Visual Fatigue Reduction Based on Depth Adjustment for DIBR System

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Abstract

A depth adjustment method for visual fatigue reduction for depth-image-based rendering (DIBR) system is proposed. One important aspect of the method is that no calibration parameters are needed for adjustment. By analyzing 3D image warping, the perceived depth is expressed as a function of three adjustable parameters: virtual view number, scale factor and depth value of zero parallax setting (ZPS) plane. Adjusting these three parameters according to the proposed parameter modification algorithm when performing 3D image warping can effectively change the perceived depth of stereo pairs generated in DIBR system. As the depth adjustment is performed in simple 3D image warping equations, the proposed method is facilitative for hardware implementation. Experimental results show that the proposed depth adjustment method provides an improvement in visual comfort of stereo pairs as well as generating comfortable stereoscopic images with different perceived depths that people desire.

Keywords: 3D TV, depth-image-based rendering, depth adjustment, 3D image warping, visual fatigue

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1. Introduction

Recently, three-dimensional television (3D TV) has drawn wide research interest [1]. More and more people desire a wonderful 3D experience through TV at home. In a 3D TV system, stereoscopic content plays an important role for constructing depth perception [2]. This gives an impetus drive to higher and higher quality 3D contents to be produced.

The conventional 3D contents are acquired and transmitted with the format composed of two streams of video [2][3]. However, even if the 3D contents represented by this format are filmed with high quality (e.g. high definition, precise control of the *shooting conditions*), they may also cause visual fatigue over different groups of people [4]. Excessive horizontal parallax, which often occurs when the content creators intend to provide stronger 3D perception, is one of the most important factors leading to visual fatigue [4][5][6][7]. Thus, it is important to provide viewers the ability to adjust the horizontal parallax (hence perceived depth) in real time to suit his/her own personal preferences [4].

Different from the conventional 3D video format, the newly Depth-image-based 3D video format, which consists of regular 2D color video and an accompanying depth-image sequence with the same spatial-temporal resolution [8], provides viewers the ability to adjust perceived depth by themselves. This format is required to use the so-called depth-image-based rendering (DIBR) technique to generate stereo pair in a 3D TV.

Several studies have been conducted on how to adjust perceived depth to avoid visual fatigue [6][9][10]. Most of them focuses on the conventional 3D video format and off-line processing. Recently, we provided a depth adjustment method for the depth-image-based 3D video format on condition that camera calibration parameters, such as intrinsic and extrinsic matrices, are known [11]. Subjective evaluations show that the depth adjustment method can generate comfortable stereoscopic images by changing calibration parameters. Different from these methods, this paper presents a new depth adjustment method with no calibration parameters needed for visual fatigue reduction for DIBR system. By analyzing 3D image warping, the perceived depth is expressed as a function of three adjustable parameters: virtual view number, scale factor and depth value of ZPS (zero parallax setting). As a result, the perceived depth can be easily adjusted by changing these parameters carefully for different viewers in real time, avoiding in this way visual fatigue for depth-image-based 3D video format.

The remaining portions of this paper are organized as follow. In section 2, we provide a 3D image warping equation that implies the horizontal sensor parallax for DIBR system. Section 3 is devoted to discuss on the relationship between horizontal sensor parallax and perceived depth, and the depth adjustment method based on this relationship is proposed. Section 4 provides a detailed discussion of experiments on visual fatigue when the proposed depth adjustment method applied to DIBR system. Conclusions can be found in Section 5.

2. 3D Image Warping

As mentioned above, if a 3D TV system adapts the depth-image-based 3D video format, then DIBR is required to be performed at the receiver side so as to create virtual views (destination images). The destination images are created by reference images and the corresponding depth images/maps, which usually includes three steps: pre-processing of depth image, 3D image warping and hole-filling [2], and the depth adjustment can be performed in 3D image warping.

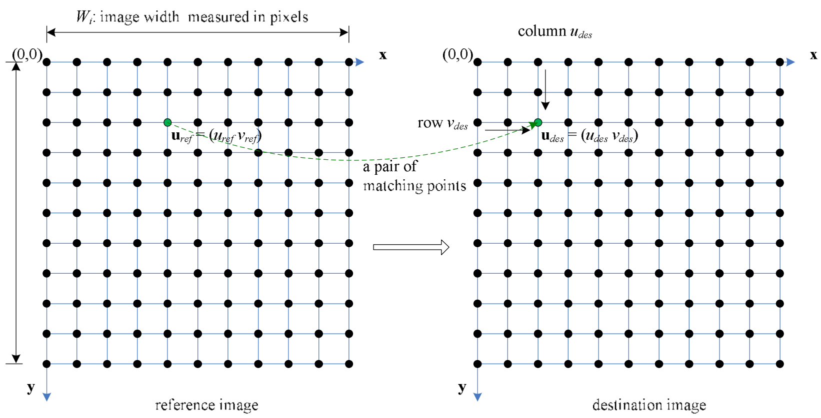


Fig. 1. Illustration of the destination image generated by 3D image warping

Theoretically, arbitrary view can be synthesized by applying 3D image warping to reference image points. For simplicity, we only consider the commonly used shift-sensor camera setup. In this case, the vertical coordinate of the projection of any 3D points on each image plane is the same [4]. Let $\mathbf{u}_{ref}(u_{ref}, v_{ref})$ and $\mathbf{u}_{des}(u_{des}, v_{des})$ be the matching points (corresponding points) in reference image and destination image respectively,as shown in **Fig. 1**. Then the 3D image warping equations, which actually defines the relationships of matching points in reference and destination images , can be deduced from the pin-hole camera model:

$$\begin{cases} u_{des} - u_{ref} = n \cdot \dfrac{r}{4096} \cdot (D_{zps} - D(u_{ref}, v_{ref})), \\ v_{des} = v_{ref} \end{cases} \tag{1}$$

where n is the number of virtual view when multi views are generated using DIBR for an auto-stereoscopic display, r represents scale factor, D_{zps} is the depth value of ZPS plane, and $D(u_{ref}, v_{ref})$ is the depth value of point (u_{ref}, v_{ref}) in depth image. The ranges of these parameter values can be found in **Table 1**.

Let $D_c = u_{des} - u_{ref}$, D_c is a variable in camera space, and usually called horizontal sensor parallax. D_c plays a crucial role in visual fatigue reduction as the perceived depth changes when D_c is changed, which will be addressed in detail in the next section.

Note that no camera calibration parameters, such as intrinsic and extrinsic matrices, are needed for generating virtual view when using (1). In addition, (1) is more facilitative for hardware implementation in contrast to the 3D image warping equations presented by [1], [2] and [12].

3. Depth Adjustment

The previous section gives a brief introduction of 3D image warping in DIBR system, and D_c is introduced for depth adjustment. This section is devoted to investigating on how to change D_c to adjust perceived depth and describing the adjustment method in detail.

3.1. Perceived Depth

The depth that the viewer perceived in viewer space is concerned with the geometry of 3D TV display system on which the generated images will be displayed, as shown in **Fig. 2**. Note that world coordinate system **xyz** is used for all objects, and the unit length is millimeter (mm). Without loss of generality, we assume that the **z**-axis of the world coordinate system passes through the screen center, and the viewer's left eye is located at $\mathbf{e}_l = [-t_x/2\ 0\ 0]^T$, and right eye, at $\mathbf{e}_r = [t_x/2\ 0\ 0]^T$ ($t_x > 0$). Under this viewing condition, the origin **o** is located at the position of cyclopean eye. Let $\mathbf{W} = [x_i, y_i, z_i]^T$ denote a "virtual" point in viewer space. If observing **W** through $\mathbf{e}_l$ and $\mathbf{e}_r$, we will get stereo pairs $\mathbf{x}_l = [x_l\ y_l\ z_l]^T$ and $\mathbf{x}_r = [x_r\ y_r\ z_r]^T$, which lie in the screen. Thus, we have

$$x_r - x_l = t_x \frac{z_i - V}{z_i} \quad (2)$$

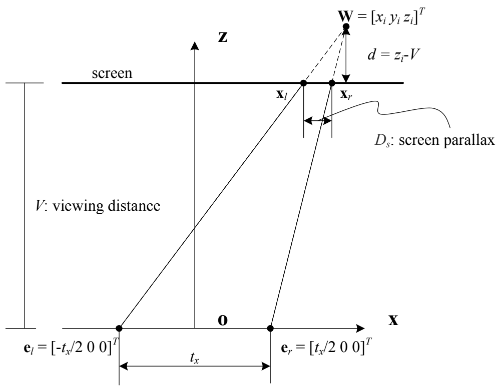


Fig. 2. Geometry of 3D TV display system

Let $D_s = x_r - x_l$, D_s is usually called horizontal screen parallax in contrast to horizontal sensor parallax. Meanwhile, let $d = z_i - V$, d is the perceived depth which directly reflects the depth perception that the horizontal screen parallax brings to viewer's eyes. Accordingly, we have

$$d = \frac{D_s V}{t_x - D_s} \quad (3)$$

It can be seen from (3) that, the depth d which the viewer perceived is determined by the horizontal screen parallax D_s. Furthermore, D_s is determined by the horizontal sensor parallax D_c:

$$D_s = \frac{D_c W_s}{W_i}, \tag{4}$$

where W_s denotes the width of screen (in millimeters) and W_i denotes the width of image (in pixels).
Substituting (1) and (4) into (3), we get:

$$d = \frac{D_c \cdot W_s \cdot V}{t_x W_i - D_c \cdot W_s} = \frac{n \cdot r \cdot \left(D_{zps} - D\left(u_{ref}, v_{ref}\right)\right) \cdot W_s \cdot V}{t_x W_i - n \cdot r \cdot \left(D_{zps} - D\left(u_{ref}, v_{ref}\right)\right) \cdot W_s}, \quad t_x W_i \neq n \cdot r \cdot \left(D_{zps} - D\left(u_{ref}, v_{ref}\right)\right) \cdot W_s \tag{5}$$

As for specific display and viewing conditions, variables in viewer space such as W_s, V and t_x cannot be adjustable. Consequently, the perceived depth d is determined by D_c, i.e. depth adjustment can be realized by controlling the amounts of the horizontal sensor parallax of stereoscopic images. Owing that horizontal sensor parallax D_c is expressed as a function of three adjustable parameters: virtual view number n, scale factor r and the depth value of ZPS D_{zps}, the depth d can be adjusted by changing these parameters during the processing of 3D image warping.

3.2. Depth Adjustment

Theoretically, we may change the value of D_c (hence perceived depth) as long as we like by changing the parameters in (5). However, several studies suggest that the maximum horizontal sensor parallax which is still comfortable for viewing is approximately 5% of the width of a image [8][12]. So we get

$$-\left(W_i \times 5\%\right) \leq D_c \leq W_i \times 5\%, \tag{6}$$

where W_i and D_c are measured in pixels, $W_i > 0$, $D_c > 0$. If D_c does not satisfy the inequation, it will cause excessive horizontal parallax and may result in visual fatigue. So, we should insure the value of D_c in accordance with (6) when performing depth adjustment.

A flowchart describing the proposed depth adjustment method is illustrated in **Fig. 3**. Three main steps are included:

a) Parameters for depth adjustment, such as n, r and D_{zps} in (5), are specified by viewers;
b) Horizontal sensor parallax D_c in camera space is evaluated to determine whether it satisfies (6). If it does not satisfy (6), then these parameters are modified by a proposed algorithm shown in **Fig. 4**; Otherwise, go to c);
c) Destination image is generated by (1) based on these parameters.

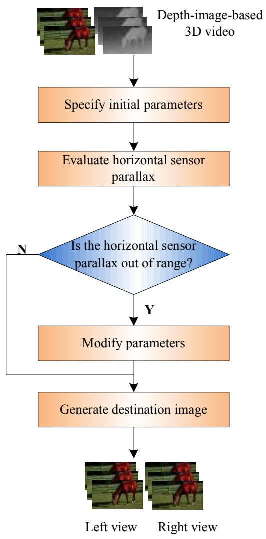


Fig. 3. Flowchart of the proposed depth adjustment method

To help the viewers in specifying a proper set of initial parameter values in step a), we recommend the default values which may cause less visual fatigue based on our and other researcher's experiments, as shown in Table 1. More details about how these values are obtained can be found below.

Table 1. Suggested parameter values that may cause less visual fatigue for the viewer

Parameter	Parameter Range	Suggested value
virtual view number n	[-4,4]	1
scale factor r	[0, W_i×80%]	W_i×30%
depth value of ZPS D_{zps}	[0, 255]	130

From Table 1, it can be seen that the number of virtual view n varies from -4 to 4, since 9 views are usually needed for auto-stereoscopic display simultaneously [13]. If the DIBR system is the type of stereoscopic display using glasses, it is better to set n = 1, becuase only one virtual view is needed to be generated, and n = 1 simplifies the warping equation. Of course, the cases that n equals other integer within [-4, 4] are also accepted provided that (6) holds.

At present, a multi-view 3D display system typically uses an 8-bit depth image due to the limitations of current depth cameras and the enough capacity to maintain sufficient image quality [14]. Hence the depth value varies from 0 to 255. As a result, the value of D_{zps} is within [0, 255]. Thus we have

$$0 \leq | D_{zps} - D(u_{ref}, v_{ref}) | \leq 255 . \tag{7}$$

Substituting (1) and (7) into (6), we get

$$0 \leq | r | \leq \frac{W_i \times 5\% \times 4096}{255 \times | n |}, \quad n \neq 0 \tag{8}$$

As can be seen from (8), when $n = 1$, we get the maximum value of scale factor r which is about W_i×80%. In order to reduce the probability of excessive horizontal parallax, the value of scale factor r is limited within [0, W_i×80%]. In our experiments, the initial value of r is set to W_i×30% (an empirical value) for all the viewers.

The choice of ZPS plane is determined by the setting of D_{zps}. As the value of D_{zps} which is comfortable for viewing should be set between a half and two thirds of maximum gray level [8], we set the default value of D_{zps} to 130 for an 8-bit depth image.

Once the parameters for depth adjustment (n, r and D_{zps}) are specified, (1) is used to evaluate the horizontal sensor parallax in step b). As for an 8-bit depth image, the value of D_c of each point may vary from D_{c_min} ($D(u_{ref}, v_{ref}) = 0$) to D_{c_max} ($D(u_{ref}, v_{ref}) = 255$) according to (1). If either of them (D_{c_min} and D_{c_max}) does not satisfy (6), parameter r or D_{zps} will be modified (n is usually not changed for it just indicates which view the user want to be rendered).

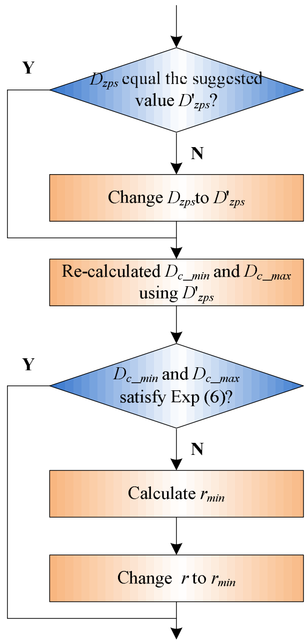


Fig. 4. Flowchart of the proposed parameter modification algorithm

The modification of r or D_{zps} is done as follows:

Parameter D_{zps} is considered first. If the previous D_{zps} does not equal the suggested value, then it is changed to the suggested value D'_{zps}, and D_{c_min} and D_{c_max} are re-calculated using the modified D'_{zps}. If either of them still do not satisfy (6), it will suggest that the present value of r changes to r_{min}, which is determined by

$$r_{min} = \min(\text{int}(r_1), \text{int}(r_2)) \tag{9}$$

where "min" is the function solving minimum value of a set, and "int" function returns the integer part of a real number. Variable r_1 and r_2 can be calculated as follows:

$$\begin{cases} r_1 = \dfrac{4096 \cdot W_i \cdot 5\%}{|n| \cdot D_{zps}}, & D_{zps} \neq 0 \\ r_2 = \dfrac{4096 \cdot W_i \cdot 5\%}{|n| \cdot \left(255 - D_{zps}\right)}. & D_{zps} \neq 255 \end{cases} \tag{10}$$

Eq. (9) and (10) can be deduced from:
Substituting (1) into (6) leads to

$$0 \leq r \leq \frac{W_i \cdot 5\% \cdot 4096}{|n| \cdot \left|D\left(u_{ref}, v_{ref}\right) - D_{zps}\right|}, \quad D\left(u_{ref}, v_{ref}\right) \neq D_{zps} \tag{11}$$

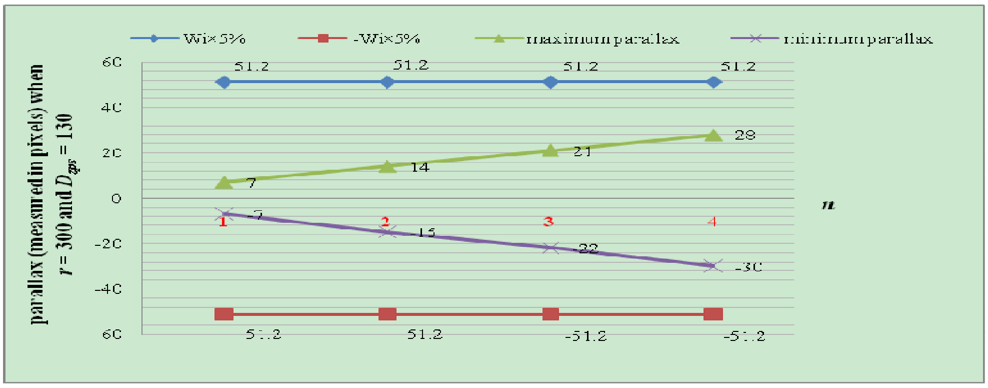
As for specific display and viewing conditions, r is only determined by $|D(u_{ref}, v_{ref}) - D_{zps}|$, and the value of $|D(u_{ref}, v_{ref}) - D_{zps}|$ varies within (0, max(D_{zps}, 255-D_{zps})]. Hence r_{min} can be calculated by (9) and (10), and r_{min} will surely satisfy (6).

Here we give a brief summary of why the visual fatigue can be reduced just by adjusting three parameters. After the proposed depth adjustment method applied, the horizontal sensor parallax D_c is limited in a modest range by adusting three parameters: virtual view number n, scale factor r and the depth value of ZPS D_{zps}. Consequently, the perceived depths of objects in viewer space will fall wihtin a comfort zone [15]. Accordingly, the accommodation-vergence conflict will be reduced. As a result, visual fatigue is reduced in the same stereoscopic viewing environment [7][15].

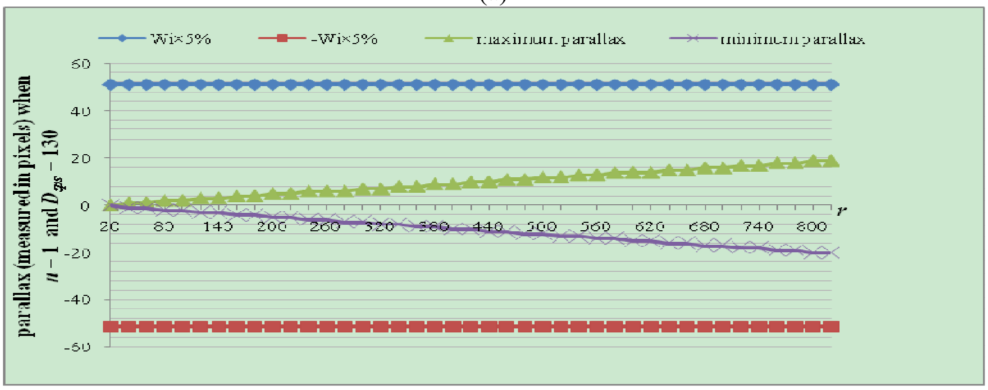
In addition, the three parameters affect horizontal sensor parallax (hence visual fatigue) in different ways. From (1) we can see a different linear relationship between each parameter and horizontal sensor parallax when the other parameters are constants. An illustration of these relationships can be found in **Fig. 5**. The trendlines of maximum and minimum horizontal sensor parallaxes reached when adjusting the three parameters respectively are plotted based on the image data of frame 0 from "Breakdance" sequences [16].

In **Fig. 5-(a)**, **(b)** and **(c)**, blue lines and red lines represent the maximum and minimum parallaxes which are comfortable for viewing, respectively. And green and violet lines represent the maximum and minimum parallaxes of the stereoscopic image reached when adjusting one of the three parameters. The horizontal axes in **Fig. 5-(a)**, **(b)**, and **(c)** show the parameters view number n, scale factor r and the depth value of ZPS D_{zps} respectively, while the vertical axes show the parallax measured in pixels. In order to show the changes of maximum and minimum parallaxes caused by parameter adjustment respectively, parameter n is set to be changed gradually while the other two parameters r and D_{zps} are kept unchanged (r = 300, D_{zps} = 130) in **Fig. 5-(a)**; in **Fig. 5-(b)**, scale factor r varies while n = 1 and D_{zps} = 130; in **Fig. 5-(c)**, parameter D_{zps} is increased gradually while r and n are constants (r = 300, n = 1).

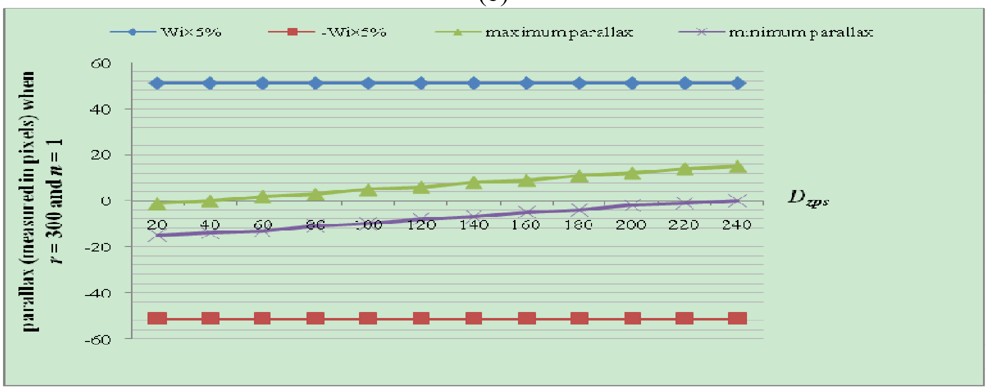
From **Fig. 5-(a)**, one can notice that the absolute values of maximum and minimum parallax increase with the increase of n. And similar relationship between the absolute values of maximum and minimum parallax and parameter r can be seen in **Fig. 5-(b)**. In **Fig. 5-(c)**, the absolute values of maximum and minimum parallax also vary with parameter D_{zps}: the maximum parallax increases while the absolute value of minimum parallax decreases with the increasing of D_{zps}. In general, there exists a different linear relationship between each parameter and horizontal sensor parallax.



(a)



(b)



(c)

Fig. 5. Parameters n, r and D_{zps} affect horizontal sensor parallax in different ways. **(a)**: linear relationship between n and horizontal sensor parallax; **(b)**: linear relationship between r and horizontal sensor parallax; **(c)**: linear relationship between D_{zps} and horizontal sensor parallax.

4. Experiment

In this section, several depth-image-based 3D sequences [16][17] are used to test the proposed depth adjustment method for visual fatigue reduction. A 17-inch time-sharing stereoscopic display was used for the subjective assessment and ten non-expert viewers, aged 20 to 35, participated in the experiment. Twenty stereoscopic images which are generated with different values of parameters n, r, D_{zps} (as shown in **Table 2**) are used in this experiment, consisting of outdoor scenes, indoor scenes, figures and geographic landscapes. The viewers watched randomly-ordered stereoscopic images at a distance of 1m from the display. The duration of each image was 10 seconds.

Table 2. Parameter settings for generating stereoscopic images with different perceived depths

image number	virtual images number n	scale factor r	the depth value of zero parallax plane D_{zps}	resolution of one image in a stereo pair
1	4	250	150	576x352
2	1	250	150	576x352
3	2	140	0	960x540
4	5	140	0	960x540
5	2	220	140	960x540
6	5	140	140	960x540
7	3	140	160	960x540
8	4	220	160	960x540
9	2	220	0	960x540
10	3	220	110	960x540
11	3	220	110	576x352
12	1	220	110	576x352
13	4	220	110	576x352
14	3	150	120	576x352
15	2	150	160	576x352
16	1	80	150	960x540
17	4	80	170	960x540
18	3	300	170	1024x768
19	4	300	170	1024x768
20	2	300	170	1024x768

In our experiment, a five-level scale including ratings of no fatigue, slight fatigue, moderate fatigue, fatigue, and severe fatigue, was used for subjective assessment [4]. Note that "visual fatigue" in this paper means "visual discomfort", hence the five-level scale mentioned above is similar to the five point category rating scale [18]. When viewing a presentation, the viewer was asked to categorize the degree of their fatigue into five categories mentioned above. **Fig. 7** shows the subjective assessment results for stereoscopic images which were generated with different parameter settings listed in **Table 2**. The horizontal axis shows the image number and the vertical axis shows the average visual fatigue score of each image marked by ten viewers. Note excessive horizontal parallaxes were introduced to some of these images when they were generated. Maximum and minimum parallaxes (i.e. D_{c_min} and D_{c_max}) of each stereoscopic image can be found in **Fig. 8**.

From **Fig. 7**, it can be seen that the average visual fatigue scores of image 4, 11 and 13 are lower than grade 2.5, and from **Fig. 8**, we find that the minimum parallaxes of image 4 and 13 exceed $-W_i \times 5\%$, which indicates excessive horizontal parallax is liable to cause visual fatigue. The reason why the score of image 11 is lower than grade 2.5 (though the parallaxes are not exceed $|W_i \times 5\%|$) lies in that the depth image is so inaccurate that obvious geometric distortions appear in the virtual image [2][8]. It is these distortions that bring the uncomfortable feeling to the viewers [7][15]. Another example can be found in **Fig. 6**.

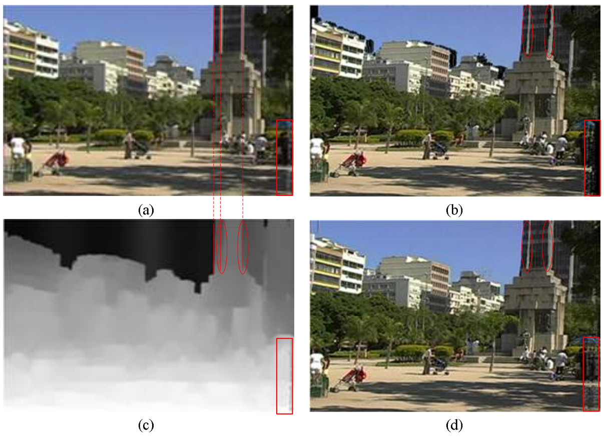


Fig. 6. Inaccurate depth image may introduce geometric distortions to the destination image. **(a)** and **(c)**: reference image and it's depth image; pixels with inaccurate depth value are noted by red lines and circles; **(b)** and **(d)**: destination image with big holes and the destination image after hole-filling. Geometric distortions can be found in the rendered image.

A special case in **Fig. 8** is that, the maximum parallax of image 1 exceeds W_i×5%, yet the score is quit high (grade 3.2). This is mainly because most parallaxes of points in depth image of image 1 are positive, and positive parallax (objects behind the screen) is in general easier to look at and minimizes eye strain [15].

In order to reduce visual fatigue, the proposed depth adjustment method was applied to the test images. **Fig. 9-(a)** shows the assessment results of image 1, 4 and 13 before and after adjustment by the same ten viewers, after the proposed depth adjustment method was conducted. The new maximum and minimum parallaxes are shown in **Fig. 9-(b)**. **Fig. 10** shows the stereoscopic images of 1, 4, and 13 before and after depth adjustment. We notice that in **Fig. 9-(a)** the scores of image 1 and image 4 are considerably improved (from 3.2 to 3.5, 2.3 to 2.8, respectively), which shows the proposed method is efficient at reducing visual fatigue in most cases when excessive horizontal parallax occurs.

Note that the improvement in the score of image 13 is slight (from 2.1 to 2.2). This is mainly due to the obvious geometric distortions contained in the images shown in **Fig. 10** (circled by red rings). As mentioned above, inaccurate depth image (especial smoothed depth image or the depth image obtained by 2D to 3D method from a single image) may introduce geometric distortions to the rendered image, and these distortions will result in severe visual fatigue if they are remarkable. In **Fig. 10**, the depth image **(i)** is so inaccurate in contrast to **(g)** and **(h)** that it leads to obvious distortions in the rendered image **(l)**. For this case, the improvement of visual comfort based on depth adjustment is limited.

From the experiment we can draw the conclusion that, the visual fatigue can be efficiently reduced just by adjusting three parameters n, r, D_{zps} which are obtained from the expression of D_c, provided that the geometric distortions contained in the images are imperceptible.

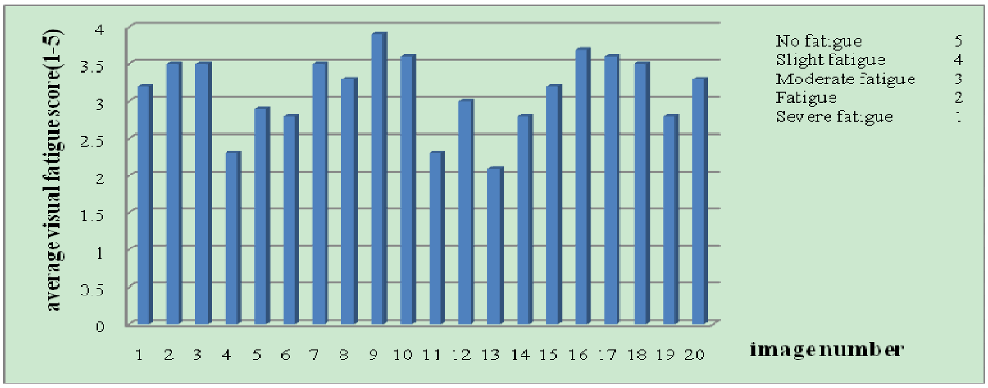


Fig. 7. Subjective assessment results for stereoscopic images

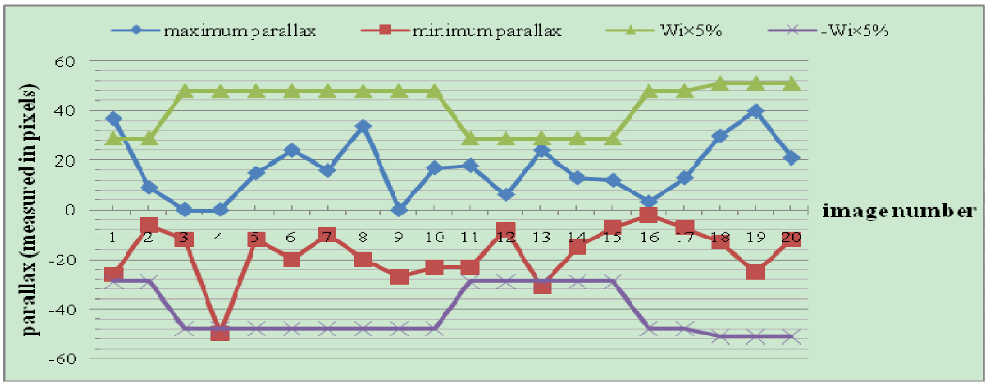
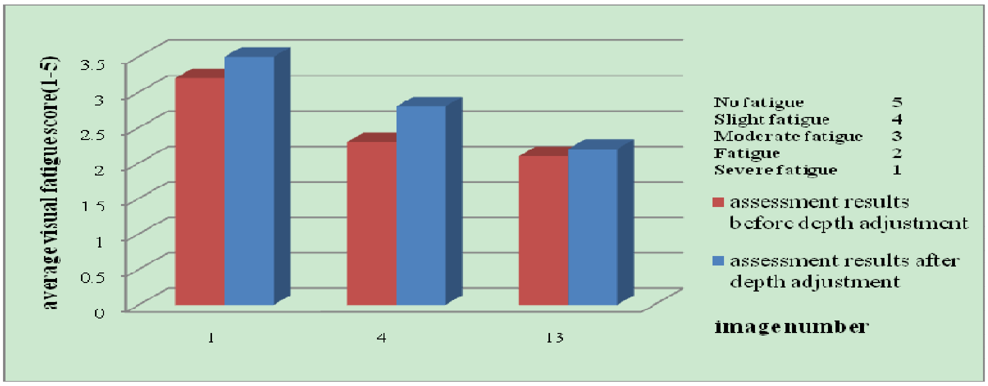
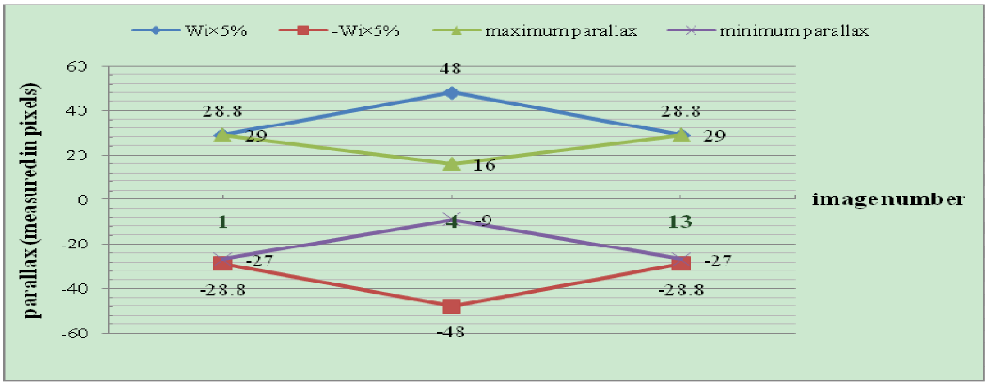


Fig. 8. Maximum and minimum parallaxes of the stereoscopic images for test



(a)



(b)

Fig. 9. Subjective assessment results of image 1, 4 and 13 before and after adjustment shown in **(a)** and their corresponding maximum and minimum parallaxes shown in **(b)**.

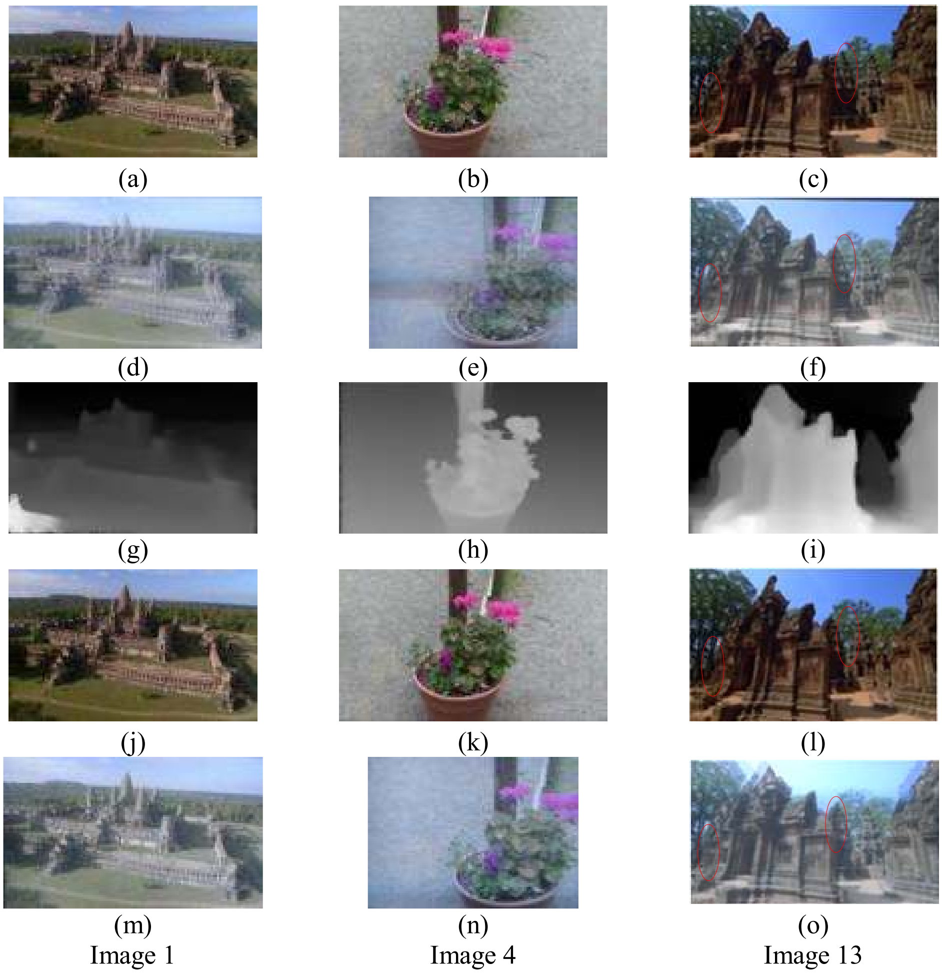


Fig. 10. Stereoscopic images of 1, 4, and 13 before and after depth adjustment. **(a)**~**(c)**: rendered right images of 1, 4 and 13, respectively; **(d)**~**(f)**: overlapped images of 1, 4 and 13 with excessive horizontal parallax before depth adjustment; **(g)**~**(i)**: depth images of 1, 4 and 13, respectively; **(j)**~**(l)**: re-rendered

right images of 1, 4 and 13 after depth adjustment; **(m)**~**(o)**: overlapped images of 1, 4 and 13 without excessive horizontal parallax after depth adjustment.

5. Conclusions

A well-known problem in 3D TV is visual fatigue. In order to reduce the visual fatigue for DIBR system in 3D TV, a new perceived depth adjustment method in which the main principle is reducing the excessive horizontal parallax to avoid visual fatigue when performing 3D image warping, is proposed. In our method, perceived depth is expressed into a function of three adjustable parameters: virtual view number, scale factor and depth value of ZPS. Adjusting these three parameters can effectively change the perceived depth of generated stereo pairs. In addition, parameters scale factor and depth value of ZPS are enough for adjustment when time-sharing stereoscopic display is used. Another advantage of the method is that no camera calibration parameters are needed either for virtual view generation or for depth adjustment, which makes it suitable for current depth-image-based 3D video format used in 3D TV [19]. Moreover, the proposed method is more facilitative for hardware implementation in contrast to previous method since the depth adjustment can be performed in simple 3D image warping equations.

In this paper, experiments are also performed to verify the method. The experimental results show that the proposed depth adjustment method can generate comfortable stereoscopic images with different perceived depths that people desire. However, performance of the method may be affected by the artifacts in depth image or virtual view. In future work, we will consider this factor together with depth adjustment for visual fatigue reduction.

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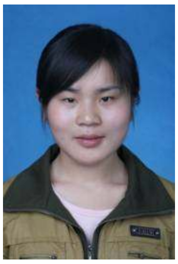

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