th cycle	RGB	3.82	17	18	18	36.5	36.2	36.0	36.2	2.77	17	18	17	35.6	35.6	35.8	35.7

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