

# OPTIMIZED CONTRAST REDUCTION FOR CROSSTALK CANCELLATION IN 3D DISPLAYS

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## ABSTRACT

Subtractive crosstalk cancellation is an effective way to reduce the appearance of ghosting in 3D displays. However, effective cancellation requires the black level of the input images to be raised above zero, which reduces the image contrast and visual quality. Previous methods for selecting the raised black level do not consider the image content; they are either based on the worst case or they do not guarantee complete crosstalk cancellation. Previous methods also scale the red, green and blue channels independently, which results in images with washed out colors. This paper provides two contributions; first we derive the minimum amount that the black level has to be raised when using linear scaling in RGB space to ensure crosstalk can be fully cancelled out for a particular image. Second we propose that instead of scaling the images in RGB space, to scale the luma channel in YCbCr color space while keeping the chroma values constant to better preserve color. We also derive the minimum amount that the luma range has to be compressed to ensure that crosstalk can be fully canceled out. Experimental results show that our methods produce images with better color and contrast compared to scaling the RGB channels based on the worst case, while still guaranteeing crosstalk can be fully canceled out.

*Index Terms*— crosstalk cancellation, stereoscopic displays, ghosting

## 1. INTRODUCTION

Most stereoscopic 3D display technologies suffer from crosstalk, where light that is intended for one eye leaks through to the other one. Crosstalk can cause the viewer to perceive “ghosting” in the 3D image, an effect where a double image is seen, particularly at high contrast edges in the image. Crosstalk and ghosting can greatly reduce the perceived 3D image quality, and in can inhibit the viewer from fusing the image and perceiving depth. A recent overview of the sources of crosstalk in different display technologies is presented in [1].

An effective method of reducing ghosting in 3D displays is subtractive crosstalk cancellation. This is a technique

where the images are processed before being displayed such that intensity of each pixel is lowered based on the amount of anticipated crosstalk from the corresponding pixel in the other view. Therefore, as the images are being displayed the crosstalk should be cancelled out, and the viewer should perceive the left and right images as if there were no crosstalk. This idea is the basis for a large number of crosstalk reduction techniques [2]-[5].

A problem with subtractive crosstalk cancellation occurs when the intensity from crosstalk is greater than the signal intensity. In this case, the subtraction will yield a negative value, which has to be clipped to zero, and the crosstalk will not be fully canceled out. To avoid this problem, the minimum pixel value can be raised above zero such that the subtraction will not give a negative result. Raising the black level reduces the dynamic range of the images, lowering contrast and visual quality. This is usually done with linear scaling [2][3][5].

Previous methods for raising the minimum pixel level are either based on the worst case (one image have a value of zero, and the other image having the maximum value), or raising the minimum value to some constant that provides a tradeoff between preserving image contrast and cancelling crosstalk. In all cases, the minimum level is raised by a constant amount, independent of the image content [2][3][5]. This is not optimal because the amount that the minimum level needs to be raised varies significantly from image to image. Some images with low contrast or low disparity need the minimum level to be raised very little whereas other images with high contrast need their range to be compressed severely to avoid visible crosstalk. Furthermore, previous methods for raising the minimum pixel level scale the RGB color channels separately, which has been shown to distort colors, giving images a washed out look [6].

In this paper, we derive the smallest amount by which the black level has to be raised in order to prevent clipping when performing crosstalk reduction on a given image. We also propose that instead of scaling in the RGB space, to scale the luma channel in the YCbCr space to better preserve colors while reducing the dynamic range. We derive the minimum amount the luma range has to be compressed to ensure that crosstalk can be fully cancelled.

The rest of the paper is organized as follows. In Section 2, we review subtractive crosstalk cancellation. Our derivations for the minimum black level raise are presented in Section 3. Experimental results are given in Section 4, and Section 5 concludes the paper.

## 2. SUBTRACTIVE CROSSTALK CANCELLATION

For completeness, here we describe subtractive crosstalk cancellation. Images are often stored as 8 bit gamma encoded red, green and blue values. These values can easily be converted into linear values as follows:

$$I_{lin} = \left( \frac{I_8}{255} \right)^\gamma \quad (1)$$

In equation (1),  $I_8$  is the 8-bit gamma encoded input for one color channel (red, green or blue),  $\gamma$  is the display gamma (usually 2.2) and  $I_{lin}$  is the linear value of that color channel scaled to the range 0 to 1. The signals reaching the viewers eyes, including crosstalk from the other image, can be modeled as:

$$\begin{aligned} I_{L,eye} &= I_{L,lin} + cI_{R,lin} \\ I_{R,eye} &= cI_{L,lin} + I_{R,lin} \end{aligned} \quad (2)$$

where  $I_{L,lin}$  and  $I_{R,lin}$  are linear values of the input left and right images, and  $c$  is the amount of crosstalk. Subtractive crosstalk cancellation works by modifying the displayed left and right images such that after the crosstalk is added, the signals reaching the viewer will be the desired images without crosstalk. This is done by making the input to the display:

$$\begin{aligned} I_{L,m} &= \frac{I_{L,lin}}{1-c^2} - \frac{cI_{R,lin}}{1-c^2} \\ I_{R,m} &= \frac{I_{R,lin}}{1-c^2} - \frac{cI_{L,lin}}{1-c^2} \end{aligned} \quad (3)$$

In (3)  $I_{L,m}$  and  $I_{R,m}$  are the modified input values. By substituting these values into equation (2), it can easily be verified that the outputs,  $I_{L,eye}$  and  $I_{R,eye}$ , will be the original images with no crosstalk. Note that applying equation (3) basically involves subtracting the right image from the left image and vice versa, with a small gain factor  $1/(1-c^2)$  applied to all terms. From equation (3), we can see that the process will fail if either of the following conditions is met:

$$\begin{aligned} I_{L,lin} &< cI_{R,lin} \\ I_{R,lin} &< cI_{L,lin} \end{aligned} \quad (4)$$

In these cases, one of the subtractions in (3) will give a negative result. Since a negative luminance cannot be displayed, the result must be clipped to zero and the crosstalk will not be fully cancelled out. To ensure that that the conditions in (4) will never occur the minimum level of

the input images can be raised from 0 to  $c$ , i.e. compressing the range of the input from  $[0, 1]$  to  $[c, 1]$ . Note that the range  $[c, 1]$  is in linear space, the equivalent range for 8 bit gamma encoded data is  $[255c^{1/\gamma}, 255]$ . For example, with 10% crosstalk and a gamma of 2.2, the minimum level would have to be raised to 90.

## 3. PROPOSED METHODS

In the following two subsections we derive the minimum amount that the image black level needs to be raised to ensure crosstalk can be cancelled out. First we present the case of linear scaling in RGB space, as is done in previous works, and next in YCbCr space, which is shown to better preserve colors while compressing the images dynamic range.

### 3.1. Optimal RGB Domain Linear Scaling

Here we derive the optimal amount to raise the minimum signal level for a particular image such that crosstalk can be fully cancelled out using equation (3), assuming that linear scaling in that RGB domain is used for compressing the dynamic range.

We assume the input left and right images are in 8-bit format and therefore have a range of  $[0, 255]$ . The function for linearly scaling the red, green and blue channels to compress their range to  $[b, 255]$  is:

$$I' = b + (1 - b/255)I \quad (5)$$

In (5),  $I$  represents a sample from any one of the color channels  $I \in (R, G, B)$ ; the same scaling is applied to every color. A larger value of  $b$  will compress the dynamic range of the image more, which lowers the image contrast. Therefore, we wish to keep the value of  $b$  as low as possible. We will derive the minimum value of  $b$  that still ensures that negative values do not occur when performing subtractive crosstalk cancellation.

Since we treat the left and right images symmetrically, we will refer to the two images as the signal image ( $S$ ) and crosstalk image ( $C$ ). Each color channel ( $R$ ,  $G$  and  $B$ ) of each pixel in each image provides a constraint on the value of  $b$ . Combining equations (1) and (4) gives the following condition for subtractive cancellation to work:

$$\left( \frac{I'_S}{255} \right)^\gamma \geq c \left( \frac{I'_C}{255} \right)^\gamma \quad (6)$$

where  $I'_S$  and  $I'_C$  are the 8-bit gamma encoded values of the signal and crosstalk images at one pixel location, after the dynamic range has been compressed. Simplifying (6) gives:

$$I'_S \geq c^{1/\gamma} I'_C \quad (7)$$

The reduced dynamic range signal and crosstalk values ( $I'_S$  and  $I'_C$ ) are calculated from the input values ( $I_S$  and  $I_C$ ) with equation (5). Substituting these into the constraint of equation (7) gives:

$$b + (1 - b/255)I_S \geq c^{1/\gamma}(b + (1 - b/255)I_C) \quad (8)$$

Solving for  $b$  gives:

$$b \geq \frac{c^{1/\gamma}I_C - I_S}{1 + c^{1/\gamma} + (c^{1/\gamma}I_C - I_S)/255} \quad (9)$$

Equation (9) tells us the minimum amount the black level has to be raised for subtractive cancellation to work for one color channel of one pixel. To find the most restrictive value of  $b$ , we can evaluate (9) six times for every pixel; for each of the  $R$ ,  $G$ , and  $B$  channels,  $I \in (R, G, B)$ , and using both the left and right images as the 'signal' image  $S \in (\text{left}, \text{right})$ . By taking the maximum of all these values over the entire image, we find the optimal value of  $b$  for this stereo image pair. Both images can then be scaled to the range  $[b_{\max}, 255]$  using equation (7), and then subtractive crosstalk cancellation can be performed using (3), with the guarantee that no negative values will occur.

In order to improve efficiency, we can avoid calculating equation (9) for every color channel at every pixel. We can first check whether the condition  $I_S \geq c^{1/\gamma}I_C$  is met for the original values. If it is, then subtractive cancellation can be performed on the original pixels with no range compression at all. Therefore, we only need to evaluate equation (9) on color samples that fail the test  $I_S \geq c^{1/\gamma}I_C$ , which is typically a small fraction of the pixels in an image (1-10%).

### 3.2. Optimal YCbCr Domain Linear Scaling

In the previous section, we have derived the minimal amount that the black level has to be raised for a particular image if scaling is performed independently on the  $R$ ,  $G$  and  $B$  channels. This is known to distort colors, resulting in images with a washed out look [2][3][5][6]. In order to raise the minimum levels in the image while better maintaining the color, we propose to apply linear scaling to the luma component of the image in YCbCr color space. Since the chroma values are not altered, the colors of the image should be better preserved. In the ITU-R BT.709 standard, which is commonly used for HDTV, the luma ( $Y$ ) has range 16 to 235. We need to compress the luma range by raising the minimum level while keeping the maximum at 235. This can be accomplished by scaling the luma as follows:

$$Y' = b + (1 - b/235)Y \quad (10)$$

As in the previous section, we wish to find the minimum value of  $b$  that will ensure condition (7) is met for every

color channel at every pixel; i.e.  $R'_S \geq c^{1/\gamma}R'_C$ ,  $G'_S \geq c^{1/\gamma}G'_C$  and  $B'_S \geq c^{1/\gamma}B'_C$ .

The equations to convert between ITU-R BT.709 YCbCr color space and RGB are [7]:

$$\begin{aligned} R &= 1.164(Y - 16) + 1.793(Cr - 128) \\ G &= 1.164(Y - 16) - 0.213(Cb - 128) - 0.534(Cr - 128) \\ B &= 1.164(Y - 16) + 2.112(Cb - 128) \end{aligned} \quad (11)$$

Using the red channel as an example, scaling the luma with (10) will change the red value to be:

$$R' = 1.164(b + (1 - b/255)Y - 16) + 1.793(Cr - 128) \quad (12)$$

Expanding the constraint  $R'_S \geq c^{1/\gamma}R'_C$  with the value for the red channel given by (12) yields the following condition:

$$\begin{aligned} 1.164(b + (1 - b/255)Y_S - 16) + 1.793(Cr_S - 128) \\ \geq c^{1/\gamma}(1.164(b + (1 - b/255)Y_C - 16) + 1.793(Cr_C - 128)) \end{aligned} \quad (13)$$

Solving for  $b$  gives:

$$b \geq \frac{1.164[c^{1/\gamma}Y_C - Y_S + 16(1 - c^{1/\gamma})] + 1.793[c^{1/\gamma}(Cr_C - 128) - (Cr_S - 128)]}{1.164(1 + c^{1/\gamma}Y_C/235 - Y_S/235 - c^{1/\gamma})} \quad (14)$$

Equation (14) gives that minimum value of  $b$  that will ensure clipping does not occur on the red channel of one pixel during crosstalk reduction. To ensure clipping does not occur in the green channel, we need the condition  $G'_S \geq c^{1/\gamma}G'_C$ , which, through a similar derivation as the red case, gives the following constraint on  $b$ :

$$b \geq \frac{\left(1.164[c^{1/\gamma}Y_C - Y_S + 16(1 - c^{1/\gamma})] - 0.213[c^{1/\gamma}(Cb_C - 128) - (Cb_S - 128)]\right) - 0.533[c^{1/\gamma}(Cr_C - 128) - (Cr_S - 128)]}{1.164(1 + c^{1/\gamma}Y_C/235 - Y_S/235 - c^{1/\gamma})} \quad (15)$$

The equivalent constraint based on the blue channel is:

$$b \geq \frac{1.164[c^{1/\gamma}Y_C - Y_S + 16(1 - c^{1/\gamma})] + 2.115[c^{1/\gamma}(Cb_C - 128) - (Cb_S - 128)]}{1.164(1 + c^{1/\gamma}Y_C/235 - Y_S/235 - c^{1/\gamma})} \quad (16)$$

To determine the most restrictive value of  $b$ , we can evaluate equations (14), (15) and (16) twice for every pixel; once taking the left image as the signal, and once taking the right image as the signal. Taking the maximum of all these values gives us the lowest value of  $b$  that will ensure clipping does not occur during crosstalk reduction at any pixel in either image. Then the luma channel of both images can be scaled with (10), converted to RGB space with (11) and crosstalk reduction can be performed based on (3).

## 4. RESULTS

Three examples of applying our methods to 3D stereo images are shown in Figure 1. We assume a display gamma of 2.2 and 7% crosstalk ( $c=0.07$ ). We compare our method against the worst case RGB domain linear scaling, (raising the black level to  $255c^{1/\gamma} = 76$ ) which is the only previously described method that can ensure crosstalk can be

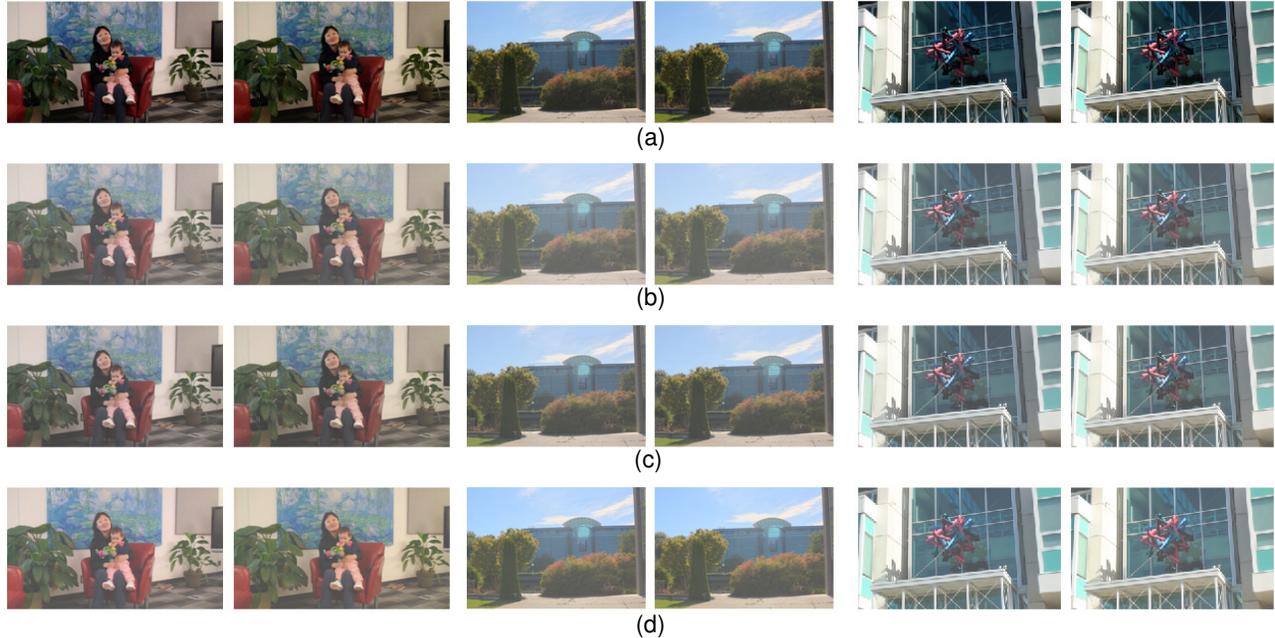


Figure 1: Comparison of different contrast reduction methods on 3D stereo images. (a) Original images (left and right) with RGB range [0, 255], (b) Worst case RGB scaling with range [76, 255] (c) Optimal RGB linear scaling (range varies image to image) (d) Optimal luma scaling in YCbCr space

fully cancelled out. An objective comparison between the methods is given in Table 1, where we show the compressed range for each image using each method and the chroma difference between the original images and compressed images measured with the CIEDE2000 color difference formula [8]. The CIEDE2000 color difference is a perceptual metric for comparing two colors based on the CIELAB color space. In order to eliminate the effect of the inherent increase in brightness present in all methods, we have set the lightness term ( $\Delta L$ ) in the CIEDE2000 formula to be zero, while retaining the terms relating to chroma and hue. This gives us a metric that measures only changes in color.

Comparing the images in Figure 1, we can see that worst-case RGB scaling (Figure 1b) gives the images a washout look. The optimal RGB scaling (Figure 1c) produces images with better contrast, but still somewhat washed out colors compared to the original images. Scaling in YCbCr space produces images with more saturated colors (Figure 1d), which more accurately reflect the color of the input images, as reflected in the significantly lower CIEDE2000 chroma difference values.

Table I: Objective Comparison of Contrast Reduction Methods

Image	Compressed Range			CIEDE2000 Chroma Difference		
	Worst Case RGB Scaling	Optimal RGB Scaling	Optimal Y Scaling	Worst Case RGB Scaling	Optimal RGB Scaling	Optimal Y Scaling
1	[76, 255]	[63, 255]	[82, 235]	2.95	2.48	0.95
2	[76, 255]	[49, 255]	[68, 235]	2.90	1.88	0.58
3	[76, 255]	[73, 255]	[84, 235]	2.32	2.24	0.72

## 5. CONCLUSIONS

In this paper we have derived the minimum amount the black level of an stereo image has to be raised in order to

ensure crosstalk can fully be cancelled out with subtractive crosstalk reduction. We have derived this for linear scaling of the RGB color channels and for scaling the luma channel in YCbCr space. Future work will focus on applying the methods to video, where temporal consistency also has to be considered.

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