DESIGNING ANAGLYPHS WITH MINIMAL GHOSTING AND RETINAL RIVALRY

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ABSTRACT

The anaglyph is a widely overlooked method of viewing three-dimensional images on any colored display. This is done by selectively filtering the image through colored lenses. Despite the simplicity of this system, the approach to designing anaglyph images remained largely empirical until a recent mathematical analysis by Eric Dubois. While the methods shown in the said work create good anaglyphs, they still exhibit a large amount of retinal rivalry which makes anaglyphs uncomfortable to view. This paper tackles modifications to the said approach to tackle several anaglyph issues, namely ghosting, retinal rivalry, and color reproduction, simultaneously. Subjective testing showed an improvement in viewer acceptance of images designed using the proposed method.

***Index Terms*—** Anaglyph, ghosting, retinal rivalry, color reproduction

1. INTRODUCTION

Anaglyphs are one of the simplest and most inexpensive ways of viewing stereoscopic images. An anaglyph system is comprised of a specially coded image shown on a given display and seen through glasses fitted with colored lenses [1]. The combination of the displayed image and the colored lenses are intended to allow for two distinct images to be viewed by the left and right eyes of a viewer respectively. It naturally follows that the perceived images are then dependent on how the displayed image is constructed and what color filters are used for the lenses.

The choice of color filters is a relatively trivial matter as the design task necessitates the use of complementary filters [2]. In fact, the most common anaglyph glasses are formed using red-cyan, green-magenta, and blue-yellow pairs. Complex filters have also been identified but are often still complementary in nature.

On the other hand, the construction of the anaglyph image is more involved. Since the conception of anaglyphs in the 1850s, most construction techniques have been empirically designed [3]. For instance, a red-cyan anaglyph may be constructed by simply discarding the red channel of the right image and replacing it with the red channel of the left image [4]. This results to a very simple method of producing anaglyphs.

Such a method, however, is riddled with problems. The spectral output of the display is likely to be very different from the filtering response of the glasses [2]. This means that some red intended for the left eye may also appear at the right eye and some cyan components may do the same. The end result is a phenomenon known as ghosting [2][5].

A second concern that arises from some anaglyph constructions is due to the way humans perceive images. If a significant difference in the left and right eye images is shown, the two images do not blend smoothly into a single three-dimensional image. Instead, one image may dominate at some point in time only to be replaced by the other images a while later. This switching of perceived images is known as binocular or retinal rivalry [1][6][7]. This is of great concern in anaglyphs as the color difference often triggers retinal rivalry causing a great amount of discomfort [8].

Finally, a third factor to be considered when constructing anaglyphs is the amount of color that can be reproduced. In the naïve construction mentioned earlier, color becomes unpredictable due to the complex interactions between the display and the glasses. It is of importance in anaglyph construction to be able to represent as much color as possible.

Most anaglyph construction techniques have been empirical in nature and little literature can be found on these [3]. A few techniques, however, have been developed scientifically. The work by Eric Dubois [3], for instance, presents a powerful framework for developing anaglyphs by using measured spectral properties of a given display and color filter set. An offshoot of this work was also shown in [1] where a different color space was used instead. These methods directly address the ghosting and color reproduction issues by attempting to build the anaglyph with the goal of making the perceived left and right images as close to the original as possible. However, without compensating for the color shifts due to the filters, these do not effectively address retinal rivalry.

In contrast, a documented empirical effort by Peter Wimmer has resulted to a different technique which tackles the issue of retinal rivalry by simple remapping of color channels [1]. However, due to the empirical nature of his approach, the other two factors are left unaddressed in his work.

This paper presents two methods largely derived from the works of both Dubois and Wimmer which attempts to balance all three factors in anaglyph design. A colorimetric approach attempts to preserve color detail as originally intended for viewing. On the other hand, a perceptual approach was also developed where colors are shown relative to each other.

2. ANAGLYPH CONSTRUCTION

As previously mentioned, the foundational works of this research are the methods presented by Dubois and Wimmer. Specifically, the methods shown by Dubois serve as the mathematical framework which will be modified to create a more robust construction method. Wimmer's work, on the other hand, is used to resolve the present retinal rivalry issues by combining features of this method with Dubois' work. To provide a concrete understanding of the proposed methods, a brief overview of these two methods is presented in this work.

2.1 Dubois' Projection Method

Dubois' method [3] of generating anaglyphs begins with an understanding of the visual pathway from the digital image values until it is perceived by the viewer. In summary, this can be broken down into several steps:

1. Digital values of the image are read.
2. The display transmits the specific colors stored in the image as a complex spectrum.
3. The spectrum of light is filtered using colored lenses.
4. The resulting spectrum is projected into the CIE XYZ color space representing the visual response.

Following this analysis, an anaglyph can be generated using the equation:

$$V_a(x) = N(R^T W R)^{-1} R^T W C_2 V(x) \tag{1}$$

where W represents a weighting matrix for emphasis in any component. In most cases, W can be defined as an identity matrix reducing the said equation to:

$$V_a(x) = N(R^T R)^{-1} R^T C_2 V(x) \tag{2}$$

V_a is a three-value vector containing the RGB values of the anaglyph image at any pixel x. V is a six-value vector for the RGB pairs representing the input stereoscopic image. R and C_2 are color matching matrices mapping RGB to XYZ values. Specifically, these were defined as:

$$R = \begin{bmatrix} A_l \\ A_r \end{bmatrix} \tag{3}$$

$$C_2 = \begin{bmatrix} C & 0 \\ 0 & C \end{bmatrix} \tag{4}$$

In these equations, A_l and A_r represent how RGB values are mapped into the CIE XYZ space with the left (red) and right (cyan) eye filters. C is the reference mapping without the filters.

A breakdown of equation (2) would then show the following steps:

1. C_2: The input RGB pairs are converted into their respective XYZ values without filters. This then represents the ideal XYZ values used as the target for the next step. No loss of information is present in this step.
2. $(R^T R)^{-1} R^T$ is a Moore-Penrose pseudoinverse of the matrix R. R by itself converts a single RGB input into a pair of XYZ values representing how a specific color is perceived through the left and right glasses. Naturally, the inverse of such an operation would map the XYZ values into a single RGB triplet. The use of a pseudoinverse is a lossy operation equivalent to a least-squares regression.
3. Normalize the output of the previous step using a normalization matrix N such that an input of $[1\ 1\ 1\ 1\ 1\ 1]^T$ would result in an output of $[1\ 1\ 1]^T$

Quite interestingly, all modifications to the Dubois' method in this work focus on altering the definition of C_2 thus changing the ideal target of the pseudoinverse. The exact modifications will be discussed in a later section but is largely based on ideas presented by Wimmer.

2.2 Wimmer's Color Mapping Method

The second method of concern in this work is not entirely scientific. In fact, the following method was documented by some other researcher [1]. Wimmer decided to use arbitrary values to define a conversion matrix shown below:

$$\begin{bmatrix} R_a \\ G_a \\ B_a \end{bmatrix} = \begin{bmatrix} 0 & 0.7 & 0.3 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} R_l \\ G_l \\ B_l \\ R_r \\ G_r \\ B_r \end{bmatrix} \tag{5}$$

The input in the above equation is the RGB pair of the input stereoscopic images and the output is the anaglyph equivalent. It becomes apparent that in this equation, the final red channel is defined solely by the blue and green components of the left image and the remaining channels are defined by the blue and green of the right image.

Since retinal rivalry in anaglyphs primarily occur as a result of luminance differences in the left and right perceived images [6][7], using only the blue and green components for both would result to a more stable perceptual response. The primary weakness in this approach lies in the fact that the red channel of the anaglyph may actually be perceived through both color filters due to the complex spectral behavior of light. This may result to ghosting issues.

3. DESIGNING ROBUST ANAGLYPHS

At this point, we are presented with two conflicting methods of designing anaglyphs. One of the methods uses matrix inversion to achieve good ghosting performance while the other uses color channel mixing for reducing retinal rivalry. The primary task in this research is therefore to find an effective means of combining the two methods to achieve a more robust anaglyph in terms of ghosting and retinal rivalry.

The first modification is dependent on an idea presented in [1]. In the said paper, it was hypothesized that the primary source of retinal rivalry in anaglyphs is difference in the CIE Lab lightness perceived between the left and right eyes. Naturally, this can be resolved by constraining the images such that the lightness at any shared pixel follows the relationship:

$$L_l^*(x) \approx L_r^*(x) \tag{6}$$

Since lightness is purely a function of the XYZ luminance, the above relationship can be satisfied when luminances are equal:

$$Y_l(x) = Y_r(x) \tag{7}$$

Moving further, these quantities are obtained by using the color matching matrices A_l and A_r on the input stereoscopic pair. In particular, we are concerned with only the luminance and thus, the only a select coefficients from these matrices are of concern:

$$Y_l(x) = a_{lYR}R_a(x) + a_{lYG}G_a(x) + a_{lYB}B_a(x) \tag{8}$$
$$Y_r(x) = a_{rYR}R_a(x) + a_{rYG}G_a(x) + a_{rYB}B_a(x) \tag{9}$$

Applying these to equation (7), the following relationship can be obtained:

$$R_a(x) = \frac{a_{lYG} - a_{rYG}}{a_{rYR} - a_{lYR}} G_a(x) + \frac{a_{lYB} - a_{rYB}}{a_{rYR} - a_{lYR}} B_a(x) \tag{10}$$

This provides a more exact relationship between the red, blue, and green components for color mixing as opposed to the fixed coefficients given by Wimmer. For the sake of simplification, the following notation will be used for these coefficients later in the discussion:

$$\alpha_G = \frac{a_{lYG} - a_{rYG}}{a_{rYR} - a_{lYR}} \tag{11}$$

$$\alpha_B = \frac{a_{lYB} - a_{rYB}}{a_{rYR} - a_{lYR}} \tag{12}$$

Going back to equation (2), it can be seen that the matrix C_2 defines the ideal targets for the left and right eye images which are based on the matrix C. To correct for retinal rivalry, the left eye target is then redefined using the following expression:

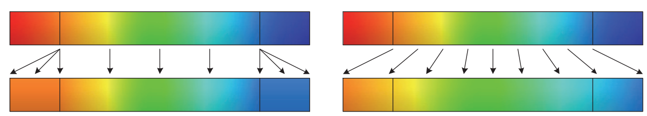
$$T = C \begin{bmatrix} 0 & \alpha_G & \alpha_B \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{13}$$

The value for C_2 can then be redefined as:

$$C_{2,c} = \begin{bmatrix} T & 0 \\ 0 & C \end{bmatrix} \tag{14}$$

This simple modification in itself provides a good measure of protection against retinal rivalry. However, the resulting color has certain limitations.

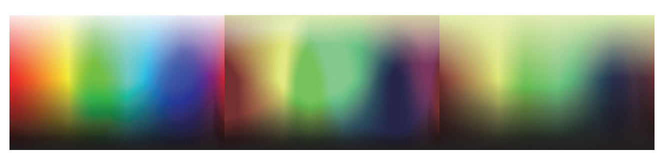
The Moore-Penrose pseudoinverse used in Dubois' method attempts to minimize the differences in the perceived colors and the target colors based on Euclidean distance in the XYZ color space. This is similar to colorimetric rendering defined in the ICC standard [9]. While such an approach may deliver images close to the original color, details are often lost particularly with gradients. An alternative is to use perceptual rendering which delivers colors relative to each other effectively compressing the color gamut. To better illustrate these two processes, refer to Figure 1.



(a) (b)

Figure 1. Simplified illustration of (a) colorimetric and (b) perceptual rendering processes.

It should be noted that this is a simplified illustration and does not show the actual relationship of colors in a complex trichromatic space. To better see the difference, Figure 2 shows a color spectrum rendered in a color-limited space using both colorimetric and perceptual techniques.



(a) (b) (c)

Figure 2. Differences in (b) colorimetric and (c) perceptual rendering. Original spectrum is shown in (a).

Since color is primarily perceived in the cyan image, perceptual rendering can be implemented in this work by again redefining the color matrix C_2:

$$C_{2,p} = \begin{bmatrix} T & 0 \\ 0 & A_r \end{bmatrix} \tag{15}$$

In this case, the target image for the right eye is now the original image directly filtered through the cyan filter. This prevents loss of color relationships and better color rendering. However, red information is now completely disregarded and any red hues would appear as dark regions. It is therefore necessary to pre-mix red into the other colors before the conversion matrix is applied. The process of doing so was shown in [1] and follows the expressions below:

$$G_l' = G_l + 0.45 * max(0, R_l - G_l) \quad (16)$$
$$G_r' = G_r + 0.45 * max(0, R_r - G_r) \quad (17)$$
$$B_l' = B_l + 0.25 * max(0, R_l - B_l) \quad (18)$$
$$B_r' = B_r + 0.25 * max(0, R_r - B_r) \quad (19)$$

The values of 0.45 and 0.25 are arbitrary constants provided in the original work. These coefficients can be altered without any loss of generality of the above equations.

4. TESTING AND RESULTS

To test the aforementioned approach, color matching matrices for a screen were obtained using a colorimeter. It should also be noted that the color matching matrix C was replaced with the standard sRGB matrix C_s as most images are encoded for the said standard.

$$A_l = \begin{bmatrix} 0.205521 & 0.013565 & 0.00141941 \\ 0.0949655 & 0.00847066 & 0.000592835 \\ 0.000275914 & 1.8169x10^{-5} & 0.00053366 \end{bmatrix} \quad (20)$$

$$A_r = \begin{bmatrix} 0.000994956 & 0.024508 & 0.065489 \\ 0.00123616 & 0.091068 & 0.0319108 \\ 0.00222796 & 0.0428684 & 0.385274 \end{bmatrix} \quad (21)$$

$$C_s = \begin{bmatrix} 0.4124 & 0.3576 & 0.1805 \\ 0.2126 & 0.7152 & 0.0722 \\ 0.0193 & 0.1192 & 0.9505 \end{bmatrix} \quad (22)$$

Using the said matrices, the following colorimetric and perceptual conversions were obtained:

$$P_c = \begin{bmatrix} 0 & 0.8640 & 0.2935 & -0.0417 & -0.1132 & -0.0027 \\ 0 & 0.0056 & -0.0026 & 0.2708 & 0.7292 & -0.0030 \\ 0 & -0.0215 & -0.0013 & -0.0926 & -0.3205 & 1.4360 \end{bmatrix} \quad (23)$$

$$P_p = \begin{bmatrix} 0 & 0.7755 & 0.2940 & -0.0008 & -0.0627 & -0.0060 \\ 0 & -0.0113 & -0.0043 & 0.0129 & 1.0027 & 0.0001 \\ 0 & -0.0040 & -0.0015 & 0.0045 & 0.0004 & 1.0006 \end{bmatrix} \quad (24)$$

Three images were tested with 28 volunteers using random pairwise comparisons of four methods – Dubois, Wimmer, colorimetric and perceptual. A binary response of which method was better in ghosting, retinal rivalry, and color was then obtained and analyzed using binomial testing. The results for these can be seen in Table 1.

To ensure the validity of the experiment, all volunteers were surveyed with regards to color blindness and prescription glasses. Only the said 28 subjects were allowed to proceed with the experiment. The testing room was also under controlled lighting with an average intensity of 99.51 cd/m^2 and color temperature of 5307K.

All results were analyzed at a 0.05 significance level using a two-tailed test. The methods which are statistically better are highlighted in Table 1 for the purpose of emphasis. It becomes clear from these results that in terms of ghosting performance, the perceptual approach clearly dominated Dubois' technique which is our benchmark technique for ghosting. Additionally, colorimetric anaglyphs showed poorer ghosting performance compared to Wimmer's technique.

Table 1. Subjective test results for different anaglyph methods

Pair Compared (A-B)	Ghosting			Retinal Rivalry			Color		
	A	B	p-value	A	B	p-value	A	B	p-value
Dubois-Colorimetric	84	84	0.531	85	83	0.469	82	86	0.650
Dubois-Perceptual	63	105	1.000	55	113	1.000	79	89	0.802
Dubois-Wimmer	85	83	0.469	74	94	0.948	98	70	0.018
Colorimetric-Perceptual	76	92	0.905	66	102	0.998	92	76	0.124
Colorimetric-Wimmer	69	99	0.992	57	111	1.000	90	78	0.198
Perceptual-Wimmer	74	94	0.948	91	77	0.158	79	89	0.802

In the area of retinal rivalry, perceptual rendering was again found to be better than Dubois' technique and additionally colorimetric rendering. Improvement over Wimmer's method was not seen although a statistically insignificant tendency towards the perceptual approach could be seen. Colorimetric rendering was found to perform poorly compared to Wimmer's approach in this aspect.

Finally, the perception of color by the viewers was found to be relatively equal for most pairs with the exclusion of the Dubois-Wimmer pair. This shows that a direct comparison of the two methods would identify Wimmer as a poorer method in terms of color.

5. CONCLUSION

Colorimetric and perceptual techniques for generating anaglyphs are shown in this paper. Based on subjective tests with a sufficiently large sample population, it was found that the methods presented have distinct features compared to the benchmarks techniques given in [1] and [3]. Colorimetric anaglyphs were found to be subjectively inferior in most aspects. In stark contrast with this, perceptual anaglyphs were found to be generally better in both ghosting and retinal rivalry. Aside from this, color perception was also not sacrificed in this technique.

To further improve these techniques, future work can be done in finding additional color spaces which provide a distance function for anaglyphs. Also, the choice of color mixing coefficients used for pre-mixing in the perceptual approach warrants further investigation to potentially yield to a mathematical approach to effectively deliver the best colors.

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