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# Three methods that improve the visual quality of colour anaglyphs

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**Abstract**
Anaglyphs are one of the most economical methods for three-dimensional visualization. This method, however, suffers from severe drawbacks such as loss of colour and extreme discomfort for prolonged viewing. We propose several methods for anaglyph enhancement that rely on stereo image registration, defocusing and nonlinear operations on synthesized depth maps. These enhancements substantially reduce unwanted ghosting artefacts, 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 of the same sequence.

**Keywords:** anaglyph, depth map, enhancement, registration

(Some figures in this article are in colour only in the electronic version)

## 1. Introduction

Anaglyphs are one of the most economical methods for three-dimensional (3D) visualization. This method was introduced by Ducos du Hauron, in 1891 [1]. Anaglyphs are artificial colour images that produce a visual effect of 3D images when viewed using colour-filtering spectacles. Such glasses can be easily acquired on the web. A web search for ‘anaglyph glasses’ will yield several online vendors [2]. Our experience also shows that one can even use glasses that are self-made from blue (green)–red transparent colour films that can be easily found in paper shops.

In order to synthesize an anaglyph, two images, referred to as a stereo pair, are required. For greyscale stereo images, the red channel of the anaglyph is taken from the left image and the blue channel from the right image. It is also possible to include a green channel from either image of the stereo pair; this results in a mostly greyscale image of better visual quality.

In principle, colour anaglyphs (anaglyphs synthesized for viewing stereoscopic colour images) can also be synthesized by permutation of the colour channels of the images. In this case, the red channel from the right stereo pair image is replaced by the red channel of the left stereo image. Synthesizing colour anaglyphs in this fashion is suitable for most images but may not achieve 3D perception in images of unbalanced colour histograms. For example, images low in red hues do not contribute enough detail to create 3D perception. Figure 1 shows anaglyphs created using the techniques detailed above. As one can see, the resulting anaglyph images are of very poor visual quality.

These images suffer from loss of colour (most anaglyph images are in greyscale, e.g. Mars Pathfinder anaglyph images released by NASA [3]) and of ghosting artefacts. These two drawbacks limit the use of anaglyphs as an acceptable 3D visualization method.

Since anaglyphs are considered the low end in 3D visualization methods, very little work has been carried out towards increasing their visual quality. Some works were focused on calibrating the image hues to the colour filters in a manner that decreases cross-talk between the eyes and matches red/green/blue (RGB) colour values to the colour glasses [4, 5]. However, systematic enhancement of anaglyphs has not been reported in the literature.

In this paper we suggest several methods for the systematic synthesis of anaglyphs with enhanced image quality that retain colour information and substantially reduce ghost image appearance. Our methods are based on exploiting the redundancy of stereoscopic images.

Section 2 describes the redundancy of stereoscopic images, section 3 details the algorithms used to enhance

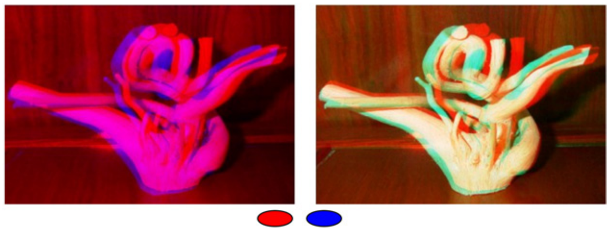

**Figure 1.** The left image is an anaglyph created by transforming the stereo pair to greyscale and using the left image as the red component and the right image as blue component of the anaglyph. The right image is an anaglyph created by permutation of the colour components of the stereo pair. In this case the red component of the right image is replaced with the red component of the left image creating the anaglyph. Viewing of these images is possible with red–blue glasses, using the red filter for the left eye and the blue filter for the right eye. Note the destructive ghosting artefacts in both images.

anaglyphs and section 4 shows how these methods influence the viewing modes of anaglyphs.

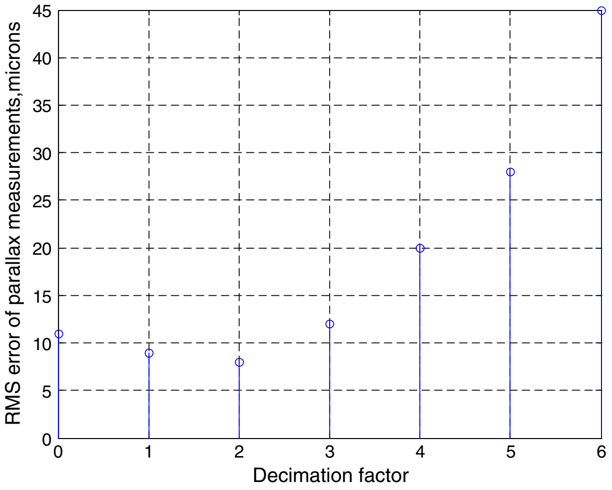

**Figure 2.** Root-mean-squared error of parallax measurements as a function of the decimation factor as measured on 31 randomly selected fragments of a training stereo air photograph analysed by a professional human operator.

## 2. Redundancy of stereoscopic images

It is well known that stereoscopic images are redundant in their information content. A fact that is, probably, less known is the extent of this redundancy. One can make an estimation of this redundancy using the following reasoning.

From the informational point of view, two images of the same scene that form a stereo pair are equivalent to one of the images and a depth map of the scene. Indeed, from two images of the stereo pair, one can build a depth map, and, vice versa, a stereo pair utilizing one image and the depth map. Therefore, the increase of the signal volume added by the second image of the stereo pair is equal to the signal volume that corresponds to the depth map.

The number of depth gradations resolved by vision is of the same order of magnitude as the number of resolved image grey levels. Therefore, the signal volume increment due to the depth map is mainly determined by the number of depth map independent samples.

Every sample of the depth map can be found by localizing corresponding fragments of two images of the stereo pair and measuring the parallax between them. All technical devices that measure depth from stereo work in this way, and it is only natural to assume the same mechanism for stereoscopic vision. The number of independent measurements of the depth map is obviously the ratio of the image area to the minimal area of the fragments of one image that can be reliably localized on another image. It is also obvious that it is, generally, not possible to reliably localize one pixel of one image in another image. For reliable localization, image fragments should contain several pixels. Therefore, the number of independent samples of the depth map will be, correspondingly, several times lower than the number of image pixels. Thus, the increment of the signal volume that corresponds to the depth map will be several times lower than the signal volume of one image. For instance, if the reliable size of the localized fragment is $2 \times 2$ pixels, it will be four times lower. For $3 \times 3$ fragments, it will be nine times lower, and so on. Practical experience suggests that, for reliable localization of fragments of one image in another image, the fragment size should usually exceed the area of $8 \times 8$–$10 \times 10$ pixels. This allows us to hypothesize that the signal volume increment associated with the depth map may amount to a few per cent or even fractions of a per cent of the signal volume of one image.

Experiments with decimation and subsequent interpolation of one of two stereoscopic images [6] provide experimental support for this estimation. Figure 2 shows the root-mean-squared (RMS) error of parallax measurements as a function of the decimation factor. These measurements were performed on a set of stereo aerial photographs of good photographic quality. For each measurement, one of the images was decimated with different decimation factors and then interpolated back to the initial size. The data were obtained by averaging the parallax measuring errors over 31 randomly selected image fragments. The decimation and interpolation were carried out in a computer and the operator was working with computer-generated images. Decimation factor zero corresponds to data obtained for initial photos (not computer generated). One can see from figure 2 that 4×- and even 5×-decimation/interpolation of one of two images of a stereo pair does not dramatically increase the measurement error. With the increase of the decimation order, the RMS error grows according to a parabolic law. Beyond 7×-decimation/interpolation, localization failures appear, and the probability for failures grows very rapidly with the decimation factor. All of this is in good correspondence with the theory of localization accuracy of image correlators [7], although the data were obtained for a human operator.

Similar experiments with random dot stereograms, measuring the time delay needed to clearly perceive 3D and 3D target detection threshold as a function of blur degree of one of two stereo images have shown similar results. The images presented in figures 3, 4 are intended to demonstrate that 5×-decimation and interpolation of one of two stereoscopic images does not substantially affect 3D perception. When viewed using a stereoscope, these images show that 3D perception as well as perceived image sharpness are conserved.

**Figure 3.** Full-resolution stereo pair (upper row) and stereo pair built from one image of full resolution and second image of 1/5th of full resolution (bottom row).

## 3. Anaglyph enhancement

Obviously, the main reason for the relatively low quality of anaglyphs is ghosting artefacts due to misalignment of the colour components that compose the anaglyph. These artefacts are, however, a direct result of the process of the stereo pair acquisition. Proper camera setup has a great impact on the ghosting effect. In theory, these artefacts can be greatly reduced by acquiring the images with low parallax. Capturing images with low parallax, however, results in images of low 3D perception. This tradeoff, therefore, does not enable acquisition of 3D images, with low artefacts, high visual quality and high 3D perception. In order to create high-quality anaglyphs while retaining 3D perception, we suggest three methods for reducing ghosting artefacts:

- stereo pair registration;
- colour component blurring;
- depth map manipulation and artificial stereo pair synthesis.

### *3.1. Stereo pair registration*

One can substantially reduce the undesired ghosting effects by means of registration of foreground, or image areas of the highest interest in the two colour images of the stereo pair (see [8, 9]). This can be carried out either globally on the entire image or locally on selected important objects in the image.

Global registration can be performed very efficiently by using a correlational filter and finding the horizontal and vertical parallax $(\Delta\hat{x}_0, \Delta\hat{y}_0)$ by localization of the highest peaks of the correlation result:

$$(\Delta\hat{x}_0, \Delta\hat{y}_0) = \arg\max(I_1 \otimes I_2)(x, y) - \arg\max(I_1 \otimes I_1)(x, y), \tag{1}$$

where $I_1$ is one image of the stereo pair, $I_2$ is the second image or its part chosen for registration and $\otimes$ symbolizes correlation in image coordinates $(x, y)$. Image correlation can be computed in the discrete Fourier transform (DFT) domain by utilizing fast Fourier transforms (FFT). In this method, known as matched filtering, the DFT spectrum of one image is multiplied by the complex conjugate spectrum of the second image. The result is obtained by computing the inverse DFT of the product.

Overall image correlation usually yields good reliability with very few cases of false registration. However, it does not allow alignment of the images around specific regions. It may be desirable, for some images, to perform the registration for a specific image fragment of a relative small size. In such cases, conventional correlation techniques frequently fail to provide reliable localization of the target image area. It has been shown that the performance of target location can be significantly improved using an adaptive correlator [10, 11]. The adaptive correlator is a variation of the matched filter. In this case, we should use a filter with frequency response

$$H(f_x, f_y) = \frac{\alpha^*(f_x, f_y)}{|\beta(f_x, f_y)|^2 \otimes W(f_x, f_y)} \tag{2}$$

where $\alpha^*(f_x, f_y)$ is the complex conjugate spectrum of the fragment of one image, selected to be localized in the second image, $|\beta(f_x, f_y)|^2$ is the squared module of the DFT spectrum of the second image and $W(f_x, f_y)$ is a spectrum smoothing window.

A standard colour anaglyph and an anaglyph enhanced by registration are compared in figure 5. As one can see, the

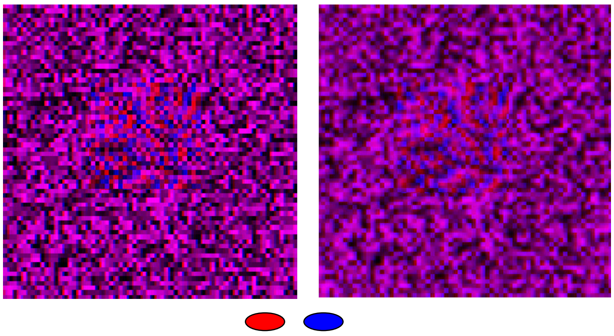

**Figure 4.** The left anaglyph was formed from two images of full resolution. The right anaglyph was formed from images of full resolution and of 1/5th of full resolution. Use the red filter for the left eye and the blue filter for the right eye.

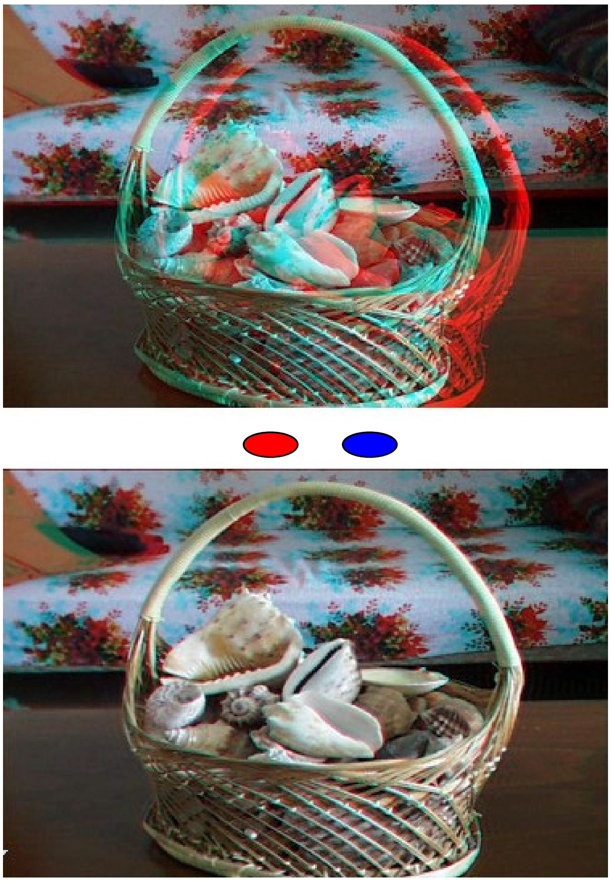

**Figure 5.** Standard colour anaglyph without image registration (top image) and anaglyph enhanced by means of image registration (bottom image). Note the reduced ghosting artefacts in the enhanced anaglyph. Use the red filter for the left eye and the blue filter for the right eye.

enhanced anaglyph exhibits substantially better visual quality when viewed without colour glasses while achieving the same or superior 3D quality when viewed with red–blue coloured glasses.

### *3.2. Defocusing anaglyph colour components*

While performing alignment on anaglyphs increases their visual quality, two problems still remain. The first is residual artefacts that may remain after the alignment. This usually occurs in anaglyphs that represent 3D scenes with objects that have large deviations of depth. The second is visual fatigue, a known problem associated with 3D visualization. This side effect arises from conflicting depth cues, namely, convergence and accommodation. Accommodation refers to the perceived distance of the object by the focusing of the eye lens. Convergence refers to the perceived distance that is estimated from the stereo pair. While viewing a 3D image, the lens focal range is determined by the distance of the viewing plane from the eye; the perceived distance, however, is different and corresponds to the 3D depth within the image. These conflicting cues cause discomfort when images are viewed for prolonged duration of time.

It is known (for example in [12]) that this conflict of cues occurs when the image is in sharp focus and the human visual system can perceive the depth from the focal range. Therefore smoothing the image may help to alleviate the problem of conflicting depth cues. Thus, in order to address both problems and to further smooth out remaining artefacts we suggest colour component blurring. Blurring of components can be carried out by several methods. The simplest and fastest is image convolution in the spatial domain with a rectangular window of constant weights:

$$\tilde{I}(x, y) = \frac{1}{(2N_x + 1)(2N_x - 1)} \times \sum_{n_x=-N_x}^{N_x} \sum_{n_y=-N_y}^{N_y} I(x - n_x, y - n_y), \tag{3}$$

where $\tilde{I}(x, y)$ is the blurred image and $I(x, y)$ is the image before convolution. The control parameter of the smoothing operation is the size of the convolution mask. In our experiments, we found that the optimal size of the window $(2N_x + 1)(2N_x - 1)$ varies between $5 \times 5$ and $11 \times 11$ pixels and should be found experimentally for every particular image.

These experiments also showed that proper selection of the colour components is crucial for obtaining good quality anaglyphs. In order to select the colour component that will be defocused we performed such a blurring operation, with varying degrees, on RGB components of several images and observed visual quality and 3D perception. In most experiments it was found that blurring of the red colour channel proved most useful in this respect. In some cases, blue component defocusing provides better results. In all experiments we have found that defocusing performed on the green channel proved destructive to the visual quality and 3D perception, as could be anticipated from the higher sensitivity of the human visual system to green hues. These tests were carried out on images of different dominant colours in order to remove the possibility of false results due to a limited database. These results are illustrated in figure 6. Figure 7 gives an example of improvement achieved by defocusing the red component of the anaglyph. One can notice that the defocusing substantially reduces ghosting artefacts and practically does not compromise preservation of 3D perception.

### *3.3. Improving anaglyphs by depth map manipulation*

Ghosting artefacts in anaglyphs are a direct result of varying depth fields in the image. Should the image be of a constant depth, anaglyph registration will be able to remove all artefacts. In cases where the dynamic range of the depths is relatively high, image alignment will have little effect in reducing these unwanted effects. In order to further improve the quality of anaglyph images with high range of depth we suggest depth map manipulation to reduce the dynamic range of the 3D information. In this method, we gain visual quality at the expense of the real metrics of the 3D image. Nevertheless, this does not harm visual perception of scenes substantially, because compression of the dynamic range is a monotonic operation that does not change the depth-wise ordering of the objects.

The method for anaglyph improvement by depth map manipulation involves three steps:

- depth map calculation from two stereo images;
- depth map dynamic range compression;

**Figure 6.** Defocusing anaglyph colour components. Anaglyphs in the left column were defocused in the red component, those in the middle in the green component, and right column anaglyphs underwent blue component defocusing.

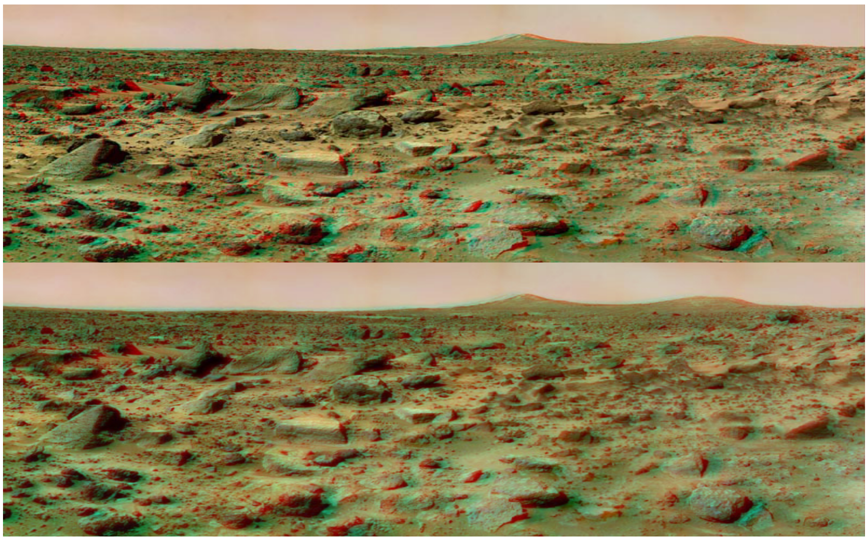

**Figure 7.** Defocusing anaglyph colour components. The original anaglyph (top image) has undergone defocusing of the red colour component (bottom image). Note the increased visual quality. (The top image was taken from NASA web site (see [2].)

- stereo pair resynthesis with the modified depth map and anaglyph creation.

A depth map is an array of data that represents the depth of the objects in the spatial coordinates of the stereo pair. According to the triangulation principle, the value of the depth map, $h(x, y)$, in each pixel $(x, y)$ in the stereo pair is proportional to the mutual displacement (horizontal parallax), $d(x, y)$, of the corresponding pixels in two images of the stereo pair $h(x, y) = Cd(x, y)$, the proportionality coefficient $C$ being determined by the optical properties of the imaging devices and the spatial coordinates of the pixels in the stereo pair. Thus, in order to calculate $h(x, y)$ it is required to find, for every pixel of one image, the coordinates of its corresponding pixel in the second image. Therefore, calculating the parallax means essentially performing pixel-by-pixel target location operations. Given the resolution of modern-day imaging devices, this must be done in an efficient way with as few erroneous results as possible.

Many methods for acquiring depth from stereo images are known (see [13, 14]). In our experiments (see [15]), we performed local adaptive image fragment correlation in a running window. In this implementation, a small neighbourhood of the pixel is taken as the target. This target is then fed to the adaptive correlator described in section 3. In order to improve efficiency, the target is searched in a small window, whose size corresponds to normal range of parallax values. In this manner, depth maps can be calculated very quickly for a given stereo pair. Since depth maps tend to be very redundant, it is sometimes sufficient to perform this operation on a subsampled version of the stereo pair, for example, every fourth pixel in the $x$ and $y$ axes. An example of a stereo pair and resulting depth map can be seen in figure 8.

The second step in this method is depth map manipulation. Our aim is to reduce the dynamic range of the depth map values. In order to perform this, we chose a method of compressing the signal dynamic range by $P$th law transformation. In this transformation, every sample of the depth map is subjected to

**Figure 8.** Stereo images (left and right images) and corresponding depth map (centre image). Although the resulting depth map does not show the exact metrics of the stereo pair, it is sufficient for the purpose of visualization.

**Figure 9.** Colour anaglyph of full depth map dynamic range (left) and that with $P$-law ($P = 0.5$) compressed depth map (right). Use the red filter for the left eye and the blue filter for the right eye.

the following modification:

$$\tilde{h}(x, y) = ah^P(x, y), \tag{4}$$

where $\tilde{h}(x, y)$ is the modified depth map sample value, $h$ is the original depth map value, $0 < P < 1$ and $a$ is a normalizing constant. In this manner, it is possible to retain the depth-ordering information within the depth map while reducing ghost effects in the non-overlapping areas in the anaglyph.

The third step, stereo pair resynthesis, requires that we generate a new stereo pair from one of the images and the modified depth map. For this purpose, the initial stereo pair image has to be re-sampled in a grid dictated by the depth map. This process requires image interpolation prior to resampling. In view of the above-mentioned insensitivity of vision to substantial blur in one of two images of stereo pair, one should anticipate that simple image interpolation methods would be sufficient. Our experiments have shown that even one of the simplest, bilinear interpolation, is capable of producing results that are satisfactory for visual observation. An example of resulting images, with and without depth map compression, can be found in figure 9. As one can see in the figure, the anaglyph that was synthesized with the compressed enhanced depth map shows substantially increased visual quality thanks to reducing the unwanted ghosting artefacts, and it retains the 3D perception without any substantial losses.

## 4. Anaglyph viewing modes

The methods of synthesis of anaglyphs described here were tested on many different types of stereoscopic images both acquired manually by means of two exposures with photographic cameras and on images found on the Internet such as those delivered by Mars Pathfinder. The synthesized enhanced anaglyphs were shown, both on computer monitors and as printouts of colour printers, for visual evaluation to numerous viewers, both individually and in groups. Excerpts from this collection of synthetically enhanced anaglyphs can be found on the web [16]. In all demonstrations, it was unanimously accepted that appropriate parameters of blur and/or depth map dynamic range compression can always be found that secure a reasonable compromise between pertaining good quality of synthetic colour anaglyph images viewed without colour spectacles and 3D perception when same images are viewed using colour spectacles. It was also found that quality of colour spectacles was not of special importance. Virtually the same results were observed with red–blue as well as with red–green anaglyphs and with anaglyphs made from transparent colour films found in paper shops. This enables us to claim that by using image registration, defocusing and depth map manipulations, one can achieve images that bear little resemblance to standard anaglyphs and that anaglyphs enhanced in this way can be viewed in 2D mode without substantially sacrificing visual quality. This becomes even more important when considering 3D video and the phenomenon of viewing fatigue. By increasing the quality and enabling 2D viewing, one can deliver 3D video content without the risk of this happening.

Another by-product of anaglyph enhancement is the ability to view the images using glasses with only a single filter. As experiments show, the human visual system is able to

**Figure 10.** Observing a colour stereo image using one full colour and full resolution image (left) and one blurred image of very low colour saturation (right).

**Table 1.** Quantitative evaluation of enhancement methods. Note that for all images, enhanced anaglyphs have better viewing success percentages than their standard anaglyphs counterpart (for the same constructing stereo pair). Note also superior subjective quality marks. Quality marks are graded from 1 to 5.

| Stereo pair | Image number | Anaglyph type | 2 filters | 1 filter | 3D mark | 2D mark |
|---|---|---|---|---|---|---|
| 1 | 3 | Standard | 100% | 17% | 4.2 | 1.8 |
| | 1 | Enhanced | 100% | 92% | 4.5 | 3.9 |
| 2 | 2 | Standard | 92% | 25% | 3.5 | 2 |
| | 8 | Enhanced | 100% | 92% | 4.4 | 3.1 |
| 3 | 9 | Standard | 83% | 0% | 3.1 | 1.4 |
| | 4 | Enhanced | 92% | 58% | 3.5 | 4.3 |
| 4 | 5 | Standard | 100% | 8% | 3.6 | 1.6 |
| | 10 | Enhanced | 100% | 75% | 4.7 | 4.6 |
| 5 | 6 | Standard | 92% | 17% | 3.6 | 1.7 |
| | 12 | Enhanced | 100% | 100% | 4.7 | 4.6 |
| 6 | 11 | Standard | 50% | 0% | 1.6 | 1.3 |
| | 7 | Enhanced | 100% | 75% | 4.6 | 4.5 |

reconstruct a colour 3D image even when one of the stereo pair images has very low colour saturation and reduced resolution. Figure 10 shows such a stereo pair, where one of the images has reduced resolution and contrast. As anticipated, parallel viewing of the images using a stereoscope enables perception of a colour 3D image, regardless of the decreased colour information.

Since the enhanced anaglyph is very similar to the original images of the stereo pair one can conjecture that the filtered image delivers only one image of the stereo pair and the unfiltered image the second image. For example, using only a red filter for the left eye results in the red channel passing through and transmitting the information of the left image, while transmitting the right image (approximated by the anaglyph) to the right eye.

In order to quantify this result, we performed a test in which anaglyphs enhanced in the methods described above were shown to subjects who were then asked to comment whether they were able to fuse the 3D image with red–blue glasses, as well as with a single colour filter. The test subjects were also asked (as supplementary data) to comment on the quality of the 3D perception and the quality of the image in 2D viewing on a scale of 1–5. For this test, 12 anaglyphs (half of which were standard anaglyph and the other half enhanced anaglyph versions of the same stereo pair) were shown to 12 viewers under identical illumination and display conditions. It was found that while nearly all of the viewers were able to fuse the anaglyphs with both glasses, in the majority of cases, fusing with a single colour filter was only possible when the anaglyphs were enhanced using the above-mentioned techniques. Subjective quality marks of the images suggest also that enhanced anaglyphs offer superior 3D perception (in either viewing mode) and increased 2D quality when viewed without glasses. These results are summarized in table 1. A document containing the test images and instructions can be found on the web [17].

## 5. Conclusions

Anaglyphs are one of the simple and economical methods for 3D visualization. Although this method has been invented more than 100 years ago, it has not obtained the prevalence it deserves. In this paper we have presented methods for anaglyph enhancement that are intended to overcome their drawbacks. Three methods were suggested to improve the visual quality of anaglyphs intended for viewing colour stereoscopic images: image alignment, blurring the image colour components and compressing the depth map dynamic range. The results we obtained show a significant improvement over standard anaglyphs. The proposed methods enable the use of anaglyphs as a high-quality, low-cost 3D visualization solution for computer screens or television monitors and may open up the market for domestic 3D visualization devices and make them acceptable as a mainstream 3D visualization technique.

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