Adaptive 3D Color Anaglyph Generation for Printing

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Abstract

Nowadays stereophotography is rapidly developing, providing a plenty of sources for stereoimages. The goal of current technology – to provide users with possibility to get high quality 3D anaglyph prints for education and entertainment. To do so it is necessary to agree color characteristics of glasses and printed colors, since errors in color transmission lead to cross-talk interference and ghosting effects. There is no easy way for user to adjust colors of anaglyph in order to coordinate characteristics of glasses and printer.

We propose a technique that allows generating anaglyphs with colors adapted to given glasses and printer colors by means of special color pattern analysis. In addition, our approach takes into account the size of the printed anaglyph image. Resulting printed images have a good quality that is confirmed by user opinion survey. The images contain fewer artifacts and look better in comparison to anaglyphs without adaptation, which are generated in existing software applications. The technique utilizes a low amount of memory and has low computational complexity.

Keywords: *Anaglyph, stereo printing, crosstalk noise, ghosting reduction.*

1. INTRODUCTION

At present time, there are a lot of sources of stereo images: 3D cameras, 3D movies, stereo-pairs can be created from two frames captured by conventional 2D camera, several software technologies allow to catch different views of the same 3D object, for example, Google Earth and parallax effect in HTML 5. 3D books have been known for several decades, they are viewed through glasses with different color filters, for example blue and red. Reconstruction of three-dimensional views by anaglyphs is one of the simplest and the most economic methods. However this method has some disadvantages such as loss of color and discomfort for prolonged viewing. In spite of the drawbacks, sometimes consumers want to print 3D color anaglyph pictures for education and entertainment. There are various user groups in Web like Flickr and others, where the process of 3D color anaglyphs generation is discussed [4, 9].

There are several PC and mobile software applications for generation of anaglyphs, for example StereoPhoto Maker, Anaglyph Maker, Anaglyph, Anaglyph Workshop, Z-Anaglyph. They have some disadvantages: settings for ghosting effect reduction do not take into account size of the printed anaglyph; there is no adaptation for given glasses and printer colors.

Usually it is assumed that viewing anaglyph on a display and adjusting of printer color profile is enough to get similarly looking printed anaglyph. However, our experiments show that it is impossible to get similar color perception while looking at a display and color hardcopy produced by a laser or ink-jet printer. From a theoretical point of view it can be easily explained, because gamut of a display and gamut of printing devices are rather different [2]. That is why printing devices manufacturers are interested in rising of printing quality of anaglyph [10].

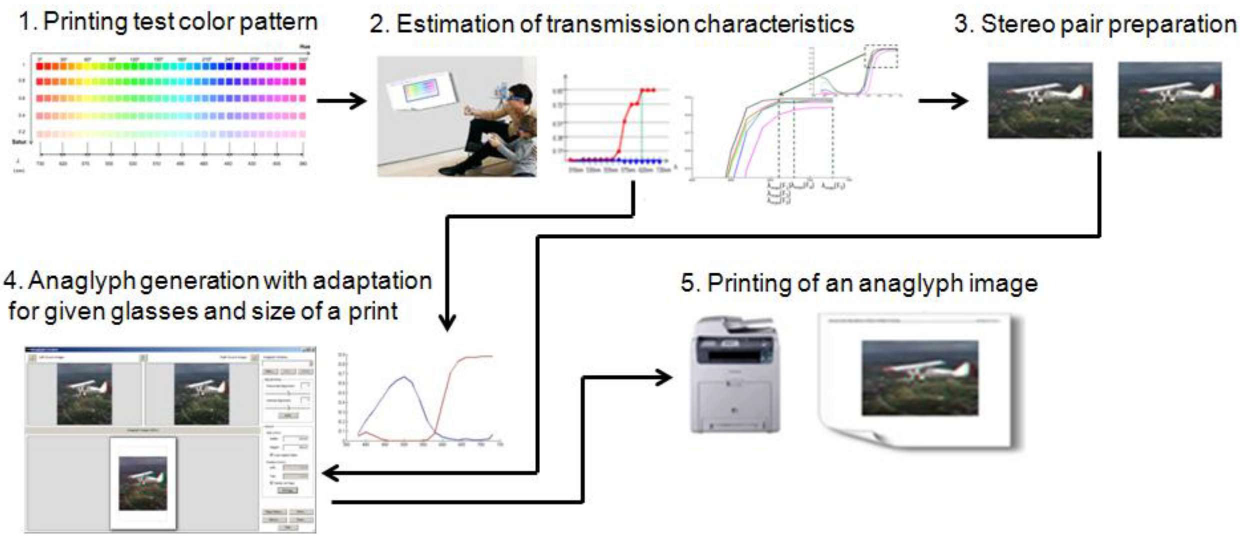


Figure 1. Algorithm of an adaptive anaglyph generation

After performing the measurements of transmission coefficient for several glasses ($\tau_r(\lambda)$ for right filter and $\tau_l(\lambda)$ for left filter) as well as reflection spectrum of printed colors, i.e. magenta $g_M(\lambda)$ and cyan $g_C(\lambda)$, by spectrometer, and analyzing estimated reflection and transmission coefficients, it was concluded that full elimination of cross-talk effect is impossible. Nevertheless, it is possible to reduce cross-talk interference by correct color setting of a printed anaglyph. As it is evident by experiment, the primary printed colors (cyan and magenta) aren't transmitted well; but our estimations show that colors selection according to given glasses allows to decrease ghosting artifacts significantly.

In this paper we propose an adaptive to spectral characteristics of glasses and printer's colors algorithm for anaglyph creation.

2. RELATED WORKS

Anaglyph generation is a difficult problem. It isn't enough to put one color channel in a left image and another in a right image. Contradictory problems should be solved in anaglyph generation process, because it is needed to code two images on a single view by colors for stereo effect making and to reproduce colors with maximum naturalness. Due to stereo and color conflicts it appears to be impossible to develop an algorithm for anaglyph creation which always produces good color representation, good details, and is permanently free from typical artifacts, such as ghosting, and region merging.

Well-grounded technique for color anaglyph generation for display is described in [1,3,5,8].

Several techniques have been proposed for the production of anaglyphs for viewing on displays. In [8] three approaches are discussed: Photoshop algorithm (PS) and its variants, the least squares algorithm (LS) proposed by Eric Dubois, that optimizes colors in the CIE space, and the midpoint algorithm (MID) that minimizes the sum of the distances between the anaglyph color and the left and right eye colors in CIE L*a*b*. Linear anaglyph algorithms will always map several different left/right eye colors to the same RGB color. The results show that the MID method produces excellent color and detail for color images but may suffer severe ghosting. Anaglyphs produced by the LS method are normally darker with less detail and require brightening or gamma correction but appear to have no ghosting. The PS method is easy to implement and works well for grayscale images but may also suffer from ghosting and poor color representation.

In [3] several methods for anaglyph enhancement are proposed that rely on stereo image registration, defocusing and nonlinear operations on synthesized depth maps. These enhancements substantially reduce unwanted ghosting artifacts, improve the visual quality of the images, and make comfortable viewing of the same sequence possible in three-dimensional as well as the two-dimensional mode.

The method for computing pixel colors in anaglyph images presented in [5] depends upon knowing the RGB spectral distributions of the display device and the transmission functions of the filters in the viewing glasses. It requires the solving of a nonlinear least-squares problem for each pixel in a stereo pair and is based on minimizing color distances in the CIEL*a*b* uniform color space.

The method proposed in [1] is adapted to the spectral absorption curves of the left and right filters of the anaglyph glasses. A projection technique is used to compute the anaglyph image that yields an image pair (after the glasses) as close as possible to the desired stereo pair. In order to generate anaglyph it is necessary to move into the XYZ space by transition matrix:

$$[C]_{kj} = c_{kj} = \int \bar{p}_k(\lambda)\, d_j(\lambda) d\lambda,$$

where $\bar{p}(\lambda)$ - color-matching function, $d(\lambda)$ - spectrum of standard illuminant. Reflection light from an image passes through color filters of an anaglyph glasses and is transformed by two transition matrixes:

$[A_l]_{kj} = a_{lkj} = \int \bar{p}_k(\lambda) d_j(\lambda) f_l(\lambda) d\lambda$ (for left eye filter) and $[A_r]_{kj} = a_{rkj} = \int \bar{p}_k(\lambda) d_j(\lambda) f_r(\lambda) d\lambda$ (for right eye filter).

An anaglyph is generated by the following formula:

$$\widehat{V}_{an}(x) = N(R^T M R)^{-1} R^T M C_2 V(x),$$

where N is normalizing matrixes for condition $\widehat{V}_{aj} \in [0,1]$, M is weighted matrix, which allows weighting of the Y component more heavily than X and Z to favor reproduction of the correct luminance, $R = \begin{bmatrix} A_l \\ A_r \end{bmatrix}$, $C_2 = \begin{bmatrix} C & 0 \\ 0 & C \end{bmatrix}$.

3. ADAPTIVE ANAGLYPH GENERATION

3.1 General workflow

In our paper we generate anaglyphs with a help of the method described in [1]. The algorithm takes into account spectral characteristics of stereo glasses. We propose a new approach for adaptation of anaglyph colors on hardcopy to stereo glasses to reduce ghosting effect to minimum.

Before anaglyph generation a process of transmission function estimation is performed. For this purpose firstly we print the color pattern (figure 1, step 1) on a target printer, then we estimate transmission coefficients of given glasses. Detailed description of test color pattern is present in section 3.3; and a sequence of actions for evaluation of transmission function of glasses filters (figure 1. step 2) by user is described in section 3.4.

Then it is needed to prepare a stereo pair (figure 1, step 3). Preparation includes geometrical aligning, color correction and enhancement. Stereo pair color correction is performed by well-known method of histogram matching [7]. After that the stereo pair is enhanced to reduce unwanted artifacts. There are two main ideas for anaglyph enhancement: decreasing of disparity range of a stereo pair and color component defocusing. Detailed description of these ideas is present in section 3.2. Then anaglyph generation is performed by method [1] with adapted transmission functions (figure 1, step 4). Also we propose a method of disparity correction for keeping 3D effect and reduction of ghosting effect appearance on an anaglyph hardcopy, because anaglyph size can be different on display and hardcopy (figure 1, step 5). It is presented in section 3.5.

3.2 Anaglyph enhancement

Decreasing of disparity range of a stereo pair includes estimation of average disparity value on a stereo pair by the following method:

$$arg_{d_i} min \sum_{(x,y)\in W} |I(x,y) - I(x+d_i,y)|,$$

where d_i - disparity with minimal value of SAD (Sum of Absolute Differences) [6] in some region on left and right images. We compute average disparity $\bar{d}$ after estimation of the disparity map. Decreasing of disparity is produced by horizontal shifting of stereo pair proportionally to $\bar{d}$. If average disparity is less than 4 pixels, stereo pair is not changed. The main idea is that disparity should not be too large relatively to image size. Therefore, horizontal shift is computed as $Shift = Q \cdot \bar{d}$, where Q is regularization coefficient which depends on ratio of average disparity and image width W in pixels, as presented on figure 2. If the value of the ratio $\bar{d}/W$ is greater than 0.03 it might inform about erroneous average disparity estimation; and shifting of a stereo pair should be made with a smaller value. All constants of the empirical approach were found during a plenty of visual experiments.

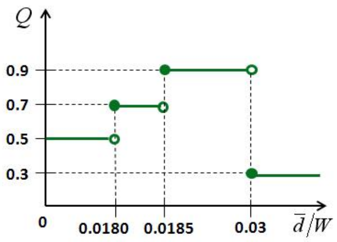


Figure 2. Dependence of the regularization coefficient from size and disparity of a stereo pair.

Figure 3. The anaglyph without disparity correction.

Figure 4. The anaglyph with corrected disparity.

Figure 3 shows the anaglyph withour disparity correction. On its harcopy ghosting effect is present. Figure 4 demonstrates the anaglyph with decreased disparity. For its generation stereo pair was shifted by 5 pixels. Ghosting effect for this anaglyph hardcopy is almost invisible.

Simple and effective way for decreasing of crosstalk noise is defocusing one color channel for both images of stereo-pair [1]. We carry out red or blue channel or both the channels smoothing by means of low-pass box-filter.

3.3 Transmission functions estimation by user

We propose to estimate transmission functions $f_l(\lambda)$ and $f_r(\lambda)$ for given glasses and printer colors. It allows to significantly reduce ghosting effect and improve quality of printed 3D color anaglyph image. For evaluation of $f_l(\lambda)$ and $f_r(\lambda)$ we print the color pattern on target printer. This pattern is a color table including all printable colors in HSL space. This pattern reveals a dependence of digital color components and reflection spectrum of these colors (another dependence of three color components (RGB) and wave length (λ). Hue corresponds to wavelength, lightness is an average between maximum and minimum values of spectrum; saturation is distance from maximum (or minimum) values of spectrum to lightness. Rows of the table are colors with various saturation (step is 0.2), columns are colors with various hue (step is 10^0).

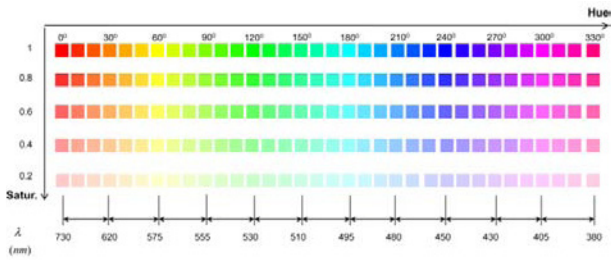


Figure 5. Test color pattern.

For estimation of transmission function user should examine the pattern through left and right filters of anaglyph glasses separately. By visibility level of color sample through the filter, the transmission function is evaluated and afterwards is applied for anaglyph generation. If the color sample is invisible, it fully passes through the filter and maximum of transmission function is at that location.

Let's left filter is red and right filter is cyan. Firstly user should examine first row with maximal saturation through red filter. We suppose that a color with hue = $10^0 \pm 10^0$ corresponds to red color of 700 nm ± 27.50 nm wave length range. If any color from the band $10^0 \pm 10^0$ is invisible, the maximum of transmission function is in the 700 nm ± 27.50 nm range. If the color is visible, user should choose the row with less saturation (one of the lower rows) and look at corresponding color sample once more. If the color yet is visible, user should choose the row with the least saturation for analysis. Value of maximum of transmission function depends on saturation that was chosen:

Row of color pattern	Saturation	Maximum of transmission (*MaxTrans*)
1	1	0.90 (90%)
2	0.8	0.85 (85%)
3	0.6	0.65 (65%)
4	0.4	0.50 (50%)
5	0.2	0.45 (45%)

For cyan filter construction of the transmission function is similar. We use cyan filter of glasses and suppose cyan color has hue = $180^0 \pm 10^0$ that corresponds to 495 nm ± 3.75 nm range. User should examine the test pattern and define visibility level of each color by grade (0…5) which corresponds to transmission. For each clearly visible point we give a 0 grade. Values of transmission function depend on maximum of transmission associated with row of color pattern and grade evaluated by observer.

Transmission	Grade	Transmission	Grade
$\boldsymbol{MaxTrans \times 1}$	5	$MaxTrans \times 0.45$	2
$\boldsymbol{MaxTrans \times 0.85}$	4	$MaxTrans \times 0.20$	1
$\boldsymbol{MaxTrans \times 0.60}$	3	$MaxTrans \times 0$	0

User should mark only invisible or semitransparent colors. In this way we obtain rough approximation of transmission functions for particular glasses.

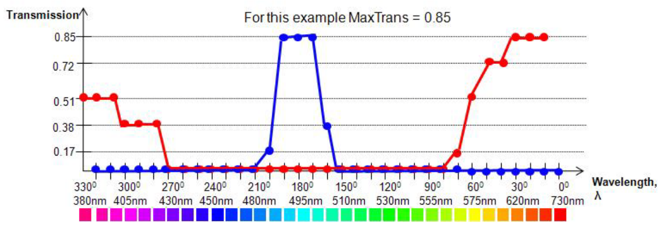


Figure 6. Transmission function evaluated by user.

3.4 Algorithm for selection of transmission function of existing filter

Usage of the transmission functions in such "pure" form lead to anaglyph image with wrong colors. We propose to use known transmission functions of Roscolux filters (http://www.rosco.com/us/filters/roscolux.cfm) and calculate functions of given glasses by selecting the nearest function to our rough approximation. Roscolux filters are used in professional photography.

In order to choose appropriate filter or glasses with transmission function (F_i) most similar to our computed transmission function, we note position of maximum of function and its value.

Then, we choose F_i as: $\left\|\lambda_{\max(F_i)} - \lambda_{\max(f)}\right\|_i \to min$ - estimation position of the maximum. Then for the maximums with equal wavelength we apply the following condition:

$$\|\max(F_i) - \max(f)\|_i \to min. \ (1)$$

For example, compare f (users' evaluation for red filter) on figure 7 and F_i (real transmission functions of Roscolux filters) on figure 8. On the top of the figure the transmission functions are presented; in the bottom the enlarged part of the graph with transmission function maximums area is shown. By analyzing wave lengths which correspond to maximums of transmission functions and according to decision rule (1) we select one of the most appropriate filters.

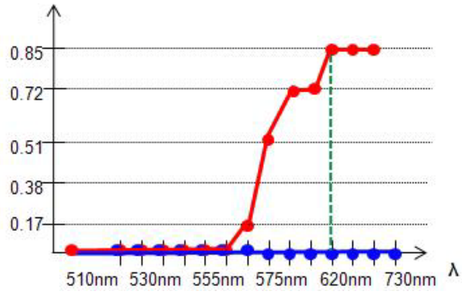


Figure 7. A part of graph of ***f***.

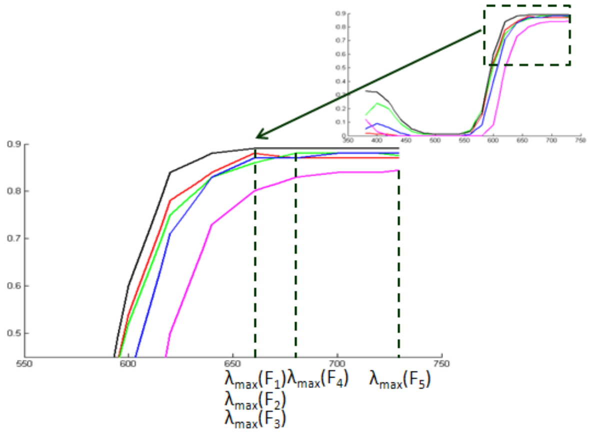


Figure 8. Choosing transmission function of Roscolux filters.

An anaglyph on figure 9 is generated with transmission functions of most common stereo glasses. Its hardcopy printed on Samsung CLP-6240 printer has perceptible ghosting effect for given glasses. An anaglyph on figure 10 is generated with transmission functions adapted for given glasses and printer colors. Ghosting effect on this anaglyph hardcopy is significantly reduced.

3.5 Adaptation to size of hardcopy

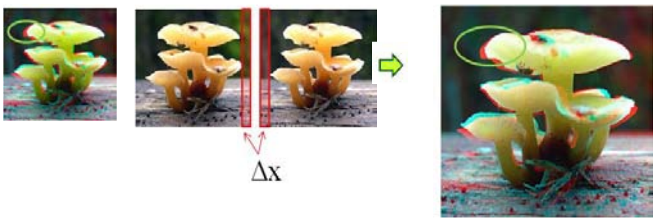
Anaglyph upsizing while printing leads to large disparity increase and emerging of ghosting effect. Downsizing leads to large disparity decrease and disappearance of stereo effect. We propose to decrease disparity value by shifting stereo pair images relative to each other before enlarging process.

In case of upsizing $\Delta x = -0.3 * \bar{d}$, where $\bar{d}$ is average disparity value computed for whole images of stereo pair, Δx is value of shift of stereo pair images relative to each other for disparity decrease. The value of constant 0.3 is chosen as a result of large number of experiments.

Vice versa in case of downsizing $\Delta x = 0.3 * \text{AvrgDisp}$ is a shift for disparity increase.

Figure 9. An anaglyph example for transmission function of most common stereo glasses.

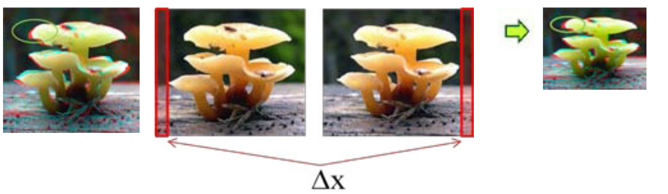
Figure 10. An anaglyph example with adaptation for given glasses.



Shifting (Remove regions $\Delta x = -0.3 * \bar{d}$)

An anaglyph with smaller disparity and ghosting effect

Figure 11. Disparity modification in case of upsizing.



Shifting (Remove regions $\Delta x = 0.3 * AvrgDisp$)

An anaglyph with preserved stereo effect

Figure 12. Disparity modification in case of downsizing.

4. RESULTS AND DISCUSSIONS

All mentioned algorithms were implemented in software application. User interface of the application is shown on figure 1. We applied Windows Presentation Foundation API for nice user interface generation. Mathematical parts of algorithms were developed on C programming language. Proposed technique utilizes low amount of memory and has relatively low computational complexity. Figure 13 demonstrates plot of processing time for anaglyph generation procedure depending on size of stereo-pair images. The computational time data were obtained on PC with dual-core 3 GHz CPU. It is already quite acceptable. Some additional platform-dependent optimizations are possible too.

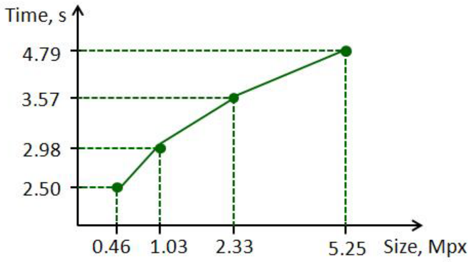


Figure. 13. Processing time for anaglyph generation procedure.

In order to perform benchmarking we used 5 mentioned above solutions for anaglyph generation and our software application. Evaluation was done by 14 observers with the same viewing conditions and glasses. We screened the subjects for normal color vision by Ishihara test plates. In our survey we used test set of 6 stereo pairs. Generated anaglyphs were printed on Samsung CLP-6240 printer. We propose to calculate quality factor of anaglyph generation as weighted sum of two subjective estimations:

$$E = \alpha_1 V_1 + \alpha_2 V_2,$$

where V1 is subjective quality of 3D visualization, V2 is subjective level of color naturalness, $\alpha_1 = 0.8$, $\alpha_2 = 0.2$. V_1 and V_2 are changed from 0 to 1 with step of 0.2; lower V_1 and V_2 are better. We prioritized weights α_1 and α_2 by using Analytic Hierarchy Process [7]. Table 1 contains comparison of the solutions for anaglyph generation obtained during our survey.

Table 1. Comparison of applications for anaglyph generation.

	Average E	Maximum E
StereoPhoto Maker	0.33	0.52
Anaglyph Maker	0.57	0.72
Anaglyph	0.45	0.56
Anaglyph Workshop	0.58	0.76
Z-Anaglyph	0.55	0.74
Proposed technique	0.30	0.58

In general our algorithm outperforms all tested solutions. The anaglyph generated by StereoPhoto Maker is presented on figure 14. The anaglyph on hardcopy has well noticeable cross-talk noise. The anaglyph generated by proposed method is presented on figure 15. The picture looks better due to enhancements.

Figure 14. The anaglyph generated by StereoPhoto Maker.

Figure 15. The anaglyph generated by proposed method.

ACKNOWLEDGMENT

Authors would like to thank Konstantin Kryzhanovsky for help with algorithm implementation and discussions about the paper. Thanks also go to Graphicon's anonymous reviewers for their comments.

REFERENCE

[1] Dubois Eric *"A projection method to generate anaglyph stereo images", Proc. of ICASSP, IEEE International Conference "Acoustic, Speech, and Signal Processing", vol.3, pp. 1661-1664, 2001.*

[2] Foley James D., van Dam Andries, Feiner Steven K., Hughes John F. *"Computer Graphics. Principles and Practice", 2nd ed., 1990.*

[3] Ideses Ianir, Yaroslavsky Leonid *"Three methods that improve the visual quality of colour anaglyphs", J. Opt. A: Pure Appl. Opt. 7, 755–762, 2005.*

[4] Lo Wan-Yen, van Baar Jeroen, Knaus Claude, Zwicker Matthias, Gross Markus *"Stereoscopic 3D Copy & Paste", Proc. of ACM SIGGRAPH Asia, Vol. 29, Issue 6, 2010.*

[5] McAllistera David F., Zhoub Ya, Sullivanc Sophia *"Methods for computing color anaglyphs", Proc. of Stereoscopic Displays and Applications XXI, SPIE Vol.7524.*

[6] Rziza Mohammed, Aboutajdine Driss "*Dense Disparity Map Estimation Using CUMULANTS*", 2011 18th IEEE International Conference on Image Processing, p. 984.

[7] Saaty T.L., *Decision Making for Leaders: The Analytic Hierarchy Process for Decisions in a Complex World*, New Edition, Analytic Hierarchy Process Series, Vol. 2, 2001.

[8] Sanders William, McAllister David F. *"Producing Anaglyphs from Synthetic Images", Proc. of Electronic Imaging, pp. 348 – 358, 2003.*

[9] Zhang Yun, Xie Pingping, and Li Hui *"Data fusion for multi-scale colour 3D satellite image generation and global 3D visualization", Proc. of ISPRS Commission VII Midterm Symposium "Remote Sensing: From Pixels to Processes, 2006.*

[10] Zeng Ruzhu, Zeng Huanzhao *"Printing Anaglyph Maps Optimized for Display", Proc. of Color Imaging XVI: Displaying, Processing, Hardcopy, and Applications, vol. 7866, 2011.*

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