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## 가중 최소자승 필터링과 색 표현 모델을 결합한 넓은 동적 영역 이미지 표현

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### High Dynamic Range Image Display Combining Weighted Least Squares Filtering with Color Appearance Model

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#### 요 약

최근 넓은 동적 영역 이미지 기술은 컴퓨터 그래픽 분야에서 화제다. 본 논문에서는 가중 최소자승(가중회귀분석) 최적화 체계에 기반하여 넓은 동적 영역 이미지를 처리하는 톤매핑 알고리즘을 제안한다. 제안하는 방법은 시각적 후광 현상을 피하는 동시에 기존의 디스플레이에서 더 지각적인 넓은 동적 영역 이미지들을 보여주기 위해 가중 최소자승 필터링과 iCAM06 모델을 결합한다. 제안된 알고리즘은 먼저 넓은 동적 영역 이미지를 base layer와 detail layer로 나눈다. Base layer는 큰 규모의 변화량을 가지고 있으며 가중 최소자승 필터링을 사용하여 얻어지고 iCAM06 모델을 포함한다. 다음으로, 인간의 시각 체계에 따라 base layer는 적응적으로 압축된다. 압축 시에는 base layer만 대비를 줄이고 detail layer를 보존한다. 본 논문에서는 객관적 화질 평가와 주관적 화질 평가를 통하여 제안하는 알고리즘을 적용한 이미지가 기존의 알고리즘을 적용한 이미지들에 비해 원본 넓은 동적 영역 이미지에 더 유사하다는 것을 보여준다.

#### Abstract

Recently high dynamic range imaging technique is hot issue in computer graphic area. We present a progressive tone mapping algorithm, which is based on weighted least squares optimization framework. Our approach combines weighted least squares filtering with iCAM06 model. To show more perceptual high dynamic range images in conventional display, we decompose high dynamic range image into base layers and detail layers. The base layers are obtained by using weighted least squares filter. Then, we adopt chromatic adaption function and non-linear compression function to deal with base layers. Only the base layers reduce contrast, and preserving detail. The image quality assessment shows that our tone mapped image is more similar to original high dynamic range image. Moreover, the subjective result shows our algorithm produces more reliable and pleasing image.

Keywords : Tone mapping, Color appearance model, Weighted least squares

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## I. Introduction

Recently, the international community for standardization has been considered a new generation of video compression technology, known as high efficient video coding (HEVC) [1, 2]. Deployment of HEVC standard is expected to be a key component in future video industry. Including support for high dynamic range (HDR) and wider color gamut (WCG) services is considered essential within the industry [3]. It is important to consider how HEVC will perform on HDR contents [4]. In this paper, we will discuss about HDR image-technology. Different from traditional images, HDR images have a wider range of luminance. Comparing with low dynamic range images (LDR), HDR images can show brighter and darker scene. However, most conventional LDR monitors have low dynamic range. The monitor display HDR scene too bright or too dark. On the other hand, it is not practical to get a HDR monitor for most users, because HDR monitors are too expensive. That is why we need HDR rendering algorithms which are also known as tone mapping operators.

Farbman's tone mapping operator is based on weighted least squares (WLS) framework [5]. It is two-scale decomposition of HDR image into base layer and detail layer. In their tone mapping algorithm, they used WLS filter to deal with HDR image luminance values. After the WLS filtering, the processed image keeps large scale information and fine detail, at the same time, avoids visible halo artifacts. However, they used simple compression strategy to base layer and did not have any process on chrominance. Such an approach brings out two problems. First, the original image color information is not suited for tone mapped image perfectly. Second, simple tone compression strategy loses luminance information in some cases, especially for the image which has higher dynamic range.

According to the two problems, we present a progressive tone mapping operator. We combine WLS filter with

iCAM06 model [6]. iCAM06 is regarded as next generation of image appearance model and developed for HDR image rendering technology. We incorporate part of iCAM06 modules in weighted least squares framework.

iCAM06 model inherits advantages from iCAM02[7] framework, such as the local white point adaption, chromatic adaption, and IPT uniform color space. Furthermore, iCAM06 extends to incorporate scotopic and photopic attributes, local contrast enhancement, local colorfulness enhancement and surround luminance dependent correction. In this paper, we incorporate chromatic adaption and non-linear tone compression modules in weighted least squares framework, while retaining important visual information.

We advocate a perceptual approach, which is particularly well-suited for human visual system and the result is more close to real world. First, we need to use WLS filter to deal with original HDR image, not only luminance values. Then, we obtained base layers, which are from different R, G, B pipelines. We applied to chromatic adaption function, IPT color space function, and tone compression function on our base layers, to achieve color correction and more perceptual color appearance.

In this paper, we discuss an edge-preserving filtering which is more robust and versatile than bilateral filter [8] in Section 2. In Section 3, we present our algorithm which combines WLS filter with modules of iCAM06 models. In Section 4, we show experimental result. Section 5 discusses about our conclusion.

## II. Framework of the weighted least squares

In this section, we introduce an effective and robust edge-preserving filter, which is based on weighted least squares optimization framework [5]. Before this, we simply discuss about diverse edge-preserving filters.

### 1. Edge-preserving filters

Many of edge-preserving filters, such as anisotropic diffusion [9], bilateral filter [8, 10] are outstanding in detail extraction. Particularly, bilateral filter is popular tool in diverse area. The reason is that bilateral filter is well suited for noise removal, at the same time, keeping fine detail. But there is fatal weakness to bilateral filter. The filter trades off its edge-preserving ability with its smoothing ability. In other words, if we want to get a fine detail image, we need to sacrifice smoothing ability. It maybe does not remove noise well. Furthermore, bilateral filter has been known to produce visible halo artifacts in tone mapped image. Thus, Farbman [5] presented WLS filter in order to reduce halo artifact. The WLS filter has the advantage of preventing halo artifacts by minimizing error between the original image and filtered image.

## 2. Weighted least squares filtering

There is an input image  $g$ , we try to get a new image  $u$ , which is smooth image after WLS filtering and we apply image  $u$  to base layer. At the same time, image  $u$  is close to input image  $g$ . The base layer  $u$ , it is obtained using minimize energy function:

$$\sum_q \left( (u_q - g_q)^2 + \lambda \left( a_{x,q}(g) \left( \frac{\partial u}{\partial x} \right)_q^2 + a_{y,q}(g) \left( \frac{\partial u}{\partial y} \right)_q^2 \right) \right) \quad (1)$$

$q$  denotes the location of an image. The first data term is to minimize the distance between original image  $g$  and smooth image  $u$ . Second term controls the smoothness of image  $u$ . The coefficients  $a_{x,q}$ ,  $a_{y,q}$  are smoothness weights and depend on  $g$ . In last,  $\lambda$  is in charge of balance between the two terms, when we increase the value of  $\lambda$ , we will get smoother image  $u$ .

Smoothing weights defined as [11]:

$$a_{x,q}(g) = \left( \left| \frac{\partial l}{\partial x}(g) \right|^\alpha + \varepsilon \right)^{-1} \quad (2)$$

$$a_{y,q}(g) = \left( \left| \frac{\partial l}{\partial y}(g) \right|^\alpha + \varepsilon \right)^{-1} \quad (3)$$

Where  $l$  denotes luminance value of input image  $g$ , and  $\alpha$  is the sensitivity to the gradients of the input image. Typically,  $\alpha$  is between 1.2 to 2.0. Parameter  $\varepsilon$  we take 0.00001.

Rewriting energy minimization function by matrix notation:

$$(u - g)^T(u - g) + \lambda(u^T D_x^T A_x D_x u + u^T D_y^T A_y D_y u) \quad (4)$$

Parameter  $A_x$  and  $A_y$  are matrices of smoothness weights. Parameter  $D_x$  and  $D_y$  are discrete differentiation operators. And unique vector  $u$  can be obtained by using the solution of the general least-squares problem in linear algebra.

$$(I + \lambda L_g)u = g \quad (5)$$

$$L_g = D_x^T A_x D_x + D_y^T A_y D_y \quad (6)$$

Parameter  $I$ , which is in eq. (5) denotes identity matrix. The final smooth image  $u$  can express as follow:

$$u = F_\lambda(g) = (I + \lambda L_g)^{-1}g \quad (7)$$

Just like we mentioned earlier, first they [5]calculated luminance of the input HDR image. Then, they got base layer after WLS filtering, and they compressed the base layer by multiplying a constant (between 0 and 1). Last, they recombined the new base layer with unchanged detail layer to get final tone mapped image.

## III. Proposed method

In this section, we show a modified base-detail decom-

position approach. It combines WLS filter and modules of iCAM06 model. Such an approach performs a perceptual and accurate result in tone mapping algorithm.

Common tone mapping operators are luminance compression which usually causes darker tones to appear brighter and distorts contrast relationships. Such a simple luminance compression strategy causes over-saturated color image. Therefore, we compress red, green, and blue channels instead of luminance. This treatment keeps RGB components ratio, thereby reducing the difference of original color.

Figure 1 is flowchart of our proposed algorithm. At first, we convert input HDR image RGB values to XYZ values by sRGB color space transform matrix [6]. Then let XYZ components pass WLS filter. Conventional tone mapping operator [5] uses WLS filter to compress only Y component. Here, we use three channels processing to reduce color distortion. After filtering, we obtain three edge-preserved base layers. Furthermore, this kind of filtering keeps large scale variation, while avoiding ringing artifact. In our proposed method, detail layers are residual of the input image and base layers.

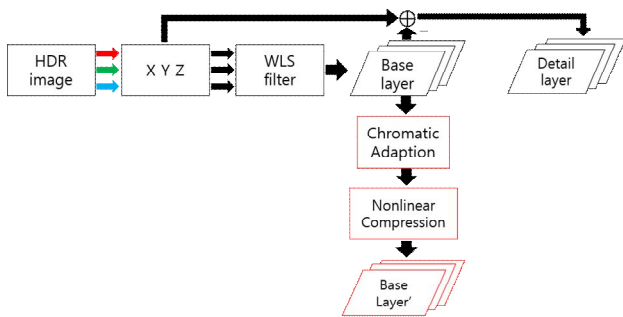


그림 1. 제안하는 알고리즘 흐름도  
Fig. 1. Proposed algorithm flowchart

Image color appearance models attempt to predict non-linearity in the visual system and provide a set of perceptual attribute predictors [6, 7]. For example, given an input image and viewing its conditions, an image color ap-

pearance model can provide perceptual attributes of each pixel. Such as colorfulness, chroma, saturation, lightness, hue, contrast and sharpness.

The goal of our algorithm is maintaining original HDR image attributes. Thus, we adopt chromatic adaption function and non-linear tone compressing function.

### 1. Chromatic adaption

Chromatic adaption function simulates chromatic adaption phenomenon in human visual system. In iCAM06 [6]color appearance model, it adopts chromatic adaption transformation embedded in iCAM which is originally from CIECAM02. The computations of the transform are given in following:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = M_{CAT02} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \quad (8)$$

$$M_{CAT02} = \begin{bmatrix} 0.7328 & 0.4296 & -0.1624 \\ -0.7036 & 1.6975 & 0.0061 \\ 0.0030 & 0.0136 & 0.9834 \end{bmatrix} \quad (9)$$

$$D = 0.3F \left[ 1 - \left( \frac{1}{3.6} \right) e^{\left( \frac{-(L_A - 42)}{92} \right)} \right] \quad (10)$$

$$R_c = \left[ \left( R_{D65} \frac{D}{R_W} \right) + (1 - D) \right] R \quad (11)$$

$$G_c = \left[ \left( G_{D65} \frac{D}{G_W} \right) + (1 - D) \right] G \quad (12)$$

$$B_c = \left[ \left( B_{D65} \frac{D}{B_W} \right) + (1 - D) \right] B \quad (13)$$

The components XYZ and  $X_W Y_W Z_W$  tristimulus values are first converted to RGB spaces. RGB adaption white image signals  $(R_W G_W B_W)$  is derived from the Gaussian low-pass adaption image at each pixel location [6].  $M_{CAT02}$  matrix denotes chromatic adaption transform which is also used in the CIECAM02 [7] model.  $D$  is incomplete adap-

tion factor ( $D=0.3$  in iCAM06 model),  $L_A$  is adaption luminance (20% of the adaption white), and  $F$  is surround factor ( $F=1$  in an average surround), respectively. Chromatic adaption transform constructs a matrix that the matrix transforms  $XYZ$  tristimulus values from a given white point to a new white point. In our case, new white point is CIE illuminant D65.

## 2. Nonlinear tone compression

In iCAM06 model [6], contrast compression is nonlinear compression. It is extended to a simulation of the cones and rods responses. iCAM06 model has outstanding prediction of human visual system.

At first, the chromatic adaption data are converted from the CAT02 space to Hunt-Pointer-Estevéz fundamentals using the CIECAM02 formula:

$$\begin{bmatrix} R' \\ G' \\ Y' \end{bmatrix} = M_{HPE} M_{CAT02}^{-1} \begin{bmatrix} R_C \\ G_C \\ B_C \end{bmatrix} \quad (14)$$

$$M_{HPE} = \begin{bmatrix} 0.3897 & 0.6890 & -0.0787 \\ -0.2298 & 1.1834 & 0.0464 \\ 0.0 & 0.0 & 1.0 \end{bmatrix} \quad (15)$$

$$M_{CAT02}^{-1} = \begin{bmatrix} 1.0961 & -0.2789 & 0.1827 \\ 0.4544 & 0.4735 & 0.0721 \\ -0.0096 & -0.0057 & 1.0153 \end{bmatrix} \quad (16)$$

The computation of nonlinear tone compression functions as following:

$$R'_a = \frac{400(F_L R' / Y'_W)^p}{27.13 + (F_L R' / Y'_W)^p} + 0.1 \quad (17)$$

$$G'_a = \frac{400(F_L G' / Y'_W)^p}{27.13 + (F_L G' / Y'_W)^p} + 0.1 \quad (18)$$

$$B'_a = \frac{400(F_L B' / Y'_W)^p}{27.13 + (F_L B' / Y'_W)^p} + 0.1 \quad (19)$$

$$F_L = 0.2k^4(5L_A) + 0.1(1 - k^4)^2(5L_A)^{1/3} \quad (20)$$

$$k = 1/(5L_A + 1) \quad (21)$$

$p$  denotes adaption level and it is a user-controllable variable (range of 0.6 to 0.85). The larger  $p$  value generates higher overall contrast in the rendered image output.  $Y_W$  is the luminance of the local adapted white image.

The rods response functions are given:

$$A_s = 3.05B_s \left[ \frac{400(F_{LS}S/S_W)^p}{27.13 + (F_{LS}S/S_W)^p} \right] + 0.3 \quad (22)$$

$$F_{LS} = 3800j^2(5L_A/2.26) + 0.2(1 - j^2)^4(5L_A/2.26)^{1/6} \quad (23)$$

$$L_{AS} = 2.26L_A \quad (24)$$

$$j = 0.00001 / [(5L_{AS}/2.26) + 0.00001] \quad (25)$$

$$B_s = \frac{0.5}{\left( 1 + 0.3 \left[ \left( \frac{5L_{AS}}{2.26} \right) \left( \frac{S}{S_W} \right) \right]^{0.3} \right) + 0.5 / (1 + 5[5L_{AS}/2.26])} \quad (26)$$

$$RGB_{TC} = RGB'_a + A_s \quad (27)$$

The rods response functions  $A_s$  is given in equation (22). Parameter  $S$  is the luminance of each pixel in the chromatic adapted image and  $S_W$  is maximum value of the local adapted white point image. Here,  $L_{AS}$  denotes scotopic luminance and  $B_s$  denotes rods saturation factor. Tone compression response is shown in equation (27).

## 3. IPT transformation

In this step, we convert tone compressed RGB signals to CIE  $XYZ$  image. IPT is uniform opponent color space, where I is the lightness channel, P is red-green channel, and T is a blue-yellow channel. The compressed data are first converted into LMS cone responses, and then converted into IPT [6]. The formulas are given:

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = M_H^{D65} \begin{bmatrix} X_C \\ Y_C \\ Z_C \end{bmatrix}, M_H^{D65} = \begin{bmatrix} 0.4002 & 0.7075 & -0.0807 \\ -0.2280 & 1.1500 & 0.0612 \\ 0.0000 & 0.0000 & 0.9184 \end{bmatrix} \quad (28)$$

$$L' = L^{0.43} \quad (29)$$

$$M' = M^{0.43} \quad (30)$$

$$S' = S^{0.43} \quad (31)$$

$$\begin{bmatrix} I \\ P \\ T \end{bmatrix} = M_{IPT} \begin{bmatrix} L' \\ M' \\ S' \end{bmatrix}, M_{IPT} = \begin{bmatrix} 0.4000 & 0.4000 & 0.2000 \\ 4.4550 & -4.8510 & 0.3960 \\ 0.8056 & 0.3572 & -1.1628 \end{bmatrix} \quad (32)$$

After chromatic adaption and tone compression processes, the output image is obtained by recombining with new base layers and detail layers.

#### IV. Experiment and results

We performed our experiment using MATLAB 2015a. Our experimental environment is based on 3.40 GHz Intel Core i5 CPU. We will show objective and subjective results in this section.

In order to evaluate our proposed algorithm, we use tone mapped image quality index (TMQI) [12]. This quality measure consists of two parts: structural fidelity and statistical naturalness. The fundamental idea of the TMQI is that a high quality tone mapped image should not only preserve the structural details in the HDR image but also present a natural appearance [13]. Let  $H$  and  $L$  be the HDR image and the tone mapped LDR image, respectively. The computation of TMQI is given by [12]:

$$TMQI(H,L) = a[S(H,L)]^\alpha + (1-a)[N(L)]^\beta \quad (33)$$

Where  $S$  and  $N$  denote the structural fidelity and statistical naturalness measures, respectively. The parameters  $\alpha$  and  $\beta$  determine the sensitivities of the two terms, and  $0 \leq a \leq 1$  adjusts the relative importance of the two components. Both  $S$  and  $N$  are upper bounded by 1 and

thus TMQI is also upper bounded by 1. In the end, they select  $a = 0.8012$ ,  $\alpha = 0.8012$ ,  $\beta = 0.3046$ , and  $\beta = 0.7088$  as their model parameters[12]. The TMQI score is the similarity between the tone mapped image and original HDR image.

We used nine test sequences: *Walk of fame*, *California highway*, *Mans Chinese*, *Fat cloud*, *Coffee shop*, *Tahoe1*, *Tinterna*, and *Belgium*. These sequences are all in HDR format. For each test sequence, we compute TMQI score and compare results. Our proposed method shows good performance compared to the conventional methods [5, 14].

Table 1 shows TMQI Score comparison of the three tone mapping algorithms. The highest TMQI score in proposed algorithm is 0.90 on *Tinterna*. The average TMQI score in proposed algorithm is 0.80.

표 1. 톤 매핑 이미지의 TMQI 수치

Table 1. TMQI Score of the tone mapped images

Sequence name	Image size	TMQI Score		
		Drago [14]	WLS[5]	Proposed TMO
WalkOfFame	3872×2592	0.72	0.76	0.79
California highway	3872×2592	0.66	0.72	0.79
MansChinese	3872×2592	0.67	0.71	0.75
Fat cloud	3872×2590	0.67	0.66	0.73
Car wall	3827×2592	0.72	0.81	0.83
Coffee Shop	2856×1872	0.71	0.79	0.82
Tahoe1	2048×1872	0.80	0.77	0.85
Tinterna	1536×2048	0.85	0.77	0.90
Belgium	1024×768	0.76	0.75	0.78
Average		0.73	0.75	0.80

Moreover, figure 2 (a) is the HDR image is shown in LDR monitor. Generally, LDR monitor displays HDR scene too dark and loses its detail. Thus, HDR image needs tone mapping operator. Figure 2 (b) shows tone mapped image which is based on WLS optimization framework [5].



(a)



(b)

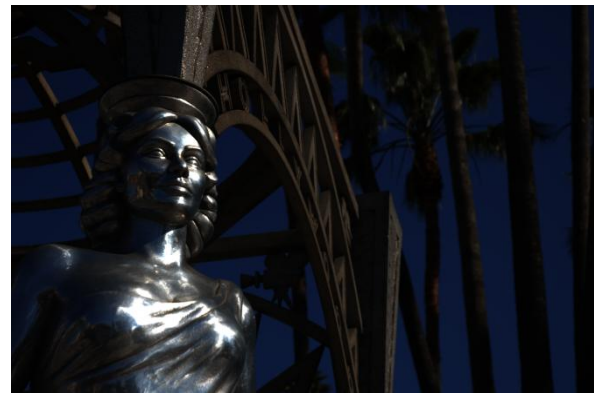


(c)

그림 2. 커피숍

Fig. 2. Coffee Shop

- (a) HDR image shows in LDR monitor,
- (b) based on WLS optimization framework,
- (c) based on proposed algorithm.



(a)



(b)



(c)

그림 3. 워크 오브 페임

Fig. 3. Walk of Fame

- (a) HDR image shows in LDR monitor,
- (b) based on WLS optimization framework,
- (c) based on proposed algorithm.

The tone mapped image shows more visible scene than non-processed image. However, our tone mapped image is much closer to real world than figure 2 (b). Especially, wooden furniture of figure 2 (c) is more realistic than (b). The color appearance of telephone booth and ceiling lamp in the image is more vivid.

## V. Conclusion

Generally, conventional tone mapping operators only process luminance scale and it causes color distortion. We have proposed a tone mapping algorithm which combines WLS filter and iCAM06 model. Our tone mapping operator inherits excellent edge-preserving ability of WLS filter. Additionally, it applies chromatic adaption function and non-linear tone compression function to deal with color reproduction. The experiment shows that our approach is better than conventional tone mapping operators. However, we considered this kind of color enhancement has a limitation. The major problem is the accuracy of the white color estimation from the reference image. The selection of the white leads to different colors in tone mapped images [15]. In another hand, computation is also a considerable issue.

In future work, we will focus on finding a progressive color enhancement strategy which can work on diverse HDR contents while avoiding the hue shifting problem.

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저 자 소 개

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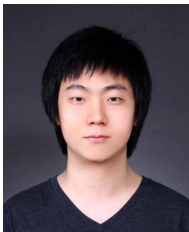
**박 미 선**

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