Instructions on Implementing the Point Spread Function Method for Spatial Resolution of Augmented Reality Head Mounted Displays

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I. Point Spread Function Pattern

Figure A1(a) shows an example the point spread function (PSF) test pattern with a 3 x 3 array of dots that are one-pixel wide or as narrow as possible through the rendering pipeline. The inter-dot spacing should be at least a factor 10 larger than the measured full width at half maximum (FWHM) of the dot to ensure each dot can be measured independently. The array should also be ≤ 2°, corresponding to the fovea of the human visual system. The test pattern can be rendered at different locations in the FOV to measure the performance across the FOV. This pattern can be rendered using RST Toolkit for Evaluation of Head Mounted Display Image Quality [1].

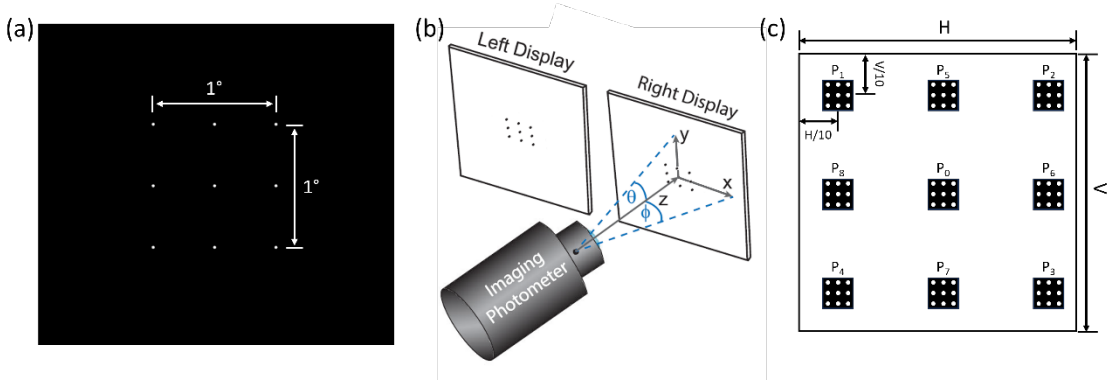

Figure A1. (a) Point spread function test pattern. (b) Experimental setup (c) Measurement points across the FOV. H: horizontal size of the virtual image. V: vertical size of the virtual image.

II. Experimental Setup

This method uses a high-resolution monochromatic array light measuring device (LMD) with photopic response mounted on a 5-axis goniometer or robot system to align the center of the entrance pupil of the head mounted display (HMD). The rotation axis should be placed approximately 10 mm behind the entrance pupil of the HMD for the eye-rotation method. Technical requirements on the LMD used are specified in IEC 63145-20-10 standard [2] and Sec. 19.2 of the Information Display Measurements Standard (IDMS) [3]. It is recommended to have at least 20:1 for the LMD to HMD pixels ratio to minimize the impact of the LMD modulation transfer function and ensure adequate sampling of the HMD pixels. Finally, the LMD should have near diffraction limited performance to minimize the impact of the LMD wavefront errors on the measurements. A sketch of the setup is shown in Figure A1(b).

III. Image Acquisition

The following procedure describes the experimental setup and image acquisition steps.

1. Align the imaging LMD at the eye point of one of the eye pieces of the HMD device. The LMD optical axis should be aligned with the center of the virtual image. Record what method was used to align the camera to the eye point.
2. Render the test pattern described in Section I at the center point, P_0.
3. Rotate the LMD is in azimuthal and elevation angles to position the center dot in the array at the center of the LMD sensor.
4. Adjust the focus of the LMD to optimize the image of the dot array.
5. Acquire an image of the dot array. Multiple images of the test pattern can be acquired to improve the signal to noise of the LMD.
6. Repeat steps 2-5 for the other positions in the FOV (P_1-P_8)
7. Steps 2-6 can be repeated with red, green, and blue test patterns to measure the wavelength dependence of the PSF.
8. Rotate the LMD is in azimuthal and elevation angles to the starting position in the center, P_0.

LMD Spatial Resolution Measurements

For PSF measurements the spatial resolution of the LMD should be significantly higher than the spatial resolution of the HMD. The spatial resolution of the LMD should be evaluated using the MTF of the LMD. After measuring the spatial resolution of the HMD, remove the HMD without changing the focus of the LMD. Place a physical target (slanted edge) at the distance of the HMD focal plane. The MTF of the LMD can be determined using the slanted-edge response in ISO 12233-2023 [4].

IV. Analysis

The following describes the image processing and analysis methods following the image acquisition in Section III.

1. Select a region of interest (ROI) for each dot in acquired 3x3 array. The size of the ROI should be the same as the inter-dot spacing in the acquired image.

   Note: The background signal level at the edge of the ROI should be approximately equal to the signal level with a uniform black test pattern to ensure the signal from the neighboring dots do not contribute to the signal. The inter-dot spacing may need to be increased and the images re-acquired until this condition is satisfied.
2. Calculate the background signal, B_k, for the first ROI by averaging the signal in the corner of each image.
3. Subtract B_k from the selected ROI.
4. Normalize the resulting PSF.
5. Repeat steps 2-4 for the other 8 dots in the ROI.

6. Take the profile in the horizontal and vertical direction for each of the nine dots. The nine profiles can be used to calculate the average value and uncertainty of the profiles in the horizontal and vertical directions.
7. Average the nine 2D PSFs.
8. Plot the 2D PSF and the PSF profile in the horizontal and vertical directions with the standard deviation for each signal value in the horizontal and vertical directions.
9. Using the averaged PSF, calculate the 2D MTF by Fourier transforming the 2D PSF using the equation:

$$MTF = \left| \frac{F\{PSF(x,y)\}}{F\{PSF(x,y)|_{f=0}} \right|$$

The MTF is normalized by the Fourier transform of the 2D PSF at a spatial frequency, *f*, of zero. The spatial frequencies can be calculated using the equation $f_{x(n)} = F_{S,x} * \frac{n}{N_x}$, where N_x is the total number of LMD pixels in the horizontal direction, n is the pixel number on the LMD and ranges from 0 to $\frac{1}{2}N_x$, and $F_{S,x}$ is the angular sampling frequency of the LMD and can be defined as $N/FOV_{LMD,x}$. A similar equation can be used for the vertical direction.

Note: If the background subtraction in step 3 did not result in approximately zero background, the value at *f* = 0 may be discontinuous from the neighboring points and either the background should be corrected or the value at *f* = 0 should be replaced by the average value of the nearest neighbors in the spatial frequency domain.

10. Plot the 2D MTF and the MTF profile in the horizontal and vertical directions.

V. Reporting

Report the eye point alignment method, dot array specifications (color, inter-dot spacing, dot diameter), angular positions in the FOV, LMD specifications (e.g. FOV, sensor size, calibration, bit-depth, lens focal length), ratio of LMD to HMD pixels, 2D PSF at each position, horizontal and vertical profile of the PSF at each position, 2D MTF at each position, horizontal and vertical profile of the MTF at each position, horizontal and vertical profile of the MTF of the LMD.

VI. References

[1] RST Toolkit for Evaluation of Head Mounted Display Image Quality

https://cdrh-rst.fda.gov/toolkit-evaluation-head-mounted-display-image-quality

[2] IEC 63145-20-10:2019 Eyewear display - Part 20-10: Fundamental measurement methods - Optical properties.

[3] Information Display Measurements Standard, SID, 2023.

[4] ISO 12233-2023