IMPROVED INTERPOLATION OF 4:2:0 COLOUR IMAGES TO 4:4:4 FORMAT EXPLOITING INTER-COMPONENT CORRELATION

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ABSTRACT

The paper deals with the interpolation problem of colour images or video whose chrominance components are downsampled according to 4:2:0 scheme. Such interpolation is traditionally done using a linear 7-tap FIR filter which introduces some blurring and colour artifacts across the edges and details. The idea discussed in the paper is to improve the interpolation through adaptive filtering. The paper shows that strong higher-order correlation is present between luminance and chrominance channels regardless of the colour representation. This correlation may be exploited to support the interpolation of low resolution chrominance using fine detail information extracted from the luminance component of higher resolution. Experimental results show that the error due to the loss of high-frequency data in downsampling and subsequent upsampling is significantly reduced by the use of the proposed technique.

1. INTRODUCTION

Colour image and video representation using luminance and subsampled chrominance (according to 4:2:0 or 4:2:2 subsampling scheme defined by MPEG standards [7, 8], cf fig. 1) is ubiquitous in applications involving lossy data compression, due to efficient utilization of the available bandwidth.

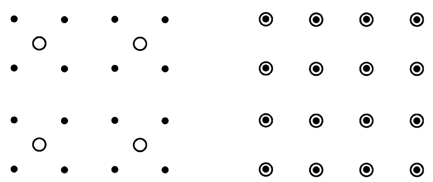

Figure 1: 4:2:0 (left) and 4:4:4 (right) image sampling scheme as defined in [8]. Positions of luminance samples are represented by black dots, while circles represent chrominance.

For displaying, image data reconstruction requires upsampling of the chrominance components to full 4:4:4 resolution prior to colorspace conversion to RGB.

The process of subsampling usually involves linear antialiasing prefiltering, using an appropriate lowpass FIR filter (1), respectively [2, 8]. Similarly, the process of reconstruction is based on the FIR filter used as an interpolator.

$$h(n) = \frac{1}{32}\left[-1, 0, 9, 16, 9, 0, -1\right] \qquad (1)$$

While offering attenuation of aliasing components, lowpass filtering introduces colour artefacts in the form of blurring and ringing. Such effects are not very disturbing in natural scene images and smooth content, but are noticeable in case of sharp edges and images with artificial content (computer graphics).

There are several attempts in the literature to improve the quality of images recontructed after chrominance subsampling. Dumitras and Kossentini [9] consider an alternative approach to the subsampling process using a nonlinear operator based on feedforward neural network. A neural-network technique with adaptive learning has been also employed by Qiu and Schaefer [10] to reconstruct regularly subsampled chrominance components. The latter approach exploits some binary edge information extracted from luminance to guide the neural network which has been previously trained to interpolate natural scene images.

Similarly, the approach to chrominance interpolation proposed here applies an adaptive scheme exploiting the correlation between luminance and chrominance gradients. Instead of a complex neural network processing, we use a very simple linear interpolation based on 4 nearest samples with adaptive adjustment of the respective weights. Adaptive filtering allows to at least partially reconstruct the missing high frequency content that is lost in the subsampling process, thus producing less distorted and sharper looking colour images.

2. COLOUR IMAGE REPRESENTATIONS AND THEIR STATISTICAL CONSEQUENCES

Statistical co-occurence of certain values of the colour components in natural scene images represented in various colour spaces was studied by Pirsch and Stenger [1], Limb and Rubinstein [2], and Wan and Kuo [4]. These works suggest that there is a strong correlation between colour components, especially in natural RGB representation.

For many years these inter-component dependencies have been taken into account in efficient data representation and compression by the use of a luminance-chrominance coordinate system, such as the YC_BC_R which offers a significant energy compaction over the RGB. In other words, most of the signal energy is contained in the luminance component, while the chrominance components exhibit both limited dynamic range and narrow bandwidth.

Abel, Bhaskaran and Lee [3] calculated the cross-correlation between luminance and chrominance components and concluded that while offering a significant energy compaction compared to RGB, the luminance-chrominance representation still exhibits strong correlation between the components, for example the cross-correlation function peaks around 0.22 in the LENA test image.

The study of statistical dependencies between luminance and both chrominance components reveal that the first-order dependence does not decrease much with colorspace transformation from RGB to luminance+chrominance. This property is also reflected by sparseness of two- and three-dimensional histograms of colour components which show a significant concentration of the distribution in certain areas of the colour space (cf fig. 2) in natural scene images. Since certain combinations of component values are much more frequent than others, we conclude that these values are highly correlated [5].

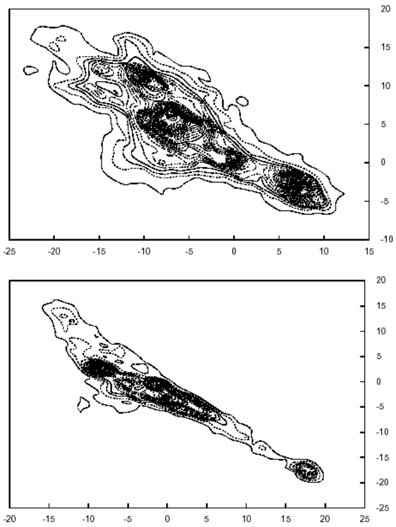

Figure 2: Two-dimensional histograms of natural scene images (single frames from the test sequences SALESMAN and CARPHONE) in the C_BC_R plane

Since images are nonstationary signals, also the correlation between their colour components is rather a local property than a global property. Therefore, linear decorrelation offered by a static (nonadaptive) colorspace transformation is not able to remove all statistical dependencies between components.

3. CORRELATION BETWEEN GRADIENTS OF COLOUR COMPONENTS

Careful inspection of luminance and both chrominance components presented as separate greyscale images leads to a conclusion that similar patterns and textures are visible in all three pictures. Perception of these similarities is possible thanks to the sensitivity of the human visual system to higher-order statistics. In order to verify these observations, let us propose an experiment which involves edge detection algorithm to mimic the image analysis that is performed by the human visual system to compare pitures. Edge detectors employ nonlinear operators which are usually sensitive to second-order and higher-order statistics. Therefore they allow to determine the amount of residual inter-component information by comparison of edge maps resulting from application of edge detectors to separate component images. In the experiments, three images of gradient magnitude are obtained through application of the Previtt operator to luminance and both chrominance images, separately (cf fig 3).

Figure 3: The output of Previtt edge-detecting operator (3×3 mask) applied to Y, C_B, C_R of the test image CLOWN.

Similarity between the gradient images obtained in this way may be measured using cross-correlation coefficient, $\rho_{x,y}$, defined as: $\rho_{x,y} = \frac{\mathrm{cov}(x,y)}{\sigma^2_x\ \sigma^2_y}$, where σ^2 denotes the energy of a component. The experimental results obtained for various natural scene images reveal that the correlation between gradient images is much higher than the correlation between raw colour components, even in RGB colour space (cf fig. 4). An interesting additional conclusion is that the correlation coefficient between luminance and chrominance gradients (which is certainly a local property) does not decrease significantly with growing window size of the Previtt operator. This suggests that a strong dependence exists even for more distant pixels.

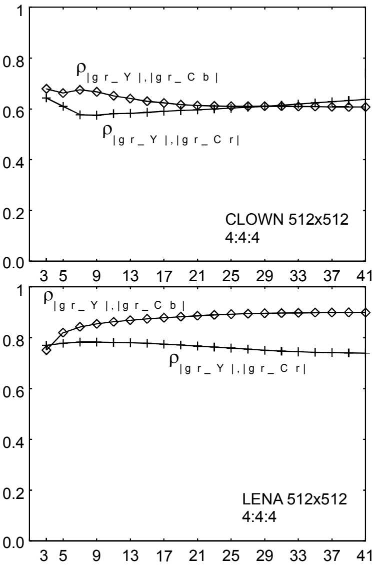

Fig. 4. Cross-correlation between luminance and chrominance gradient magnitudes calculated for the test image CLOWN (left plot) and LENA (right plot) versus window (square mask) size

The general conclusion is that the residual inter-component dependencies after colorspace transformation may be exploited in further image processing e.g. a very efficient compression. On the other hand, interpolation of chrominance should benefit from luminance-based adaptation.

4. ONE-DIMENSIONAL INTERPOLATION OF CORRELATED SIGNAL DATA

Consider a 1-D signal (a vector of image pixels from one row or column) that is composed of densely sampled luminance (L_0, L_1, and L_2 samples located at x_0, x_1, and x_2 positions, respectively) and subsampled chrominance component (samples C_1, and C_2 available only at x_1, and x_2 positions, the value of C_0 at the position x_0 is unknown).

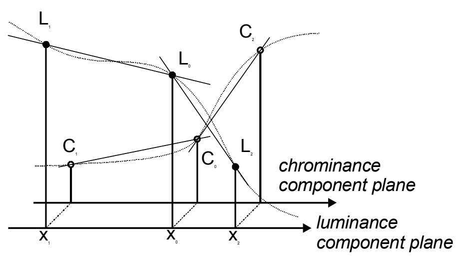

Figure 5: Gradients matching between luminance and chrominance

We can determine the slopes of axes passing through neighboring samples, as shown in fig. 5. Since magnitudes of luminance and chrominance gradients are mutually highly correlated, the ratios of neighboring slopes calculated in luminance and those calculated in chrominance component are similar, therefore we can note down a relation (2)

$$\frac{\left|\dfrac{L_1 - L_0}{x_1 - x_0}\right|}{\left|\dfrac{L_2 - L_0}{x_2 - x_0}\right|} \cong \frac{\left|\dfrac{C_1 - C_0}{x_1 - x_0}\right|}{\left|\dfrac{C_2 - C_0}{x_2 - x_0}\right|}, \tag{2}$$

or simpler
$$\frac{|L_1 - L_0|}{|L_2 - L_0|} \cong \frac{|C_1 - C_0|}{|C_2 - C_0|}. \tag{3}$$

It is possible to derive the estimated value of the unknown chrominance sample as $\hat{C}_0 = k_1\, C_1 + k_2\, C_2$ where

$$k_1 = \frac{|L_2 - L_0|}{|L_2 - L_0| + |L_1 - L_0|}, \quad k_2 = \frac{|L_1 - L_0|}{|L_2 - L_0| + |L_1 - L_0|}. \tag{4}$$

Note, that (4) defines nonnegative weights, such that k_1+k_2=1, and C_0 is obtained through interpolation between two known values, C_1, and C_2. The adaptation here consists in taking into account the relation between values of L_0, L_1, and L_2. If L_0 is a linear interpolation of L_1, and L_2, than the resulting k_1 and k_2 will lead to a linear interpolation between C_1, and C_2. On the other hand, if there is an edge in luminance domain between locations x_1, and x_2, and the value of L_0 is very similar to one of L_1 or L_2, while it is dissimilar to the other one, the interpolation will be very nonlinear and there will be a corresponding step in chrominance domain.

5. INTERPOLATION OF SUBSAMPLED CHROMINANCE (4:2:0) TO FULL RESOLUTION (4:4:4)

There are several ways to adopt a one-dimensional formula (4) to a two-dimensional signal (an image). The implemented algorithm operates in two steps (cf. fig. 6). Some intermediate chrominance samples (light-gray bullets in the left picture) are calculated first from their two nearest neighbors (as depicted by the arrows) according to the formula (4). Next, two separate interpolations are calculated along diagonals of the sampling grid using the original and intermediate samples. The final values are obtained by a linear combination of these two concurrent results (dark-gray bullets in the right picture).

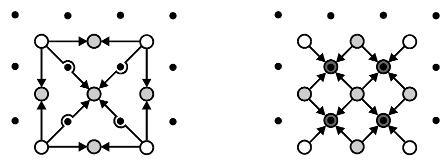

Fig. 6. Two-step algorithm for interpolating chrominance samples missing in 4:2:0 resolution

6. EXPERIMENTAL RESULTS

Experimental verification of the proposed interpolation method allows to compare its performance to traditional interpolation using standard FIR filter. For the purpose of this test, several colour images were converted from RGB to

YC_BC_R initialy preserving full 4:4:4 resolution, and subsequently subsampled to 4:2:0 resolution using the standard 7-tap FIR filter. The subsampled images were separately interpolated back to 4:4:4 resolution using the proposed adaptive interpolation and standard linear interpolation with FIR filter (4). These two reconstructed images were compared to original 4:4:4 images. As shown in table 1, the proposed interpolation technique clearly outperforms the standard method, with reconstruction error reduced by 3 to 6 dB. For visual comparison, error images were obtained (the images of pixelwise difference between the reconstructed and the original image, amplified by 20) and shown in fig. 7. The luminance in both pictures is constant and equal, while color saturation represents local error magnitude.

Table 1: Experimental results: comparison of new adaptive interpolation to standard FIR interpolation

Test image	Standard FIR	New method
BOATS	33,6 dB	35,1 dB
	35,8 dB	38,2 dB
CLOWN	34,9 dB	37,2 dB
	35,6 dB	38,5 dB
LENA	37,7 dB	43,6 dB
	37,3 dB	43,7 dB

7. CONCLUSIONS

The paper shows, that high correlation between colour components may be efficiently exploited in processing with inter-component control, especially by the use of gradient magnitudes. A new interpolation technique has been presented for upsampling of images and video frames with reduced resolution of chrominance. Experimental results show that introduction of luminance adaptation to chrominance processing leads to significantly improved the quality of reconstructed images.

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Fig. 7. Images of colour error obtained as amplified difference between reconstructed and the original image. Left picture: standard FIR interpolation, right picture: proposed adaptive interpolation; Comparison of error histograms: FIR interpolation (narrow dark bars) vs proposed adaptive interpolation (wide bars)