MEASUREMENT OF PERCEIVED SPATIAL RESOLUTION IN 3D LIGHT-FIELD DISPLAYS

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ABSTRACT

Effective spatial resolution of projection-based 3D light-field (LF) displays is an important quantity, which is informative about the capabilities of the display to recreate views in space and is important for content creation. We propose a subjective experiment to measure the spatial resolution of LF displays and compare it to our objective measurement technique. The subjective experiment determines the limit of visibility on the screen as perceived by viewers. The test involves subjects determining the direction of patterns that resemble tumbling E eye test charts. These results are checked against the LF display resolution determined by objective means. The objective measurement models the display as a signal-processing channel. It characterizes the display throughput in terms of passband, quantified by spatial resolution measurements in multiple directions. We also explore the effect of viewing angle and motion parallax on the spatial resolution.

Index Terms— 3D displays, light-field displays, spatial resolution, resolution measurement, subjective experiment

1. INTRODUCTION

3D light-field (LF) displays [1] are capable of providing 3D images with a continuous motion parallax over a wide viewing zone, and viewers can experience spatial vision inside this zone without wearing 3D glasses. Instead of showing separate 2D views of a 3D scene, they reconstruct the 3D light field describing a scene as a set of light rays. One way to implement such a display is using an array of projection modules emitting light rays and a custom holographic screen [2]. The light rays generated in the projection modules hit the holographic screen at different points and the holographic (reconstruction) screen as seen Figure 1, which makes the optical transformation that composes rays into a continuous 3D view. Each point of the holographic screen emits light rays of different color to the various directions. However, it is important to note that such screens do not have discrete pixels since the light rays can pass through the screen at arbitrary positions.

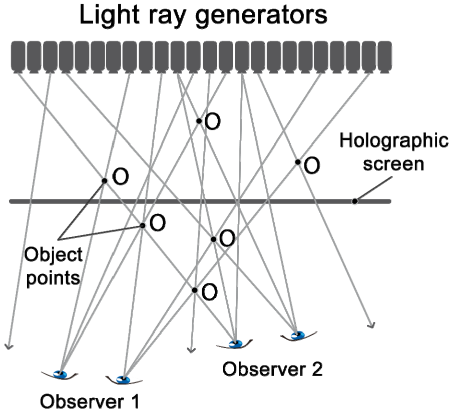


Figure 1: Light-field display architecture

When using properly designed LF displays, light rays leaving the screen spread in multiple directions, as if they were emitted from points of 3D objects at fixed spatial locations. This gives the illusion of points appearing either behind the screen, on the screen, or floating in front of it, achieving an effect similar to holograms.

For 2D displays, essential information such as spatial resolution and observation angle is standardized [3] and easily available to end users. For 3D displays in general, a common standard does not exist yet, and manufacturers rarely provide information about the display capabilities or provide 2D-related parameters. For example, the capabilities of a 3D display are given in terms of the underlying TFT matrix resolution and the number of unique views, which does not explicitly define what viewers can see [4].

2. RELATED WORK

Most previous work on 3D display characterization is only applicable for stereoscopic and multi-view (MV) displays. An approach to model multi-view displays in the frequency domain is presented in [5], where test patterns with various density and orientation are used. However, the inherent assumption about 3D displays having a sub-pixel interleaving topology does not apply in the case of LF displays. The method presented in [6] is based on proprietary measurement equipment with Fourier optics, and is targeting MV displays. The Information Display Measurement Standard [3] provides a number of methods to measure spatial and angular resolution (in chapters 17.5.4 and 17.5.1 of [3]). However, the angular resolution measurement method relies on counting local maxima of a test pattern, and assumes that the display can show two-view (stereoscopic) test patterns, which is a very unnatural input in case of LF displays, not having discrete views. This method also assumes that the pixel size of the display is known, which, not having discrete pixels, is also not applicable for LF displays.

In this work, we present a subjective experiment to evaluate the spatial resolution of LF displays, which has a direct influence on the perceptual quality of a LF display. We analyze the effect of different viewing angles on the measured and perceived resolution, as well as the effect of motion on the perceived resolution.

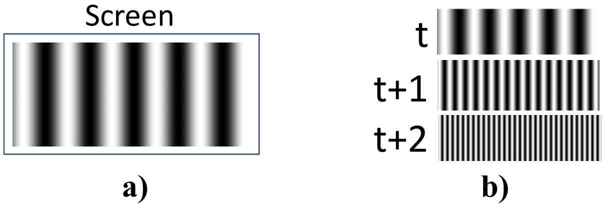
We specifically experiment with displays produced based on the HoloVizio technology [2], however the methodology can be directly adapted to other LF displays [11][12][13].

3. OBJECTIVE MEASUREMENT OF SPATIAL RESOLUTION

The method we have used for measuring the objective resolution has been presented in our previous work [7], therefore it is not detailed here. To be able to show the correspondence between the objective and subjective approach, a short summary of the algorithm follows. What is new, is that we have executed the resolution measurement from different viewing angles relative to the screen.

The 2D spatial resolution of a LF display cannot be directly measured in terms of horizontal and vertical pixel count. This is due to the specific interaction between the discrete set of rays coming from the projectors and the continuous LF reconstruction screen. In order to recreate a valid 3D effect, rays coming from different projectors might not form a regular structure. Correspondingly, the group of rays visible from a given direction does not appear as pixels on a rectangular grid [5].

Therefore we chose to quantify the display's capability to produce fine details in a given spatial direction. This is achieved by measuring the so-called "pass-band" of the display [10]. Pass-band measurement consists of a series of pass/fail tests, where each test analyses the distortions introduced by the display on a given test pattern. It starts with a test pattern showing sinusoidal black and white patterns (see Figure 2a) on the screen with a given frequency and orientation. The image on the screen is photographed and analyzed in the frequency domain. If the input (desired) frequency is still the dominant frequency on the output (distorted) image, the frequency of the current test pattern is considered to belong to the pass-band of the display.



a) **b)**

Figure 2: a) Sinusoidal pattern for spatial resolution measurement; b) Sinusoidals of increasing frequency used for the spatial resolution measurement

By repeating the pass/fail test for multiple test patterns with different frequency (see Figure 2b) and directions (0º, 22.5º, -22.5º, 45º, -45º, 67.5º, -67.5º and 90º in our experiments), one can find the range of input frequencies that can pass through the system. Signals with measured frequencies lower than the frequency of the generated signal (i.e. aliased frequencies) are classified as distortions [10]. We consider distortion with amplitude of 5% of the original (input) signal to be barely visible, and distortion with amplitude of 20% as unacceptable. Based on these thresholds, two sets of resolution values can be derived. One is what we call *distortion-free resolution*, i.e. the amount of cycles per degree the display can reproduce in a given direction, without introducing visible distortions (5%). The other is *peak resolution*, which characterizes the maximum resolution for which the introduced distortions do not mask the original signal (20%).

As the LF image is comprised of a set of light rays originating from various sources, sampling and visualizing this pattern is not trivial. For this purpose, and for visualizing the test patterns of the subjective experiment, we have developed pattern generator software that enumerates all the light rays emitted by the display. By knowing where the light rays originate from and where they cross the screen's surface, the intensity of the specific light ray is determined, much like a procedural texture.

This measurement has been performed on the same LF display from a central viewpoint, as well as from the edge of the Field of View (FOV).

4. SUBJECTIVE TEST OF PERCEIVED SPATIAL RESOLUTION

To quantify what resolution human viewers are able to see, we have developed a test that involves subjects distinguishing small details on the screen, and iteratively finding the detail size they cannot properly see anymore. We aimed at constructing a test that subjects are familiar and feel comfortable with. The perceived spatial resolution has been measured using a test similar to the tumbling E eye test charts [8]. In our case, symbols of different size have been shown on the screen of a LF display, and viewers have been asked to record the orientation of the symbols.

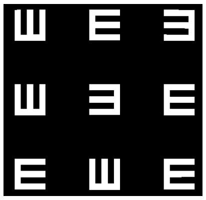


Figure 3: 3x3 E signs with randomized direction

In each iteration a viewer can see nine equally sized symbols on the screen, arranged in a 3x3 layout, the orientation of each symbol randomly chosen from the four possible orientations (left, right, up, down), as shown on Figure 3. The test software records the rendered symbols along with the symbol size, timestamp and the ID of the test subject. The subject is asked to record the nine orientations on paper, that is, draw the symbols into a 3x3 grid with the same orientation he/she can see.

In the next iteration, the size of the symbols is decreased 1.3 times, and the next set of randomized symbols is presented. The viewer records the orientation of the new set of symbols. The rendered symbol orientations and the perceived orientations recorded by test subjects are then compared to see where the orientations cannot be seen by the test subjects. When ophthalmologists perform eye tests, a line of a specific symbol size is considered read when more than half of the characters are read correctly, thus we use the same criteria [9].

The application used to render the symbols on the LF display is based on the same technique we used to render the spatial resolution test patters in the sense that the color of the emitted light rays is determined procedurally, that is, a GPU shader is executed for each light ray, which, based on the ray parameters and the pattern to be rendered, calculates if the specific light ray should be white or black. This is in contrast with rendering approaches that start with a flat texture depicting the intended test pattern, and generate the light rays by applying a set of transformation and filtering steps. This rendering method ensures that the test patterns are rendered with the highest possible fidelity with no degradations caused by the rendering process.

The subjective tests were conducted with nine subjects, sitting 5m away from a 140” diagonal LF screen. The room has been darkened so that external light reflected from the screen does not affect the perception of patterns. The analysis of the results show that on average, subjects started to introduce recognition errors in iteration 6, and have fallen below the 50% threshold in iteration 8, close to the level of random guess (25%), as shown on Figure 4.

5. COMPARISON OF OBJECTIVE AND SUBJECTIVE RESULTS

The results of the subjective tests show that the level where subjects started to introduce recognition errors roughly corresponds to 150% of the peak resolution as determined by the objective measurement, even though the average performance at this level is still 92%.

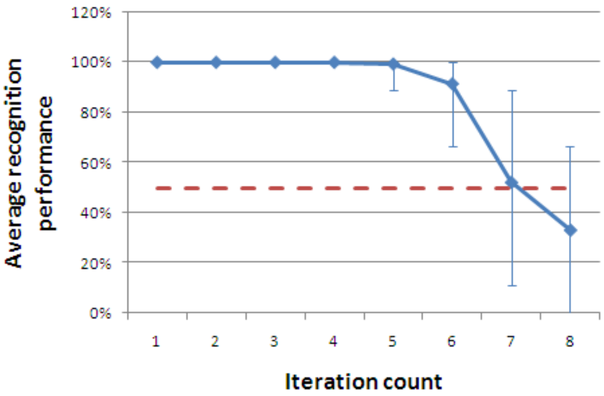


Figure 4: Average recognition performance. Dashed line marks 50% threshold.

Interestingly, even in the next iteration (1.3x smaller size) subjects performed slightly higher than the 50% recognition threshold. The reason for the higher perceived resolution might be that the human vision system is very good at determining shapes even when they suffer from distortions.

We have found that the objective measurement is strict in the sense that when the 20% distortion level is reached, the original patterns are still visible at some areas and some viewing directions on the screen, although heavily distorted or even invisible in other areas.

The correspondence between the resolution represented by the sinusoidal pattern and the E symbols is determined in the following way: the feature size in case of the tumbling E test pattern is the thickness of one line segment in the E, while the feature size of the sinusoidal is a half period.

6. VIEWING ANGLE DEPENDENCE

In all displays, the perceived resolution when watched from the center or from other angles is different. Due to the way the emitted rays are typically distributed in a LF display we expected that the resolution will be slightly lower at the sides of the FOV.

To check the viewing angle dependence of the measured and perceived resolution of the display, we have performed both the objective and subjective resolution measurements from the center of the viewing area, and the side of the viewing area.

The results of the objective resolution test show that the horizontal resolution is slightly lower when perceived from the edge of the FOV, see Figure 5. The results of the subjective tests also show that the performance of subjects in recognizing the correct orientation of symbols is slightly lower when they were positioned on the side of the viewing zone. The decrease of accuracy starting at iteration 6 is steeper in this case. Moreover, some subjects made a mistake with relatively large symbol sizes, which did not occur when they were positioned in the center.

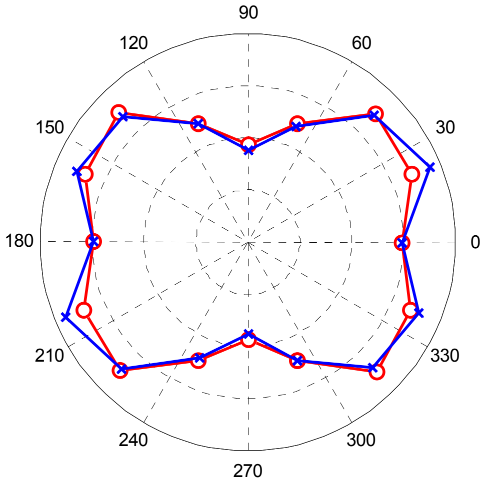


Figure 5: Difference between measured resolution from the center (blue / x) and the side (red / o) of the FOV. The plot shows the measured resolution in test patterns of different directions.

With the smallest symbol size we can see subjects performed slightly better from the side view, but we consider this irrelevant, as both results (31% and 33%) are close to random guess (25%), and are only shown here for completeness.

7. MOTION PARALLAX DEPENDENCE

During the subjective tests we have realized that subjects, although sitting, have been moving their heads excessively, especially when observing very small symbols. When asked, they confirmed that head parallax helps them to see the correct orientation of small symbols on the screen. In order to check the importance of motion parallax on the perceived resolution, we repeated the experiment with no head movements allowed. Comparing the results of the eye chart test with and without head movements shows that looking at the same display from multiple directions let subjects see finer details, thus increasing the perceived spatial resolution. While subjects performed slightly above the 50% threshold in iteration 7 in the normal test, their performance dropped below 50% in the last two iterations when no head movements were allowed.

The reason for this effect is rooted in the non-uniform pixel structure of LF displays, that is, the light rays visible from one viewing angle may sample the 3D scene at slightly different locations than from different angles. That is, when viewers are moving their heads, they are looking for the positions where the direction of the symbol can be seen.

We should note that the measured resolution as seen by a still camera can be just as high as the perceived resolution of a viewer with no head movements allowed.

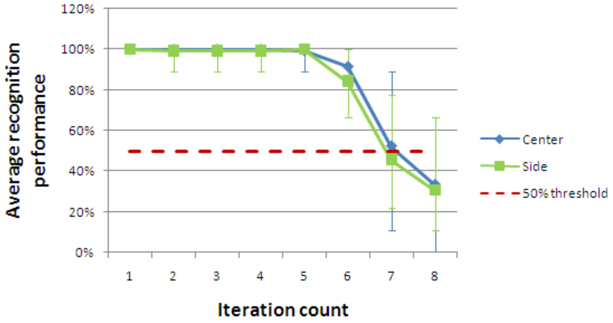


Figure 6: Average recognition performance from the center, and from the side of the LF display's FOV

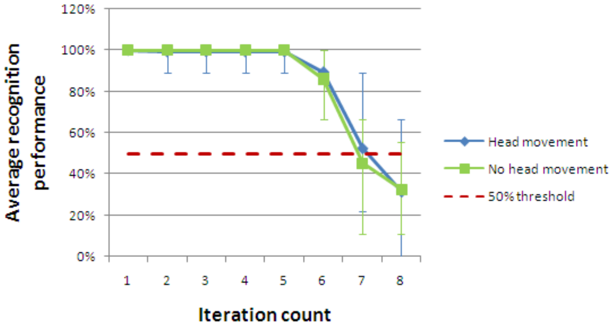


Figure 7: Average recognition performance with and without head movements

8. CONCLUSIONS AND FUTURE WORK

Both an objective measurement method and a subjective test have been presented for measuring the spatial resolution of LF displays, which can be applied to any LF 3D display. The results of the measurement and subjective tests have been compared, and a difference has been found. The dependence of resolution on viewing angle has been checked and confirmed. It has also been shown that an observer could see finer details when head movements were allowed compared to the case when the head position was fixed on a LF 3D display, and commented on the possible causes. These results highlight some of the many differences between 2D displays and 3D LF displays. These differences have consequences on content creation, processing, compression and rendering for LF displays.

Future work will aim at the development of an objective measurement or estimation method for determining the perceived resolution of moving viewers.

9. ACKNOWLEDGEMENTS

The research leading to these results has received funding from the PROLIGHT-IAPP Marie Curie Action of the People programme of the European Union's Seventh Framework Programme, REA grant agreement 32449.
The authors would like to thank the active participation of test subjects.

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