Instructions on Implementing the Line Spread Function Measurements

I. DESCRIPTION

This method uses a goniometer and a camera to measure the spatial profile of a one-pixel wide (vertical or horizontal) line on an HMD, known as the line spread function (LSF). The method describes a method for measuring the spatial resolution and modulation transfer function (MTF) for one eyepiece across the field of view of the HMD. Units: cycles per degree.

II. APPLICATION

This method can be used for any near eye display.

III. SETUP

This method uses a high-resolution monochromatic array LMD with photopic response mounted on a 5 degree of freedom (DoF) goniometer or robot system to align the center of the entrance pupil of the HMD. Prior work demonstrated that eye-rotation methods, opposed to pupil rotation methods, are necessary to capture the impact of eye gaze due to the pupil shift as the eye rotates1, which is illustrated in Figure A1. Therefore, the rotation axis should be placed approximately 12 mm behind the entrance pupil of the HMD for the eye rotation method. The entrance pupil of the camera should be selected according to Sec. 19.2 of the Information Display Measurements Standard (IDMS) [1]. 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, Moire patterns, and ensure adequate sampling of the HMD pixels.

As shown on the right panels of Figure A1, the test pattern is a one-pixel wide vertical or horizontal line on the HMD that is displayed at different locations in the FOV of the HMD. The measurements are acquired by rotating the LMD until the line is centered on the LMD. The angular spacing of the lines in the FOV can be adjusted to map the spatial resolution across the FOV of the HMD.

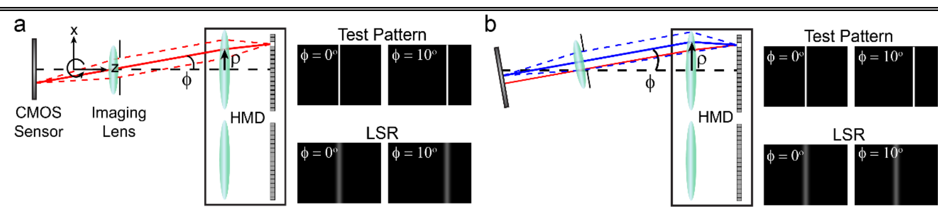

Figure A1. Measurement configurations for the line-spread response (LSR) of a VR HMD using a saturated white line test pattern that is scanned across the display of the VR HMD and imaged onto the camera. (a) Wide-field (pupil-rotation) measurements are acquired with the camera fixed at $\phi = 0^{o}$ and the white pixel imaged to a position on the camera at angle, ϕ, relative to the optical axis of the HMD. The solid red line indicates the ray that passes through the center of the aperture of the measurement setup, known as the chief ray, where r is the height of the chief ray on the lens of the HMD. (b) Eye-rotation measurements are acquired by rotating the camera to keep the position of the white line static on the camera. The solid blue line is the chief ray after rotation. The chief ray for the wide-field method is shown in red as a reference. Right column: Sketches of the input test pattern and resulting LSR at $\phi = 0^{o}$ and $\phi = 10^{o}$.

IV. PROCEDURE

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

1. Align the center of the camera entrance pupil at the eye point of the HMD device. The camera 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 a one-pixel wide vertical line in the center of the HMD.
3. Adjust the focus of the LMD to optimize the image of the line.
4. Acquire an image of the line.
5. Move the angular position of the rendered line in the test pattern in the +x direction by the desired amount.
6. Repeat steps 4 and 5 until measurements are acquired across the desired field of view in the +x direction.
7. Repeat steps 4-6 for the -x direction.
8. Render a one-pixel wide horizontal line in the center of the HMD.
9. Repeat steps 4-7 for the +y and -y directions.
10. Steps 2-9 can be repeated with red, green, and blue lines to measure the wavelength dependence of the LSF.

Note: To further improve the sampling of the HMD, the camera can be rotated by approximately 5 degrees relative to the display, which is similar to the slanted-edge response in ISO 12233-2023.

V. ANALYSIS

To determine the spatial resolution and MTF of the HMD, the acquired image must be analyzed to determine the LSF. The following steps are adapted from ISO 12233-2023 for evaluating the edge-spread response of a camera:

1. Rotate the image of the line to be vertical (horizontal) to remove any rotation of the LMD to the HMD.
2. Sum the signal over multiple pixels along the direction of the line starting centered at the origin. For example, for a vertical line sum 100 pixels along the y-direction centered at y = 0. Alternatively, a median filter can be applied to smooth the data.
3. The resulting data is the LSF for the center of the display in the horizontal (vertical) direction. The LSF a that location can be plotted as a function of angular size of the image based on the FOV. An example is shown in Figure A2a for lines at $\phi = 0^o, 5^o, 10^o$ in the FOV.
4. The resolution in the horizontal (vertical) direction of the HMD can be defined and the full-width-half maximum (FWHM) of the LSF.

The LSF can also be used to calculate the MTF of the HMD since, $MTF = |\mathcal{F}(LSR)/\max[\mathcal{F}(LSR)]|$, is calculated from the absolute value of the Fourier transform of the LSF. The measured MTF is a combination of the MTF of the HMD and the LMD. Therefore, if the MTF of the LMD is known, the MTF of the HMD can be determined using the equation $MTF_{NED} = MTF_{Total}/MTF_{LMD}$. Note that if the LMD significantly oversamples the HMD pixels, $MTF_{NED} \approx\approx MTF_{Total}$. Finally, the angular frequencies can be calculated from the angular values by using the equation,

$$f_{H/V}(n) = \; F_{S,H/V} * \frac{n}{N_{H/V}} \;,$$

where $N_{H/V}$ is total number of LMD pixels in the horizontal or vertical direction, n is the pixel number on the LMD and ranges from 0 to $\frac{1}{2}N_{H/V}$, and $F_{S,H/V}$ is the angular sampling frequency of the LMD and can be defined as $_{H/V}/FOV_{LMD,H/V}$.

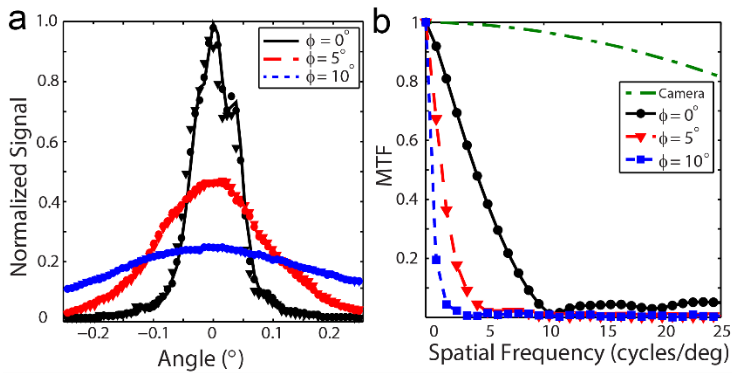

Figure A2: Example LSF data for a VR HMD using eye-rotation with measurements at ϕ = 0°, 5°, and 10° shown in black, red, and blue, respectively. (b) MTF data from the LSF in (a).

I. REPORTING

Report the eye point alignment method, line color, angular line location, LMD angular resolution, angular scanning method, pixel ratio of LMD to HMD, LSF for each line location, and MFT for each line location.

II. COMMENTS

This method is intended to be used for horizontal and vertical lines on the HMD. The angular resolution in the horizontal and vertical directions maybe different depending on the subpixel configuration of the HMD.

Reference:

1. Information Display Measurements Standard, SID, 2023.