Color Image Coding based on the Colorization

Takashi Ueno, Taichi Yoshida and Masaaki Ikehara
EEE Dept., Keio Univ., Yokohama, Kanagawa 223-8522, Japan
E-mail: { ueno, yoshida, ikehara }@tkhm.elec.keio.ac.jp

***Abstract*—Colorization is a method which adds color components to grayscale images using color assigned information provided by the user. Recently, a novel approach to image compression called colorization based coding has been proposed. It automatically extracts color assignations from original color images at an encoder and restores color components by colorization method at a decoder. In this paper, we propose the method which improves the conventional color image coding methods by regarding colorization as interpolation. At the encoder, the proposed method subsamples chrominance components considering colorization and subsampled chrominance components are compressed by conventional methods. At the decoder, subsampled chrominance components are interpolated by colorization. Simulations reveal that the proposed method improves quality of reconstructed images, objectively.**

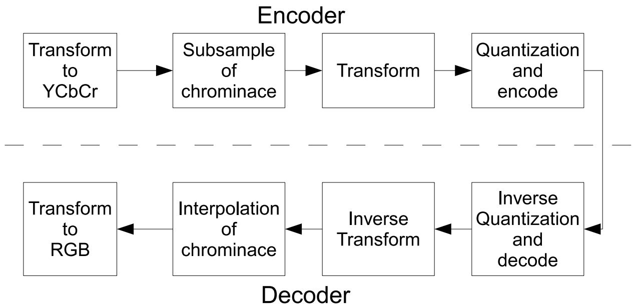


Fig. 1: Conventional color image coding methods

I. Introduction

Colorization [1] is a technique which adds color components to grayscale images using the color assignation provided by users. Restoring color from grayscale images is an ill-posed problem. Levin *et al.* assume neighbor pixels which have similar luminance have similar chrominance. The colorization propagates the color assignation according to the assumption.

Recently, novel color image compression methods based on the colorization have been proposed [2]–[5]. These methods called colorization based coding take advantage of the fact that an information amount of the color assignation is less. The methods automatically extract the color assignation from original color images at the encoder, and transmit the color assignation and compressed luminance to the decoder. At the decoder, color components are restored by using the colorization [1].

Previous studies [2]–[5] have proposed various methods of extracting the color assignation. The color assignation is extracted as pixels [2]–[4]. Cheng's method adds pixels to the color assignation by iterative selections using the colorization [2]. However, the initial color assignation has redundancy. Ono's method reduces redundancy of Cheng's method [3]. Inoue's method resolves a problem of the colorization that chrominance is smoothed excessively by considering local correlations between luminance and chrominance [4]. Miyata *et al.* extract the color assignation as lines [5].

In this paper, we propose a simple method which improves the conventional color image coding by the colorization. In conventional coding, chrominance components are subsampled at the encoder, generally. The proposed method improves a visual quality of images encoded previously by the proposed new colorization. The proposed method subsamples chrominance like the conventional coding methods, and treats subsampled chrominance as the color assignation. Subsampled chrominance is interpolated using the colorization at the decoder. Moreover, we propose the subsampling method which minimizes the error between the original and the interpolated chrominance using the colorization. Then, we can obtain better reconstructed images. The proposed method can use an encoder and a decoder of conventional methods, as it is. So, the proposed method is compatible with conventional methods. The proposed method achieves to improve objective qualities of reconstructed images compared with the conventional one.

II. Review

A. Color Image Coding

An overview of conventional color image coding methods is shown in Fig.1. At the encoder, original images are transformed from the RGB color space to the YCbCr color space. The human visual system is sensitive to changes of not chrominance, but luminance. To reduce the amount of information, from this property, chrominance components (Cb, Cr) are generally subsampled. Luminance and subsampled chrominance are transformed into the frequency domain, and then quantized and encoded. At the decoder, images are reconstructed by inverse processes.

At the decoder, subsampled chrominance should be interpolated. In the conventional methods, linear interpolation methods are used. Therefore, decoded chrominance components blur near edges.

B. Levin's Colorization

In this section, we show the Levin's colorization method [1]. The colorization is a method which adds color components to grayscale images using the color assignation provided by the user. We applied the algorithm to YCbCr color images.

Some notations are defined as follows: $\mathbf{y}$ is the luminance component corresponding to Y, and $\mathbf{u}$ is the chrominance component corresponding to Cb or Cr. Let n be the number of pixels in the original image and r be an index of pixels in the raster-scan order $(0 \leq r \leq n-1)$. $\mathbf{u}$ $(\mathbf{u} \in \mathbb{R}^n)$ is a column vector which contains color components restored by the colorization and is ordered by the raster-scan. $\mathbf{x}$ $(\mathbf{x} \in \mathbb{R}^n)$ is a column vector which contains chrominance values, and $\mathbf{x}$ has non-zero values only for pixels provided as the color assignation by the user. $\mathbf{y}(r)$, $\mathbf{u}(r)$, and $\mathbf{x}(r)$, are r-th elements of $\mathbf{y}$, $\mathbf{u}$, and $\mathbf{x}$, respectively. Ω is a set of chrominance pixels. $N(r)$ is a set of neighbor pixel indices of the r-th pixel.

The colorization method is based on an assumption that neighbor pixels which have similar luminance also have similar chrominance. Based on this assumption, the cost function is defined as

$$\begin{aligned} J(\mathbf{u}) &= \sum_{r \notin \Omega} \left(\mathbf{u}(r) - \sum_{s \in N(r)} \omega_{rs} \mathbf{u}(s) \right)^2 \\ &+ \sum_{r \in \Omega} \left(\mathbf{u}(r) - \mathbf{x}(r) \right)^2, \end{aligned} \tag{1}$$

where ω_{rs} is defined as

$$\omega_{rs} \propto \exp\left(-\frac{(\mathbf{y}(r) - \mathbf{y}(s))^2}{2\sigma_r^2} \right),$$

it is normalized, and σ_r^2 is a variance of luminance in $N(r)$. Suppose $\mathbf{W}$ is $n \times n$ matrix which contains ω'_{rs}, and it is defined as

$$\omega'_{rs} = \begin{cases} 0 & r \in \Omega \\ \omega_{rs} & \text{otherwise} \end{cases}. \tag{2}$$

Using $\mathbf{A} = \mathbf{I} - \mathbf{W}$ ($\mathbf{I}$ is $n \times n$ identity matrix), (1) is equal to

$$J(\mathbf{u}) = \|\mathbf{x} - \mathbf{A}\mathbf{u}\|^2. \tag{3}$$

When $|\Omega| \neq 0$, $\mathbf{A}$ is a regular matrix. Thus, $\mathbf{u}$ is obtained by solving the following equation.

$$\mathbf{u} = \mathbf{A}^{-1}\mathbf{x} \tag{4}$$

III. Proposed Method

In this section, we describe the proposed method. The overview of the proposed method is shown in Fig.2. The proposed method is the same as the conventional color image coding methods except for subsampling of chrominance components and interpolation.

A. Proposed Colorization

General images typically vary slowly in the space domain, i.e., neighbor pixels are likely to have similar values. Hence, we modify the weighting function (1) to add a distance term. The proposed colorization formulates a new cost function as

$$\omega_{rs} \propto \exp\left(-\frac{(y(r) - y(s))^2}{2\sigma_r^2} \right) \exp\left(-\frac{m^2 + n^2}{2\sigma^2} \right), \tag{5}$$

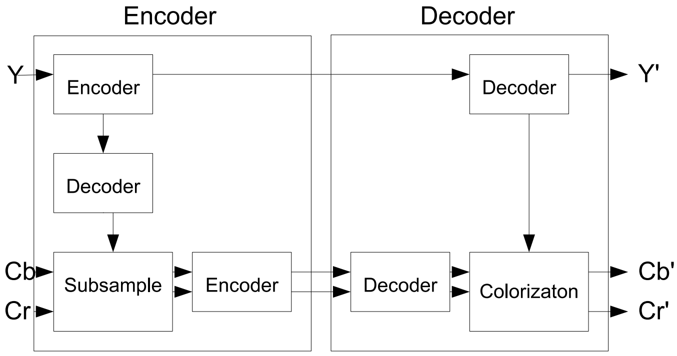


Fig. 2: Proposed method

m is a vertical distance and n is a horizontal distance from the target pixel. σ^2 is a variance of gaussian. This distance term computes weights decreasing with distance from the target pixel. So, the proposed colorization is done based on both the geometric closeness and the photometric similarity like a bilateral filter [6]. According to [6], we can get smooth color and preserved edges which are tuned to the human perception by using this weighting function.

B. Interpolation of Chrominance using the Colorization

The proposed method replaces the interpolation of the conventional color image coding methods with the colorization. At the encoder, luminance and subsampled chrominance are encoded by conventional methods. At the decoder, subsampled chrominance has to be interpolated. The subsampled chrominance is interpolated based on the colorization. To utilize the colorization, subsampled chrominance is upsampled from $m_0/2 \times m_1/2$ to $m_0 \times m_1$ matrix. The proposed method utilizes given pixel values as the color assignation to restore chrominance.

The conventional interpolation method does not consider edges. Then the interpolated chrominance causes blur around edges. In general, luminance changes drastically around edges. Since the weighting function of the colorization is determined by the intensity difference of luminance and pixel distance, the proposed interpolation method can keep edges.

C. Subsample of Chrominance for the Colorization

In the previous section, we use the subsampled chrominance as it is. To improve the coding performance, we show a subsampling method which minimizes the error between the original and the interpolated chrominance. Because extracting the color assignation influences the degradation of images which cannot be recovered by the colorization, the quality of colorized images depends in a large part on methods of extracting the color assignation. We deal with the subsampled chrominance as the color assignation. The proposed subsampling aims to obtain optimal subsampled chrominance for the proposed colorization.

The colorization matrix $\mathbf{A}$ is calculated from luminance compressed by conventional methods. (3) is equal to

$$J(\mathbf{u}) = \|\mathbf{u} - \mathbf{A}^{-1}\mathbf{x}\|^2. \tag{6}$$

We redefine $\mathbf{u}$ as original chrominance in (6). We can get the color assignation vector $\mathbf{x}$ which minimizes the degradation of restored images by minimizing (6) for $\mathbf{x}$. However, the length of that $\mathbf{x}$ is same with the length of $\mathbf{u}$. To subsample $\mathbf{x}$, an upsample matrix $\mathbf{U}$ is defined. To define $\mathbf{U}$, we consider a case that $m_0 \times m_1$ matrix $\mathbf{X}$ is upsampled to $2m_0 \times 2m_1$ matrix $\hat{\mathbf{X}}$. $\hat{\mathbf{X}}$ is defined as

$$\hat{\mathbf{X}}(i,j) = \begin{cases} \mathbf{X}(i/2, j/2) & \text{if } i,j \text{ is even} \\ 0 & \text{otherwise} \end{cases}, \tag{7}$$

where $i,j \in \mathbb{Z}$, $0 \le i \le m_0 - 1$, and $0 \le j \le m_1 - 1$. $\mathbf{X}$ and $\hat{\mathbf{X}}$ are ordered by the raster-scan to be column vectors $\mathbf{x}$ and $\hat{\mathbf{x}}$, and a relationship of vectors is described a

$$\hat{\mathbf{x}} = \mathbf{U}\mathbf{x}. \tag{8}$$

We define subsampled chrominance as $\mathbf{v}$. The cost function of subsampling is defined as

$$\hat{J}(\mathbf{v}) = \|\mathbf{u} - \mathbf{A}^{-1}\mathbf{U}\mathbf{v}\|^2. \tag{9}$$

When the size of original image is $m_0 \times m_1$, subsampled chrominance $\mathbf{v}$ is $m_0/2 \times m_1/2$ matrix. $\mathbf{v}$ is obtained by minimizing (9) for $\mathbf{v}$. Then, we define $\mathbf{H}$ as $\mathbf{A}^{-1}\mathbf{U}$. Setting the partial derivative of $\hat{J}$ to be zero, we derive

$$\frac{\partial \hat{J}}{\partial \mathbf{v}} = -2\mathbf{H}^T(\mathbf{u} - \mathbf{H}\mathbf{v}) = 0. \tag{10}$$

The optimal subsampled chrominance can be expressed as

$$\mathbf{v} = (\mathbf{H}^{\mathbf{T}}\mathbf{H})^{-1}\mathbf{H}^T\mathbf{u}. \tag{11}$$

$\mathbf{v}$ is subsampled chrominance which minimizes the degradation of restored images.

IV. Simulation

In a simulation, JPEG is used as the conventional color image coding method. In the proposed method, luminance and subsampled chrominance are encoded and decoded through JPEG. In JPEG, luminance and subsampled chrominance are segmented into 8×8 blocks. Each block is transformed by the discrete cosine transform (DCT) and is quantized by the JPEG quantization table. JPEG quality can be adjusted from 0 to 100 by scaling this quantization table. DC coefficients are encoded by differential pulse-code modulation (DPCM) and Huffman coding. AC coefficients are encoded by Huffman run-length encoding.

The proposed method 1 applies the proposed interpolation which is described in III-B and the proposed method 2 applies both the proposed interpolation and the proposed subsampling which are described in III-B and III-C respectively.

Three color images (128 × 128 [pixels]), *Lena*, *Mandrill*, *Airplane*, shown in Fig. (3), are used as test images. We use the peak signal-to-noise ratio (PSNR) and structural similarity

(a) Lena (b) Mandrill (c) Airplane

Fig. 3: Test images

(SSIM) value as an objective evaluation of image quality. PSNR is defined as

$$\mathrm{PSNR[dB]} = 10\log_{10}\left(\frac{255^2}{\mathrm{MSE}}\right), \tag{12}$$

where MSE is a mean squared error. SSIM is the image quality assessment based on the degradation of structural information, better for the human visual estimation than traditional image quality assessments such as PSNR. SSIM between images $\mathbf{X}$ and $\mathbf{Y}$ is defined as

$$\mathrm{SSIM} = \frac{(2\mu_x\mu_y + C_1)(2\sigma_{xy} + C_2)}{(\mu_x^2 + \mu_y^2 + C_1)(\sigma_x^2 + \sigma_y^2 + C_2)}, \tag{13}$$

where μ_x is the average of $\mathbf{X}$ and μ_y is the average of $\mathbf{Y}$. σ_{xy} is the covariance of $\mathbf{X}$ and $\mathbf{Y}$. σ_x^2 is the variance of $\mathbf{X}$ and σ_y^2 is the variance of $\mathbf{Y}$. C_1 and C_2 are constants. Result numbers are averages of PSNR and SSIM of the three RGB components. Table I and II shows a comparison of the proposed method with JPEG. Fig. 4 to 6 show comparison reconstructed image in JPEG quality 75.

These tables show that the proposed methods are better than JPEG in most cases, objectively. Especially, our methods are effective for *Lena* and *Airplane*. Since these images contain many low-frequency components, our method is effective for those images. This is because the colorization is good at dealing with images which contain many low-frequency components. The proposed method 2 is better than the proposed method 1 especially in *Mandrill* which contains many high-frequency components. Since the proposed method 2 gets subsampled chrominance which minimizes the degradation of restored chrominance, small changes of chrominance can be restored as compared to the proposed method 1.

V. Conclusions

In this paper, we proposed a method which improves the conventional color image coding methods using colorization. By subsampling chrominance for the colorization and interpolating using the colorization, the proposed method reduce the degradation of restored chrominance. The simulation shows that the proposed method has better performance than JPEG in objective quality.

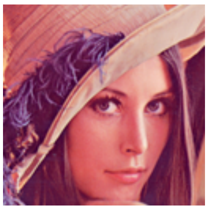
Subsampling of the proposed method does not consider quantization errors of chrominance. It is a future work.

TABLE I: Comparison by PSNR [dB]

Lena			
Size [KByte]	JPEG	Prop. 1	Prop. 2
2.14	26.40	26.85	26.85
2.99	28.29	28.75	28.73
4.36	30.21	30.65	30.73
5.70	31.92	32.36	32.50
Mandrill			
Size [KByte]	JPEG	Prop. 1	Prop. 2
2.56	22.76	23.08	23.10
3.90	24.51	24.72	24.79
5.75	26.65	26.82	26.98
7.68	28.71	28.57	28.89
Airplane			
Size [KByte]	JPEG	Prop. 1	Prop. 2
1.55	28.41	29.34	29.29
2.14	30.78	31.59	31.53
3.08	33.28	33.85	33.94
4.02	34.86	35.42	35.65

TABLE II: Comparison by SSIM

Lena			
Size [KByte]	JPEG	Prop. 1	Prop. 2
2.14	0.804	0.817	0.816
2.99	0.857	0.867	0.866
4.36	0.898	0.904	0.904
5.70	0.920	0.923	0.924
Mandrill			
Size [KByte]	JPEG	Prop. 1	Prop. 2
2.56	0.714	0.731	0.734
3.90	0.801	0.809	0.810
5.75	0.861	0.868	0.869
7.68	0.899	0.898	0.903
Airplane			
Size [KByte]	JPEG	Prop. 1	Prop. 2
1.55	0.850	0.871	0.872
2.14	0.895	0.905	0.906
3.08	0.927	0.929	0.929
4.02	0.940	0.945	0.943


(a) Original


(b) JPEG


(c) Prop. 1


(d) Prop. 2

Fig. 4: Lena


(a) Original


(b) JPEG


(c) Prop. 1


(d) Prop. 2

Fig. 5: Mandrill


(a) Original


(b) JPEG


(c) Prop. 1


(d) Prop. 2

Fig. 6: Airplane

References

[1] Anat Levin, Dani Lischinski, and Yair Weiss. Colorization using optimization. *ACM Transactions on Graphics*, Vol. 23, pp. 689–694, 2004.

[2] Li Cheng and S.V.N. Vishwanathan. Learning to compress images and videos. In *Proceedings of the 24th international conference on Machine learning (ICML)*, pp. 161–168, New York, NY, USA, 2007. ACM.

[3] S. Ono, T. Miyata, and Y. Sakai. Colorization-based coding by focusing on characteristics of colorization bases. In *Picture Coding Symposium (PCS), 2010*, pp. 230 –233, dec. 2010.

[4] Yoshitaka Inoue, Takamichi Miyata, and Yoshinori Sakai. Colorization based image coding by using local correlation between luminance and chrominance. *IEICE Transactions*, Vol. 95-D, No. 1, pp. 247–255, 2012.

[5] T. Miyata, Y. Komiyama, Y. Sakai, and Y. Inazumi. Novel inverse colorization for image compression. In *Picture Coding Symposium, 2009. PCS 2009*, pp. 1 –4, may 2009.

[6] C. Tomasi and R. Manduchi. Bilateral filtering for gray and color images. In *Proceedings of the Sixth International Conference on Computer Vision*, ICCV '98, pp. 839–, Washington, DC, USA, 1998. IEEE Computer Society.