Quality of Experience Measurement for Light Field 3D Displays on Multilayer LCDs

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Abstract: Multi-layer light field displays (MLLFDs) are a promising computational display type which can not only display hologram-like 3D content but will also be well compatible with normal 2D applications. However, quality of experience (QoE) measurement for MLLFDs is always an important yet challenging issue. Despite existing research works on MLLFDs, most of them only provide QoE results with qualitative evaluation, e.g., software simulation of a few 3D images/videos, rather than rigorous quantitative evaluation. This work targets at building a unified software and hardware measurement platform for different MLLFD methods, and comprehensively measuring both objective and subjective performance based on virtual object models (VOMs). To the best of our knowledge, it is the first time that such performance has been measured for MLLFDs. In addition to use the existing disclosed virtual object sequences, this paper further proposes three customized virtual models, which are the USAF-E model, the view angle model and the concave/convex object model for accurate measurement of spatial resolution, viewing angle and depth resolution. A toolbox for MLLFD measurement with proposed models is also released in this paper. The experimental results demonstrate that our proposed measurement method, models and toolbox can well measure MLLFDs in different configurations.

Keywords: Light field display, QoE measurement, virtual object model, depth of field, viewing angle, depth resolution, toolbox.

1. INTRODUCTION

Three-dimensional (3D) displays have received considerable interest in recent decades. 3D display technologies using glasses, parallax barriers or lenticular sheets based on binocular parallax have been applied in various commercial products. However, these technologies suffer from the discrepancy between accommodation and convergence, which may cause visual confusion and fatigue. To solve this problem, volumetric displays \(^1\)-\(^2\) and holographic displays \(^3\) have been developed. A huge amount of data would be involved to provide a true 3D image with both correct focus and parallax cues, and this prevents these technologies from being widely accepted for daily use. In addition to these pure optical or physics-based techniques, a computational 3D display technology known as compressive light field display has been investigated \(^5\)-\(^7\). In these multilayer light field displays, light emitted from a back display layer passes through one or more transparent display layers. With suitably computed images they can provide a hologram-like image without the use of complicated holographic techniques. Since parallax barrier and lenticular sheets are not used in this display method, it would not decrease the display resolution and is compatible with 2D displays. However, although some measurements on these displays such as color, luminance, and peak signal to noise ratio (PSNR) use the same methods as 2D displays, others such as spatial resolution, depth resolution, and field of view still need tailored methods to acquire light field 3D measurements.

Different from some other works of the 3D content-based image quality measurement \(^7\), \(^8\), this paper only focuses on light field 3D display measurement and takes 3-layer light field 3D display as the example. In order to help validate the proposed measurement techniques we built a uniform multi-layer light field display (MLLFD) measurement platform with two different configurations; polarization-based MLLFDs \(^9\) and attenuation-based MLLFDs \(^5\). In the polarization-based configuration there are only two polarizers, one in front of the front LC layer, the other one behind the rear LC layer, as in Fig. 1(a), while the attenuation-based configuration has polarizers between every pair of liquid crystal displays (LCDs), which is shown in Fig. 1(b).

![Fig. 1. (a) Polarization-based (left) and (b) attenuation-based (right) multi-layer LCDs.](image-url)
In this paper Section 2 will introduce the related work, Section 3 will propose a uniform framework of layered light field display and two classical configurations under this framework, while Section 4 will discuss our elaborated test models. The following Section 5 will clarify the testing procedure and results for the two classical configurations using the proposed test toolbox and virtual object models (VOMs) and Section 6 summarizes existing contributions and discusses the future work.

2. Related work
The focus of most previous 3D display characterization work is on stereoscopic and multiview displays. In [10], an approach is proposed to model multiview displays in the frequency domain with different density and orientation in test patterns. The sub-pixel structure is relevant in this kind of measurement but in light field displays it is not. Multiview displays measurement is also discussed in [11], whose method uses proprietary measurement equipment with Fourier optics. However, this equipment cannot measure system performance of light field display because the view angle of MLLFD is much bigger than normal multiview displays. In [12], another view-based measurement instrument is described, but it does not apply for typical light field displays which model the light field beams for an optimized region directly. Projector-based light field displays are measured in [13] for spatial resolution, angular resolution and depth resolution, but these methods cannot be used in multilayer light field display directly.

For MLLFDs, polarization-based light field displays and attenuation-based light field displays are measured by PSNR based on software simulated results [4-6, 9], but there is insufficient physical measurement on these displays. In [14] it proves the limit of depth of field for MLLFD, but without an extremely high-speed screen, the theoretical limit cannot be achieved with on-shelf hardware resources for a practical prototype. The optimized view angle with eye tracking is introduced in [15], and the designed view angle for static content with parallax is reported in [16], but the real perceived view angle for a static display has not been measured. More subjective results of MLLFDs are shown in [17], however, there is no quantified measurement for these subjective results on different kinds of MLLFDs. Therefore, this paper proposes three test models and one toolbox with corresponding test methods that are particularly applicable to measure light field displays on multilayer LCDs.

Following the 2D Display Measurement standard [18] and previous 3D Display Measurement metrics [10-13] proposed for 3D display, this paper measures software simulated PSNR, Luminance, color gamut, spatial fidelity and depth of field, viewing angle, depth resolution, subjective metrics [19] (Naturalness, Quality, Depth, Brightness, and Eyestrain), and moiré fringing in a quantifiable way.

3. Tensor Display Framework
Now, there are two mainstream optical configurations for MLLFD on LCDs, including polarization-based [23] and attenuation-based [24, 25] light field displays. Although they are using different techniques for light field modeling, they both share a uniform framework to reconstruct the light field for display. In the following subsection, physical modeling, mathematic modeling and light field reconstruction algorithm will be introduced successively. Note that, as the prototypes shown in reference [5] and [9], modeling is implemented based on the ideal condition, some practical factors will not be taken into consideration in the models, such as light is not on axis for polarizer.

A. Optical Modeling of Light Field

1. Polarization-based light field
For the polarization-based display, the 3 panels were stacked one after the other encoded by only a single pair of crossed linear polarizers (Fig. 1). Each LCD, in this case, acts as a polarization rotator. The whole configuration is considered as one single spatial light modulator (SLM). This model makes use of Malus’ law:

\[ I = I_o \times \sin^2(\phi), \]  

where the intensity that passes through the first polarizer is \( I_o \) and the polarization angle from SLM is \( \phi \). By varying the voltage applied through the electrode array of the LCD, 2D images could be rendered with different levels of grey or RGB according to the induced rotation. The polarization rotation angle \( \phi \) must be in the range of between 0 to \( \pi/2 \) radians in order to produce all the different levels of grey or RGB [9].

The output intensity (\( I_{out} \)) based on Malus’s law for this 3-layer polarization-based configuration is shown as below.

\[ I_{out}(\alpha_1, \beta_1, \gamma_1) = I_{in} \times \sin^2(\phi_{\alpha_1} + \phi_{\beta_1} + \phi_{\gamma_1}). \]  

From the equation, \( I_{in} \) is the input intensity coming from the backlight and rear polarizer, \( \phi_{\alpha_1}, \phi_{\beta_1}, \) and \( \phi_{\gamma_1} \) are the rotation angles of the rear, middle, and front LC layers at pixel \( \alpha_1, \beta_1, \) and \( \gamma_1 \) respectively. It is obvious that the intensity of the light beam \( \alpha_1, \beta_1, \gamma_1 \) which passes through the pixel \( \alpha_1, \beta_1, \) and \( \gamma_1 \) is different from light beam \( \{\alpha_2, \beta_2, \gamma_1\} \) as shown in the left of Fig. 2. Thus the information displayed from the same pixel \( \gamma_1 \) that comes from different directions is not the same.
Considering the optical characteristic of the polarization-based configuration, the target light field can be presented by polarization angles $\phi_{x,y}$, and the final reconstructed polarization angle of light field $L_{x,y}$ can be calculated by the additive value of polarization angle $\alpha$, $\beta$, and $\gamma$.

2. Attenuation-based light field

For the attenuation-based light field display, a polarizer is required between each two stacked LCD panels and each polarizer has to be orthogonal to its neighbor LCD. In this configuration, each LCD acts as an SLM. The intensity of the emitted light beam ($I_{out}$) can be determined by taking the product of the input intensity ($I_{in}$) from the rear polarizer and the transmittances at three layers. The transmittances are decided by the pixels that the light beam passes through each LCD panel.

$$I_{out}(\alpha, \beta, \gamma) = I_{in} \times (T_{\alpha} \times T_{\beta} \times T_{\gamma}). \quad (3)$$

From the equation, $T_{\alpha}$, $T_{\beta}$, and $T_{\gamma}$ refer to transmittance of the rear, middle, and front LCD panel, respectively, and $\alpha$, $\beta$, $\gamma$ refer to the pixel location of each LCD. Similarly, it is also obvious that the intensity of light beam $\{\alpha, \beta, \gamma\}$ is different from $\{\alpha, \beta, \gamma\}$ as shown in the right of Fig. 2. Thus the information displayed at the same pixel $\gamma$ that comes from different directions is also not the same.

Considering the optical characteristic of attenuation-based configuration, the target light field can be presented by transmittance $T_{\alpha,\beta,\gamma}$. The final reconstructed transmittance of light field $L_{\alpha,\beta,\gamma}$ can be calculated by the multiplicative value of transmittances $\alpha$, $\beta$, and $\gamma$. In this paper, three sub-pixels, red, green, and blue, will be treated as separate channels for processing.

B. Mathematic modeling of light field

After the optical modeling for light field, we can represent the 3-layer reconstructed light field as a restricted 3-order tensor:

$$L' = C \otimes R, \text{ for } L_{\alpha,\beta,\gamma} = \begin{cases} 1 & \text{if } (\alpha, \beta, \gamma) \text{ gives a light field beam} \\ 0 & \text{otherwise} \end{cases} \quad (4)$$

where $\otimes$ is the Hadamard (elementwise) product. $L'$ is a three order tensor, which represents the display content of the reconstructed light field in a restricted view angle in the following optimization, as shown in Fig. 2. In the experiments, the software optimized view angle is 10 degrees for both horizontal and vertical directions. $C$ is a 3-order binary-valued weight tensor for calibrating the light beam and its passing path (the pixels that passed through), and the value of this matrix rigidly corresponds to every restricted light beam in the light field. $R$ is the 3-order tensor, which represents all of the candidate combinations by each 3 pixels on the three layers. The value for each discrete coordinate in $R$ is given by:

$$R_{\alpha,\beta,\gamma} = \begin{cases} \phi_{x,y} + \phi_{z} + \phi_{y}, & \text{Polarization} \\ T_{x} \times T_{y} \times T_{z}, & \text{Attenuation} \end{cases} \quad (5)$$

Thus, $R$ is assigned to different expressions with the polarization-based and attenuation-based display. It can be an optimal set of polarization rotations or transmittances of each pixel on the three layers. Accordingly, the upper and lower bounds of $R$, are $\pi/2$ and 0 for polarization-based light field display, or 1 and 0 for attenuation-based light field display.

C. Optimized Light Field Reconstruction

Based on the above light field modeling, an optimal set of $R$ is found by solving the constrained linear least-squares problem:

$$\text{arg min}_{R} \|L - C \otimes R\|^2, \text{ for } L_{\alpha,\beta,\gamma} = \begin{cases} \phi_{x,y} & \text{Polarization} \\ T_{\alpha,\beta,\gamma} & \text{Attenuation} \end{cases} \quad (6)$$

where $C \otimes R$ is the reconstructed light field introduced in formula (4). $L$ is the original light field and its value is defined with different value based on different optical modeling. In the paper, formula (6) is solved by an offline LSQLIN (linear least squares with linear constraints) solver [9], which was certified that can obtain a quite accurate solution of light field reconstruction for both polarization-based light field model and attenuation-based light field model. Here, note that formula (5) and (6) of attenuation-based configuration can be linearized by transforming both the original light field $L_{\alpha,\beta,\gamma}$ and reconstructed light field $R_{\alpha,\beta,\gamma}$ into their logarithmic space.
3. Proposed Subjective Test Model

A. USAF-E Chart Model for Perceived Resolution and Depth of Field

As resolution and depth of field (DOF) are extremely important parameters relating to light field displays, seeking a convenient subjective assessment method for them is important. One valuable tool is the USAF resolution chart [20] where sets of three horizontal and three vertical bars with descending size are reproduced on a display and subjects are asked whether they can resolve these; the smaller the size that can be resolved, the higher the resolution the display has. One shortcoming of the USAF chart is that subjects have to state whether or not they can resolve the lines; however, this is open to interpretation. In this paper, a more robust method is used where the orientation of the lines is arranged in a random fashion and the three lines are converted to 'E's; subjects then have to declare the orientation of the 'E' on a score sheet.

Light field displays have an optimum depth at which the reproduced resolution is maximum, and the resolution will decrease as the displayed distance becomes further from this, whether nearer or further from the viewer. The resolution can be readily seen as a series of resolvable bars with a series of non-resolvable bars below with the decreasing size bars from top to bottom.

Fig. 3(a) shows different characteristics where the horizontal and vertical 'E's represent an ideal display that has no DOF limitation. Fig. 3(b) shows the USAF-E model dimensions. It has 9 depth planes in a staircase configuration that have a 5 mm depth separation giving a total of 40 mm separation between front and back.

Fig. 3. (a) Proposed USAF-E depth model. (b) USAF-E model dimension (length: mm).

B. Viewing Angle for Field of View

Inspired by MIT’s prototype [5] where a black line on the image of a small car appears to split up as the image is viewed off-axis, this effect is extended to be utilized to determine a subjective measure of the field of view. Due to limitations of the algorithm, a line that appears to be continuous when viewed on-axis, appears to split up when viewed above a certain critical angle. Although this critical angle can be measured, we cannot rigorously give the required criteria in terms of well-defined parameters as it is based on subjective assessment. A Solidworks model of a line on a slanting surface (Fig 4) provides a more controlled image than that of the car. The model consists of two parts; one is a 100 mm × 100 mm × 10 mm cuboid, and the other is a wedge-shaped object with 10 mm thickness. In this paper, only horizontal viewing angle was measured as the measurement of the vertical range was less straightforward and the 3D performance is mainly from horizontal parallax [22].
For measurement, the image of view angle object in Fig. 4(a) is shown to the subjects, who must remain as close as possible to a viewing distance of one metre and move their lateral position to the left and to the right, as shown in Fig. 6(a), until the vertical line on the image appears to 'break up' into separate jagged sections as shown in Fig. 5(b). When this occurs they must cover their left eye and look up to a scale marked in degrees that is located behind the display. Above the display is a pointer that lines up with the angle at which the subject is located as shown in Fig. 6(b).

Fig. 5. The displayed view angle object appears to (a) "normal" in polarization-based configuration at -5 degrees off axis, while (b) "break up" in attenuation-based configuration at +30 degrees off-axis.
C. Concave/Convex Object for Depth Resolution

In subjective measurements, it is important that there is a method used to determine whether users can perceive depth. A very useful physical object was developed at the National Physical Laboratory in the UK for assessing the usefulness of 3D for performance enhancement in remotely viewed medical tasks [21]. This object consists of 60 mm diameter convex and concave surfaces that have a random square pattern printed on them. Again, the object was duplicated in Solidworks, and Fig. 7 shows images of the convex and concave objects.

In the measurement, there are eight screens showing the subjects the images of depth object, in which the left image uses polarization-based modeling method to produce and the right image uses attenuation-based modeling method to produce. Screens 1 and 2 have an object depth of 16 mm, Screens 3 and 4 an object depth of 8 mm, Screens 5 and 6 an object depth of 4 mm and Screens 7 and 8 an object depth of 2 mm. In each case, subjects were asked whether the object was convex or concave and then record their answers on score sheet; also, the time to respond was recorded.
by the person in charge of the trial. Care was taken to hide the second image whilst the first was being observed in order to not affect the subjects' reaction speed.

The response times were recorded to determine the ease degree that subjects could perform the task and the related weightings were applied as TABLE I.

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<th>Score</th>
<th>Evaluation</th>
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<tr>
<td>0</td>
<td>Could not tell</td>
</tr>
<tr>
<td>1</td>
<td>Difficult (&gt; 4 seconds)</td>
</tr>
<tr>
<td>2</td>
<td>Hesitation (≤ 4 seconds)</td>
</tr>
<tr>
<td>3</td>
<td>No hesitation (less than one second)</td>
</tr>
</tbody>
</table>

4. Measurements

For measurement implementation, we establish a light field display prototype with consumer electronics. The hardware prototype was built using three Asus VG248QE 24” LCDs and two NVIDIA Quadro graphic cards, which can demonstrate “1920×1080” resolution images or videos with a 144Hz refresh rate. In the proposed measurement, all of the virtual object models and test sequences are rendered as 7x7 images with a field of view of 10 degrees in both the horizontal and vertical direction. That means the software simulated viewing angle should be [-5, +5 degrees].

The display prototype shown in Fig. 8(a) uses the three-layer structure of Fig. 1. The left side uses polarization configuration, while the right side uses attenuation configuration. For the polarization one, we only use two orthogonal polarizers. One is behind the rear layer and the other one is before the front layer. For the attenuation, we use three polarizers, wherein the front and middle are orthogonal, and so are the middle and rear. Additionally, the distances between each two LC layers are 1.5 cm. Note that, there is no additional diffuser added into the prototype for Moiré fringing mitigation. The original polarizers that were removed Asus LCD were reused for this as they have a diffusing anti-glare surface.

![Fig. 8.(a) Hardware prototype of compressive light field display, and (b) ELDIM.](image)

The luminance and color of the prototype were measured by placing an ELDIM VCMaster3D 3D display analyzer in front of the display screen while maintaining at the recommended working distance of 15mm away from the lens, as shown in Fig. 8(b). The measurements were taken for 1, 2 and 3 layers of the prototype for comparison, respectively.

A. Objective:

1. PSNR

The layered light field decompositions are performed based on the MIT light field database [5] and our proposed test models using an Intel CPU Core (3.6 GHz) PC with 64G RAM. The MIT light field database includes 6 test sequences and all of them are 7x7 images, which generates a field of view of 10 degrees for both horizontal and vertical directions. The resolution of each light field image is 512x384. Here we compare the average PSNR of three RGB channels for objective comparison.

Fig. 9 shows the average receiver operating characteristic (ROC) performance curves of polarization-based light field decomposition [9] and attenuation based light field decomposition [5], respectively. The LSQLIN solver is used to generate the layered images. Without considering the error of the model itself, the polarization-based light field decomposition method has better simulated PSNR performance than attenuation-based light field decomposition method. More experimental results and supporting materials can be referred to: [http://www.shizhengwang.info/SID2016-QoE](http://www.shizhengwang.info/SID2016-QoE).
Fig. 9. ROC curves towards PSNR for different iterations. Messerschmitt A and Dice A are in polarization-based light field decomposition, while Messerschmitt B and Dice B for attenuation-based.

2. Luminance

Luminance is the luminous intensity per unit area of light traveling in a given direction. The unit used is candela per square metre (cd/m²). The luminance was taken for 1-layer, 2-layer and 3-layer display for comparison. The 2 and 3 layer tests are in both polarization-based and attenuation-based configuration. The LCD screens all displayed pure white for this test.

Fig. 10. (a) Luminance result for normal single layer LCD, (b) average luminance result of center 5 degree for 1-layer, 2-layer, and 3-layer prototypes with different configurations: 1-layer normal LCD (1N), 2-layer polarization-based display (2P), 2-layer attenuation-based display (2A), 3-layer polarization-based display (3P), 3-layer attenuation-based display (3A).
Fig. 11. Luminance result for (a) 2 layer, and (b) 3 layer with polarization-based configuration.

Fig. 12. Luminance result for (a) 2 layer, and (b) 3 layer with attenuation-based configuration.

Fig. 10, 11, and 12 show the results of the luminance measurement for 1-layer, 2-layer and 3-layer display with two configurations, respectively. For the 1-layer display, the average luminance of centre 5 degree is 345.4 cd/m^2 which is close to the given specification of the ASUS VG248QE LCD monitor of 350 cd/m^2. For the 2-layer and 3-layer polarization-based displays, the average luminance of centre 5 degree is 37.4 cd/m^2 and 4.7 cd/m^2, respectively; while for the 2-layer and 3-layer attenuation-based displays, the average luminance of centre 5 degree is 33.4 cd/m^2 and 3.7 cd/m^2, respectively. It can be seen that there is a drastic drop in the luminance as more layers are introduced. We can conclude that more layers for the prototype could produce a better 3D quality effect; however, the brightness would be reduced significantly. Additionally, the luminance of the
polarization-based display is better than that of the attenuation-based display. Therefore, the prototype would benefit from having a backlight with greater intensity.

3. Color Gamut
Colour shifts can also be an important source of imperfection in multi-layer light field displays. Based on the dedicated optical design with the medium angular aperture (±50°) and large size CCD (16M pixels), ELDIM VCMaster3D also includes 5 color filters designed specifically for each CCD sensor. Thus, the ELDIM instrument has the capability to measure the color and show this on a 1976 CIE chromaticity diagram. The CIE system characterizes the color by a Y parameter for luminance and two other color coordinates x and y which state the point on the chromaticity diagram. It basically shows all the possible colors in a graph with red, green, and violet in the corners of the diagram. The 1976 CIE chromaticity diagram is a revision of the standard diagram created in 1931. It contains similar information to the 1931 CIE diagram and is merely scaled differently [11].

![Fig. 13. CIE diagram for 1 layer red, 2 layer red, and 3 layer red with (a) polarization-based configuration and (b) attenuation-based configuration.](image)

Fig. 13 shows the results of normal single-layer LCD and polarization-based as well as attenuation-based multi-layer LCD on the 1976 CIE chromaticity diagram. The area of the triangle shows the range of all the colour mixture from the pure red, green, and blue that can be shown by the prototype.

From the results, the polarization-based 2-layer and 3-layer display will reduce the colour region compared to the original single layer display, while the attenuation-based 2-layer and 3-layer display will increase the colour region compared to the original single layer display. The experimental result of attenuation-based multi-layer display matches the conclusions of [5], which concludes that the color region of multi-layer display should be better than single-layer LCD, but that of polarization-based multi-layer display cannot match the conclusion of [9], whose conclusion is the performance of polarization-based configuration should be better than the attenuation-based one. This is because the previous work of polarization-based display is on an in-plane switching (IPS) screen whereas the measurements in this paper are on a twisted nematic (TN) screen. Since this paper focuses on quality of experience (QoE) measurement rather than on the light field display itself, the results on the TN screen are still of relevance here.

B. Subjective
The subjective trials were carried out on a group of 12 subjects whose ages ranged from 24 to 70. At the start of each trial, the subject was tested for visual acuity with an ‘E’ chart, stereo acuity with a Randot stereo vision tester and for good measure, color blindness with a set of Ishihara test figures. All subjects had 20/20 vision, a stereo acuity of ≤ 70 second of arc and none were color blind. The color blindness test is not strictly necessary but only takes around one minute and is an additional indicator of generally good visual health.

After testing each subject was briefed for around five minutes on what they should be aware of in the images and on how to fill in the score sheet given to them. For all trials, they were requested to maintain a viewing distance of one metre from the screen and to remain in the straight-ahead position as indicated by 0° position on the angle scale, except when carrying out the viewing angle measurements.

1. Perceived Resolution and Depth of Field
The subject was presented with an image of the depth chart object obtained by using polarization-based modeling method and asked to mark the direction of the ‘E’ on the score sheet which was later analysed to determine which answers were correct. The process was then repeated with the image obtained by using attenuation-based modeling method.

In practice, the boundary of the resolvable bars is U-shaped so that the larger the area of this zone, the better is the DOF of the display; this can be seen in Fig. 14. Analysing the subjective performance in Fig. 13 and statistical data in Fig. 14, it can be found that the accuracy of character recognition is decreasing along with the reducing perceived resolution in the same depth; while also decreasing with the raising depth from the middle layer in the same level of perceived resolution. Therefore, it must reasonably trade off the performances between the perceived resolution and depth of field according to the display requirements when designing or using this kind of display.
Fig. 14. The subjective performance of USAF-E based on (a) polarization and (b) attenuation.

The results from the trials on polarization-based and attenuation-based configurations can be compared readily when the totals in the summation tables are represented by differing shades of one color. In Fig. 15 the all-correct results with a score are depicted by 'pure' red (R = 255, G=0, B = 0) and completely wrong or undetermined results with a score of 0 are depicted by white (R = 255, G = 255, B = 255).

Fig. 15. Comparison of USAF-E chart results using color.

2. Viewing Angle

The viewing angles at which the 'break-up' of the line on the object occurs are plotted in Fig. 16. These show a clear difference in the performance between polarization-based configuration and attenuation-based configuration where the average viewing angles are 14.6° and 11.6°, respectively.
However, the accuracy in its present form should be open to question; for example, there is a larger variation in the upper and lower angular limits than would be expected from a simple observation of the apparent break-up of a vertical line in an image. One possible explanation for this is that subjects have been inadequately briefed before the trial.

Another indication that the experimental method may benefit from improvement is that the first six measurements show a large variation whereas the last six show more consistency; possibly perfecting the procedure plays a part here.

Fig. 16. The subjective assessment of viewing angle.

3. Depth Resolution

TABLE II shows the results with allowance for subject’s response times, in which ‘P’ stands for polarization-based configuration, while ‘A’ stands for attenuation-based. There are several conclusions that can be drawn from these. Note that in the second row from the bottom 'V' indicates the object in that column is concave and 'X' indicates that it is convex.

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depth 16 mm 8 mm 4 mm 2 mm
The most obvious observation here is that there are no results with a score of 3 showing that even if the subject could actually tell the difference, the task always involved difficulty or hesitation. This might not necessarily be an indication of the quality of the display but might be due to the nature of the test object; the intended object had an even random square pattern on it with an even distribution of vertical and horizontal edges across its complete area. The object made in Solidworks has a radial pattern in its centre; although in principle the functioning of the display system should not be affected by the image content, in practice, such an extreme pattern could well skew the results.

As there is possible doubt regarding the suitability of the object, it might be unsafe to use these results as a reliable measure of the depth resolution. The inconclusive results for a depth of 2 mm could either indicate that the display is incapable of having a depth resolution of 2 mm or it could cast doubt on the object’s suitability. The subjective performance of convex/concave object is shown in Fig. 17.

![Image](b)

**Fig. 17.** The subjective performance of convex/concave object: the left side is polarization-based display; the right side is attenuation-based display.

It is interesting to note that the convex object has better performance for polarization-based configuration at depths of 16 and 8 mm, and attenuation-based configuration performs better at 4 mm depth. The explanation for this could be that the object pattern where the central region is radial and the outer region is more like the originally intended square pattern has a different effect on concave and convex patterns with different depths. The bottom line is that the principle of the technique is most likely sound but that the object would benefit from improvement.

4. **Naturalness, Quality, Depth, Brightness, Eyestrain and Moiré fringing**

The participants received a brief instruction explaining the procedure of the experiment, in which the dependent variables, as well as the different assessment scales, were explained. Participants assessed the two images using different scales. The perceived naturalness, image quality, depth and brightness were scored using the scale standardized by ITUBT 500-11 (ITU, 2000), which was labelled with the adjectives [bad]-[poor]-[fair]-[good]-[excellent]. Intermediate marks were added to allow the participants to refine their judgments. Fig. 18 shows the true display performance of test sequence "Messerschmitt" and "Dice". The perceived eyestrain was scored on a 9-point scale that ranged from [very low] to [very high]. Before the experiment started the different attributes (naturalness, image quality, depth, brightness and eye strain) were explained to the participants. The stimuli were displayed on the screen until the participants assessed all the dependent variables. The order of the stimuli was randomized to counterbalance order effects.

![Image](a)

**Fig. 18.** The subjective performance of (a) test sequence "Messerschmitt" on the side-by-side prototype: the left side is polarization-based display and the right side is the attenuation-based display; (b) test sequence "Dice" on the side-by-side prototype: the left side is polarization-based display and the right side is attenuation-based display.

The subjects filled in the section of the score sheet and also a similar section for a ‘dice’ image. The results are shown in a series of histograms in Fig. 19 where the upper plots are for the “bubble car (Messerschmitt)” image and the lower plots are for the “dice” image. The blue bars give the results for polarization-based configuration and the red bars for attenuation-based configuration. Although there is a considerable spread of results in every plot, clear differences can be seen by comparing results; for example, *Algorithm B* consistently scores more ‘goods’ for image quality and depth. The
fact that there are large spreads in the results could be an indication that the initial briefing for each subject was inadequate and here is an area where further refinement of the procedure is probably required.

Fig. 19. Subjective results.

Moiré fringing is a significant problem with multi-layer displays so measurement of its subjective effects is of real importance. The perceived fringing was also scored using a five-point scale standardized by ITUR. 500-11 (ITU, 2000) [19]. The scores range from 1 for not perceptual through to 5 for very annoying.

The subjects were shown four images, these were: plain white with no diffuser in front of the screen, plain white with a diffuser, an image with no diffuser and an image with a diffuser. The results are shown in Fig. 20 and, as might be expected the use of a diffuser makes the images more pleasing and the fringing is less annoying when an image is shown.

Fig. 20. The subjective results of Moiré fringing.

5. Combined Performance

As the range of depth that can be displayed and a subjective measure of the image quality for a particular depth have been determined, these two metrics can be combined in a single figure to give a readily comprehended indication of the overall display system performance. The figure can be further enhanced by overlaying the intended depth over the actually displayed depth and by showing a photo of the modified USAF depth chart image on the screen, whereas the plotted red boundary is for 100% correct answers according to the USAF-E results in Fig. 14. On the plan of intended and actual depth, the position of the glass layers is also shown. This is used to aid the analysis of potential artefacts, for example, the possible clustering of depths around the display panel layers. Also blurred regions have been added to provide a pictorial indication of the image quality; this is probably not necessary and simply the examination of the photograph at the bottom is sufficient.

All these features are shown in Fig. 21 where subjective quality, depth range and distortion, and actual appearance can be visualised at a glance. The image quality curve was plotted from values that are simply the sum of the number of correct scores each column of the object receives from all the subjects and does not take into account the resolution attached to each score. A statistically more correct method will probably give more accurate results; however, in the first instance, this method provides a quick answer that can be used for comparing one display against the other. Also, there may be other measures of image quality, rather than simply the identification of the orientation of the ‘E’ shapes displayed that are more appropriate. This will be the subject of further study.

In the particular display and algorithms that were used for characterization, areas where they could be improved can be readily identified. One important finding is that the display cannot show images appearing in front of the screen and that the best quality images are formed at the plane of the screen. This means that images that should be formed in front merely become blurred but do not show depth; therefore, only half of the depth potential is being used. In this particular case the algorithm should be modified to provide depth forward of the front screen, or alternatively move the in-focus plane back, say to the middle screen. A toolbox for MLLFD measurement with proposed models and public test sequence is released in the supporting materials for readers’ references: http://www.shizhengwang.info/SID2016-QoE.
6. Conclusion

Multi-layer light field display is a promising novel display for future 2D/3D compatible display. Considering there is no sufficient quantitative QoE measurement on MLLFD yet, this paper implements a comprehensive QoE measurement on this display. The main contributions of this paper include: 1) both objective and subjective performance metrics have been measured based on virtual object model (VOM); 2) three new VOMs have been proposed for QoE measurement: USAF-E model, concave/convex object model and view angle model; and 3) combining with the proposed VOMs, an MLLFD measurement toolbox is released with this paper. Based on the measurement results, the real physical performance of MLLFD is still far from the theoretical upper limit of its depth of field. Thus our future research plan includes incorporating a high refresh rate dynamic ferroelectric liquid crystal (FLC) barrier into this display to enhance the temporally multiplexed ability and introducing the Jones matrix model of TN screen to polarization-based MLLFD for correcting the color gamut.

7. Acknowledgement

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References