PASSBAND MEASUREMENT METHODOLOGY FOR MULTIVIEW 3D DISPLAYS

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ABSTRACT

This work presents a measurement methodology that estimates the perceived visual quality of a multiview 3D display. It uses the notion of a display passband, which considers the display as a signal processing channel and describes which spatioangular frequencies can be visualised with an acceptable quality. The methodology starts by measuring the optical parameters of the display. Then, a set of test signals are visualised on the display and photographed from a range of observation directions. Each test image is a sinusoidal grating with three frequency components – horizontal, vertical and angular one. The spectrum of each photograph is calculated and the distortions introduced by the display are analysed in the frequency domain. A model of the contrast sensitivity function (CSF) is applied in order to estimate the visually predominant frequency. If the dominant frequency in the input remains dominant in the output, the input frequency is deemed as belonging to the display passband. In the last step, the shape and size of the derived passband is used to calculate the equivalent spatioangular resolution of the display.

Index Terms **—** 3D displays, multiview displays, visual quality, passband

1. INTRODUCTION

The so-called "3D" displays attempt to generate a realistic representation of a three-dimensional scene [1]. They do so by recreating a range of image features (known as *depth cues*) which are essential for perceiving a scene in three dimensions. A 3D display creates *binocular depth cues* by sending a separate image towards each eye of the observer. In can also provide *parallax depth cues* (i.e. "look-around effect") by showing different images as the observer moves in front of the display.

This paper aims to find a method that can be used to quantify the ability of a 3D display to faithfully recreate a 3D scene. In the case of 2D display, knowing its horizontal and vertical resolution gives intuitive idea about the level of scene detail that can be reproduced. However, most multiview displays have non-rectangular pixel grid and suffer artefacts, which arise from spatial and inter-perspective aliasing [2]. Previous research on display quality attempts to derive the quality of a 3D display by measuring of its optical parameters [3] or trough subjective tests [4]. Aiming to have an objective metric, that can approximate the subjective quality of a 3D display, we introduced the concept of a *display passband* [5]. Our approach is to consider the display as a signal processing channel, and measure the ability of this channel to carry signals with negligible distortions. This paper extends the previous work on display passband by introducing angular frequency component and by measuring the passband from a number of observation positions. To examplefy the method, the paper includes measurement results for two different models of multiview displays.

The next section describes the basic operation principles of multivew displays. Section 3 describes the concept of display passband, and the framework used for passband measurements. Section 4 gives details of the display models used in the tests, presents details of measurement procedure and shows the results of the measurements. Section 5 contains the conclusions.

2. MULTIVIEW DISPLAYS

Multiview displays recreate binocular and parallax depth cues by casting different images towards different directions. Each of these images is known as a *view*. Each view is visible from a certain area in front of the display, known as a *viewing diamond* [3]. In most multiview displays the views are distributed in horizontal direction only, and the centers of the viewing diamonds appear at equal distances along the *optimal observation line*. The distance between the optimal observation line and the display is called *optimal viewing distance* (OVD) [6]. In this paper, the range of observation positions, where different views are seen is called *view-span*. An observer staying at the optimal observation line can perceive binocular depth without the need of special glasses. For this reason, multiview displays are also classified as *autostereoscopic* ones. In the example in Figure 1a, a multiview display has 8 views (marked "v1" to "v8"), and the eyes of the observer are in views "v6" and "v7".

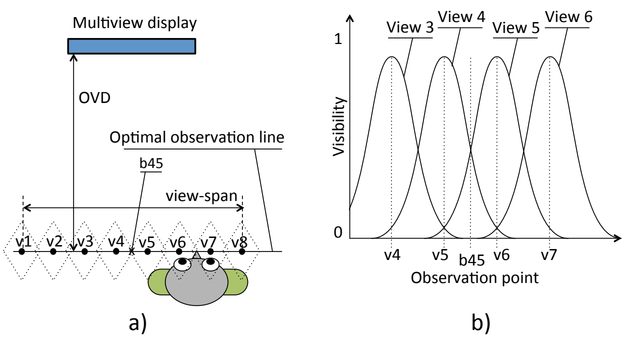

Figure 1, Visibility of different views in a multiview display: a) position of the viewing diamonds, b) angular visibility functions of the views

In order to provide smooth head parallax a multiview display has gradual transition between the visibilities of the neighboring views. The normalized brightness of a view as a function of the observation angle is known as *angular visibility function*. The visibility functions of neighboring views are overlapped as shown in Figure 1b. Each view has its maximum visibility in the center of its viewing diamond. Between two neighboring viewing diamonds exists a point, where two views are equally visible, as marked with "b45" in Figure 1.

A typical multiview display uses a TFT matrix to generate the images in each view. The TFT elements (also known as subpixels) are distributed between the views. At each viewing diamond only a subset of the subpixels are visible. There are two

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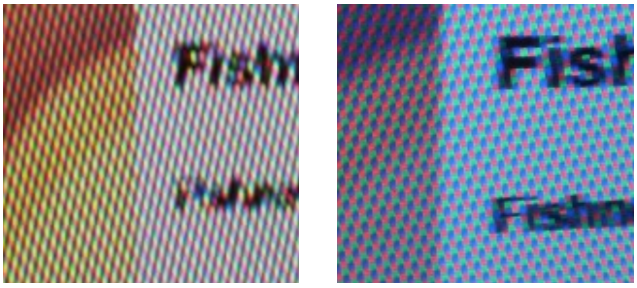
methods to create an angular visibility function for a view – using a *parallax barrier*, which blocks the light from some sub-pixels is being blocked, or using a *lenticular sheet*, which redirects light by optical means [1]. As a result the f sub-pixels that belong to one view do not appear on a rectangular grid. A parallax barrier produces visible gaps between the elements, as shown in Figure 2a. A lenticular sheet causes the visible elements to appear as having a non-rectangular shape as seen in Figure 2b. In both cases, the visible grid interferes with the underlying signal, and the level of distortions depends on the orientation and the spatial frequency of the underlying image [4].



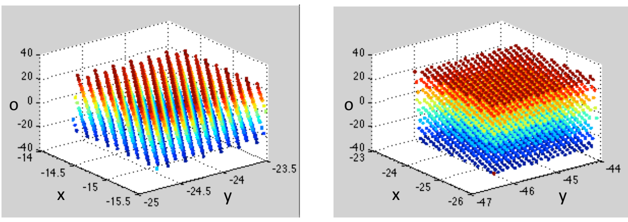
a) b)

Figure 2, Texture distortions introduced by a different multiview display types: a) visible gaps between pixels introduced by parallax barrier, b) non-rectangular pixel grid introduced by lenticular sheet.

3. DISPLAY PASSBAND

3.1 Spatioangular sampling function

The position, direction and wavelength of each ray in 3D space can be described by a continuous function, known as *light field*. It can be fully described by a 7-D *plenoptic* function [8]. Autostereoscopic 3D displays can generate limited light field (for example the radiance along any ray is constant) and a 4-D function is sufficient. The output of multiview displays, which generate horizontal parallax only, can be described by a 3-D function. In a previous work we proposed the function $L(x, y, o)$, where each ray of is described by crossing a point (x, y) on a plane and a point (o) on a line [9]. For simplicity, one can disregard the projective distortions caused by observing a rectangular display frame at different angles, and assume an orthogonal space where the triplet $I = L(x, y, o)$ describes the intensity I of the display surface point with coordinates x, y as seen from position o on the optimal observation line.



a) b)

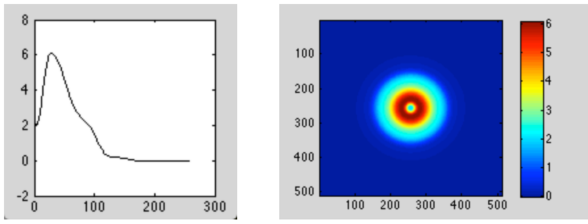
Figure 3, Spatioangular sampling functions of multiview displays (only part of the point cloud is shown): a) 24-view display, b) 8-view display. The axes are labeled in centimeters.

The set of rays generated by a multiview display can be described as a set of points in the same x, y, o space. Assuming continuous light field function $L(x, y, o)$, that set of points describe where the display can "sample" the light field. In this paper, such set of points is called the *spatioangular sampling function* (SSF) of the display. For example, Figure 3 shows the SSFs of two multiview displays. Figure 3a gives the SSF of a display with 24 views and Figure 3b gives the SSF of an 8-view display. For clarity, only part of the SSF, corresponding to to a small area near the lower left part of the screen, is shown.

3.2 Visibility of display distortions

Multiview displays attempt to recreate continuous light field of a 3D scene using a small set of discrete TFT elements. Technology limitations and design trade-offs lead to a number of non-linear distortions – aliasing and imaging, caused by the position of the visible sub-pixels, and crosstalk caused by the overlapping of neighboring viewing diamonds [6]. The visibility of these effects depends on three components: 1) the spatioangular sampling function of the display; 2) the frequency components of the original signal; 3) perceptual properties of the human visual system (HVS), such as the contrast sensitivity function and pattern masking [7]. In presence of strong dominant spatial frequency, image distortions might become less visible [5].

This paper proposes the following algorithm for estimating if a dominant frequency is present. First, the spectrum of the image is calculated. The second step is to apply a CSF weighting mask, which models the relative contrast sensitivity of the eye. The weighting mask follows the shape of the spatial CSF at photopic level as described in [7], p.136. The CSF is measured in cycles-per-degree (CPD), but knowing the size of the image and the observation distance, one can calculate the CSF as a function of the signal period in pixels. The relative weights of the function are shown in Figure 4a. Using the CSF weights one can prepare a 2D CSF mask where the weights in each position are calculated according to the distance between the weight and the center of the mask. For example, the CSF weighting mask for an image of 512x512px and observation distance of 120cm is shown in Figure 4b.



a) b)

Figure 4, CSF weighting window: a) relative CSF weights modeling the sensitivity of the HVS at photopic level, b) 2-D CSF weighting mask for spectrum size of 512x512px and observation distance of 120cm.

The third step of the algorithm is to find the two largest peaks in the spectrum (the mirrored images of each peak are excluded from the search). The last step compares the amplitudes of the two largest peaks. If the amplitude of the largest peak is more than 5 times higher than the second largest peak, the image is deemed to have a strong dominant frequency. Assuming that the intended signal is the one with the dominant frequency, its presence may mask the visibility of signal distortions. In a previous work we demonstrated that at the signal to distortion ratio of 5:1 a good estimate of the threshold at which distortions become hardly noticeable [5].

3.3 Passband estimation framework

The passband of a 3D display determines the set of frequency components for which the intended signal is predominantly visible [5]. One can estimate the passband of a display by visualizing a set of test signals and assessing which test signals can be reliably reproduced. Each test signal should be shown shown on

the display and measured (e.g. by taking a snapshot) from a range of observation positions. If the intended signal remains predominant as seen from all observation positions, the test signal is deemed to "pass" trough the display channel, and its frequency components are deemed to belong to the display passband.

The block diagram of the proposed passband estimation framework is shown in Figure 5a. Each test signal contains three frequency components: horizontal frequency f_x, vertical frequency f_y and angular frequency f_o. The horizontal and vertical components define cycles per centimeter of the display surface, and the angular component defines cycles per centimeter along the observation line. The test signal is a 3-D volume in which the intensity of each point is defined as:

$$I_{x,y,o} = \frac{1}{2}\sin\left(\pi \cdot \mathrm{x} \cdot \mathrm{f_x} + \pi \cdot \mathrm{y} \cdot \mathrm{f_y} + \pi \cdot \mathrm{o} \cdot \mathrm{f_o}\right) + \frac{1}{2} \qquad (1)$$

An observation position o is selected. The value of o is use to render a slice of the 3-D volume, and the slice is used as a reference signal. A test image is prepared for the display, by sampling the 3-D test signal according to the display's spatioangular sampling function. The camera is placed at position o and a photograph of the display is taken. Both the reference signal and the photograph are cropped and resized according to the camera magnification factor. The cropped reference signal produces a reference image, which describes how the test signal should appear at observation position o. The crop of the photograph produces distorted image, which describes how the test signal actually appears from the desired observation position.

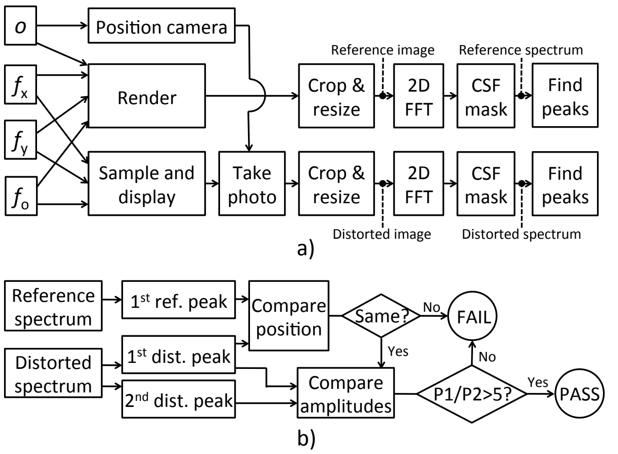


Figure 5, Passband estimation framework: a) processing steps, b) decision diagram of the pass/fail analysis

The frequency spectra of the reference and distorted images are calculated. The CSF weighting mask is applied to both spectra. The largest peak of the reference spectrum and the two largest peaks in the distorted spectrum are found (mirrored spectral peaks are excluded). The pass/fail analysis is performed according to the decision diagram shown in in Figure 5b. Two criteria are evaluated: 1) the positions of the largest peaks in the reference and in the distorted spectra are the same; 2) the amplitude on the largest peak in the distorted spectra is 5 times larger than the amplitude of the second largest peak. If both criteria are evaluated, the test signal is deemed to "pass". If the test signal "passes" for all observation positions, the f_x, f_y, f_o frequency triplet is deemed to belong to the display passband. The display is tested for a range of frequency triplets. Each triplet defines a point in a 3-D space. The union of all points that belong to the display passband is used to derive the 3D passband of the display.

4. MEASUREMENTS

4.1 Measurement procedure

We used two displays for the experiments. One is X3D-24 produced by Opticality (hereafter known as "X3D"), and the other is Alioscopy 3D HD 42" produced by Alioscopy ("Alioscopy"). The X3D display uses parallax barrier, while the Opticaltiy display uses lenticular sheet. First, the optical parameters and the interleaving map of each display were derived as described in [6]. The X3D display was found to have 24 views, optimal visibility distance of 120cm and distance between the centers of the viewing diamonds of 2cm. The Alioscopy was found to have optimal observation distance of 450cm and distance between the centers of the viewing diamonds of 6cm. Parts of the spatioangular sampling functions of these displays are shown in Figure 3.

Preliminary measurements were used to get a rough estimate of the passband boundaries of each display. The passband scanning of X3D was done for $f_x \in [-3,3]$ and $f_y \in [-3,3]$ cycles per cm, both with a step of 0.1 cycles per cm, and $f_o \in [-1; 1]$ cycles per cm with a step of 0.01 cycles per cm. The passband scanning of Alioscopy was done for $f_x \in [-6,6]$ and $f_y \in [-6,6]$ cycles per cm, both with a step of 0.2 cycles per cm, and $f_o \in [-0.14; 0.14]$ cycles per cm with a step of 0.02 cycles per cm. A computer-controlled camera positioning system was used to move the camera between the measurement positions, as shown in Figure 6. Each display was measured at its optimal viewing distance (120cm for X3D and 450cm for Alioscopy). Each display was measured at 5 points along the observation line. The outer points coincide with the centers of two neighboring viewing diamonds (views 12 and 13 for X3D, views 4 and 5 for Alioscopy). The middle measurement point was selected to appear in the center between two viewing diamonds, where the visibility of the adjacent views is equal. In each case, the CSF mask was calculated according to the measurement distance. All measurements were done in a dark room.

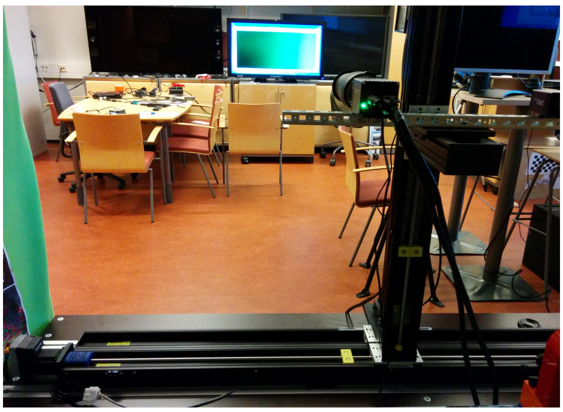


Figure 6, Passband measurements of Alioscopy 3D HD 42" using automated camera positioning

4.2 Results

The results from the measurements can be seen in Figure 7. The "3D" passbands of X3D and Alioscopy are shown in Figure 7a and Figure 7c respectively. The "3D" passband indicate the visual quality of the display when showing 3D scenes with binocular and parallax depth cues. The "2D" passbands of the displays, measured for $f_o = 0$ are shown in Figure 7b and Figure 7d. The "2D" passband is related the quality of images with no parallax, i.e. 2D images with no apparent depth. In both cases, larger and more uniform passbands correspond to better display quality.

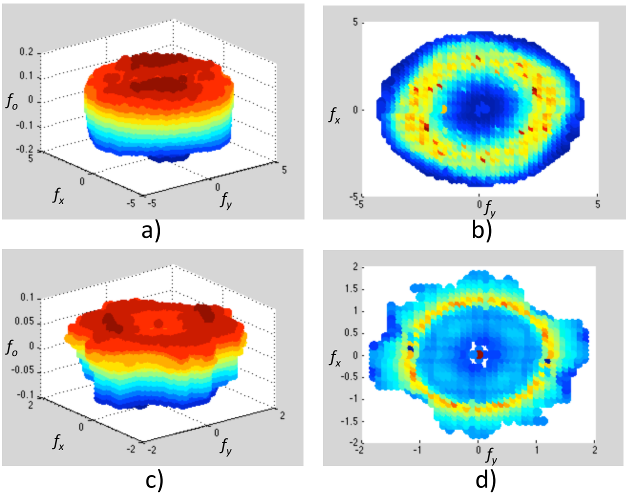


Figure 7, Measured passbands of multiview displays: a) 3D passband of X3D, b) 2D passband of X3D (for $f_o = 0$), c) 3D passband of Alioscopy, d) 2D passband of Alioscopy (for $f_o = 0$). The axes are labeled in cycles per centimeter.

4.3 Equivalent spatioangular resolution

In order to derive a simplified and more "intuitive" metric, one can approximate the 3D passband with a cuboid. However, and approximation that encompasses all passband points does not take into account the shape and uniformity of the passband. This paper suggests the following algorithm for passband approximation: 1) create a cuboid with a given x, y, o dimensions, which is centered at the point of origin $f_x = f_y = F_o = 0$; 2) inside the cuboid, count the number of points where a passband test passed, and subtract the number of points where a passband test failed (e.g. using the scanning step, sum the "pass" points, and subtract the "fail" points); 3) calculate the score for all cuboid sizes (up to the cuboid size that contains all passband points) and find the maximum. The cuboid with the biggest score is the best rectangular approximation of the continuous areas in the passband. The dimensions of that cuboid are indicative for the range of equivalent horizontal, vertical and angular frequencies that the display can produce. Assuming that at least two samples are needed per cycle, one can convert the equivalent frequency into equivalent sampling density. Finally, knowing the display size one can convert the sampling density to equivalent resolution. In the case of angular frequencies, this would give the equivalent number of cameras for the view-span. The results of fitting a cuboid and the equivalent spatioangular resolution for the two displays used in our experiments are given in Table 1. For example, the light field generated by X3D is equivalent to the field captured by 10 cameras (5cm apart), each one with resolution of 358 by 224px. The light field generated by Alioscopy is equivalent to the one captured by 7 cameras (10cm apart) each one with resolution of 279 by 156px.

5. CONCLUSIONS

This paper presented a measurement methodology, which can be used to derive the 3D passband of a multiview display. The 3D passband determines the set of spatioangular frequencies, which are reproduced by the display with negligible level of distortions. The passband can be used as an indicator of the perceived quality – the larger and more uniform 3D passband corresponds to a better display. Fitting a cuboid to the passband allows one to derive the equivalent spatioangular resolution of the display in terms of number of cameras and resolution of each camera. As a example of the methodology, the paper presented measurement results for two models of multiview displays – one using lenticular sheet and another using parallax barrier.

Table 1 – Equivalent passband frequency, sampling density and resolution of the displays used in the measurement experiments.

	X3D-24			Alioscopy 3D HD 42"		
	Horizontal	Vertical	Angular	Horizontal	Vertical	Angular
Absolute distance (cm)	49.6	31	48	93	52.31	64
Maximum passband frequency (cycles per cm)	4.20	4.20	0.14	2.00	2.00	0.07
Equivalent passband frequency (cycles per cm)	3.60	3.60	0.10	1.50	1.50	0.05
Equivalent sampling density (samples per cm)	7.20	7.20	0.20	3.00	3.00	0.10
Equivalent resolution	358px	224px	10 (9.6) cameras	279px	156px	7 (6.4) cameras

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