User Manual: Instructions on Implementing the Geometric Distortion Measurement Method on Video See-Through Augmented Reality Head-Mounted Displays

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Instructions on Implementing the Geometric Distortion Measurement Method on Video See-Through Augmented Reality Head-Mounted Displays

I. Physical Target

Figure A1 shows an example physical target of a 9 x 9 dot array. This can be a high-contrast physical target, or a digital image (e.g., white dots on black background) shown on a flat-panel display. The physical target should cover a large test area of at least 30 x 30 cm^2 with constant spacing between neighboring dots (a_{sp}) smaller than 4 cm. The dot diameter can be selected between 2 to 5 mm depending on the image resolution and sensitivity of the VST cameras. A smaller dot size is recommended for improved accuracy of geometric distortion measurement.

Note that the angular dimension of the physical targets depends on the distance between the target and visual point. The target dimension may need to be magnified when placed at a longer distance (e.g., greater than 100 cm).

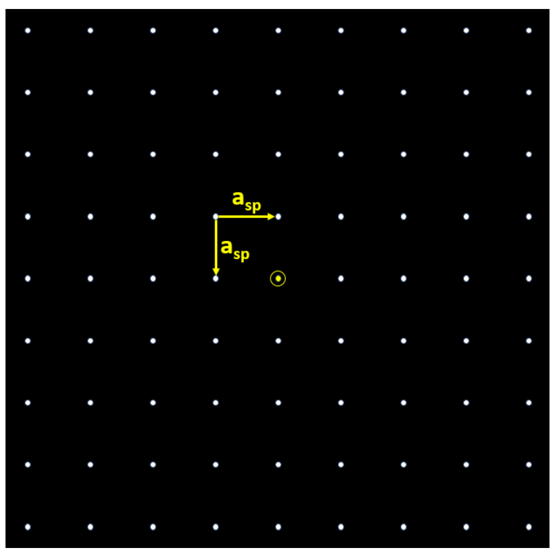

Figure A1. Example visualization of a physical 9 x 9 dot array for geometric distortion on VST HMDs.

II. Experimental Setup

Figure A2 illustrates the bench setup using the goniometric method to measure geometric distortion on VST HMDs. The evaluated VST HMD and a light measuring device (LMD) are mounted on a combination of motorized stages enabling 3-degree-of-freedom (3-DoF) translation in x, y, and z for LMD and HMD alignments; and 2-DoF rotation in azimuth (φ) and elevation (θ) to determine the 3D position of the dots. The LMD should be mounted on the goniometer (2-DoF rotation stages) on top of orthogonal translational stages to emulate an eye rotation geometry [1]. The eye rotation bench setup is illustrated in detail in IEC 63145-20-10 [1]and ICDM IDMS standards (Chapter 19) [2]. Alternatively, a robotic system with capability to read out the angular and spatial parameters can be used to mount the LMD. The goniometer should achieve an angular accuracy of less than 0.1°. A lens with a 3 to 5 mm entrance pupil in front of the lens is recommended. The rotation center should be pivoted at about 10 mm behind the entrance pupil location featuring the eye rotation geometry [1,2].

Notes:

- This method requires a 2-DoF goniometer to determine the angular position in azimuth and elevation for each target dot using an eye rotation geometry [1, 2].
- The image resolution of the LMD need to be adequate to resolve both the physical and virtual dots passing through the VST HMD. To accurately determine the dot position (see Sec. III for details), the dot diameter need to cover at least 10 pixels on the obtained image by the LMD.

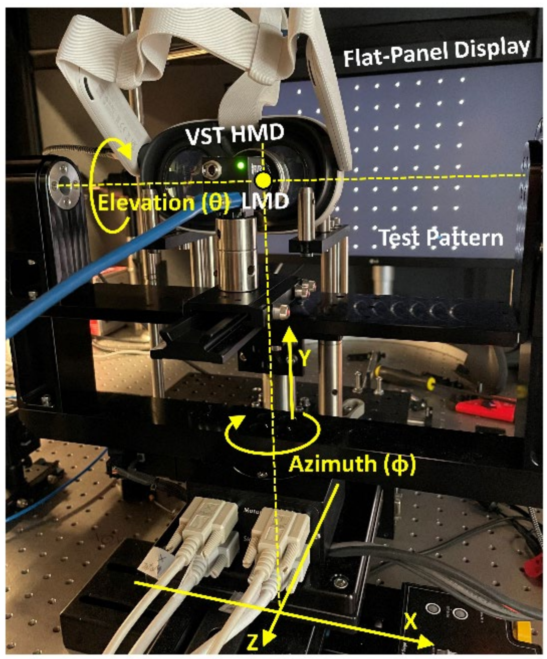

Figure A2. Experimental bench setup for geometric distortion measurement on VST HMDs using the eye rotation configuration [3].

III. Geometric Distortion Measurement

The following procedure describes the experimental setup and geometric distortion measurement steps.

1. Place the physical target approximately at the measurement distance from the rotation center. The measurement distance can be determined corresponding to the intended use of the device.

2. Before mounting the VST HMD, align the LMD (using the 3-DoF translation stages) with the central dot such that the optical axis of the LMD perpendicular to the 2D physical target with azimuth and elevation at zero ($\theta = \varphi = 0$).
3. Measure the distance (z_{LMD}) between the rotation center of the LMD and the physical target (central dot) with an error smaller than 1 mm. This can be achieved using the calibration procedure described in [3]. The distance measurement is critical as the error in z_{LMD} will affect the accuracy of spatial position as described in Sec. IV.
4. As illustrated in Fig. A3, after fixing the placement of the LMD and the target, mount the VST HMD on a separate stage such that the eye point of one of the eye pieces of the VST HMD is aligned with the LMD. This step aligns optical axes of the LMD and HMD eyepiece lens [2]. Record what method was used to align the LMD to the eye point.

   Note that the VST HMD may have a single or multiple VST cameras as shown in Fig. A3. This step does not aim to align the VST cameras to the physical target.

5. For each dot (dot position i) physically located at ($x_{0,i}$, $y_{0,i}$, $-z_{LMD}$) with respect to the rotation center, adjust the LMD azimuth and elevation angles (ϕ_i, θ_i) using the goniometer such that the optical axis of the LMD aligns with the target dot (e.g., dot center aligns with the center pixel of the image). The physical dot position ($x_{0,i}$, $y_{0,i}$) can be determined by known dot spacing a_{sp} with central dot at (0, 0). Record the values of φ_i and θ_i.
6. Repeat step 5 for all the dots on the physical target.
7. [Optional] Move the physical target to a different distance. A magnified physical target may be needed for a long target distance beyond 100 cm (see the Note in Sec. I). Repeat steps 5 and 6 for each target distance. If distance calibration is needed, repeat steps 2 to 6 instead.
8. Repositioning the LMD at the eyepoint of the other eyepiece and repeat the entire measurement.

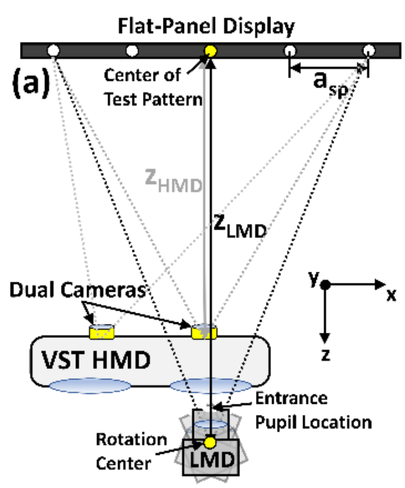

Figure A3. Schematic illustrations of the experimental setup for geometric distortion measurement on (a) dual-camera and (b) single-camera VST HMDs [3].

IV. Analysis

The following describes the analysis methods to compute VST geometric distortion following the image acquisition in Section III.

1. Assuming the virtual dot with angular position of (φ_i, θ_i) is backprojected to the depth distance z_{LMD}, compute the 2D position (x_i, y_i) of the virtual dot by
$$x_i = \tan\varphi_i \cdot z_{LMD} \text{ and } y_i = \tan\theta_i \,/\, \cos\varphi_i \cdot z_{LMD}.$$
2. Compute the distance error in vector space between the backprojected dot position to its real position ($x_{0,i}$, $y_{0,i}$) by
$$\vec{d}_i = (x_i - x_{0,i},\ y_i - y_{0,i})$$
3. Compute the absolute distance error between the backprojected dot position to its real position by
$$|d_i| = \sqrt{(x_i - x_{0,i})^2 + (y_i - y_{0,i})^2}$$
4. Repeat steps 1 and 3 for all the dots at position i.
5. Plot the 2D distance error map of the vector field $\vec{d}$ and absolute error $|d|$. See Fig. A4 as an example.

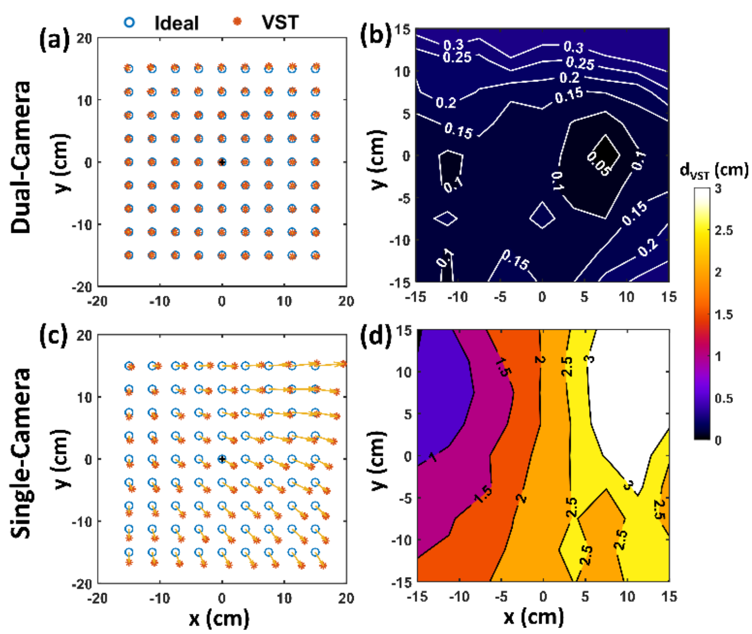

Figure A4. Example VST geometric distortion in 2D distance error maps in vector field (a,c) and absolute error (b,d) for dual-camera (a,b) and single camera (c,d) VST HMDs [3].

V. Reporting

For each eyepiece of the HMD (i.e., left and right), report the VST camera design (single-camera or dual-camera), dot array specifications (inter-dot spacing, dot diameter), measured target distance (z_{LMD}), 2D distance error map in vector field and absolute error with individual position records ($x_i, x_{0,i}, y_i, y_{0,i}$).

VI. References

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

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

[3] Zhao, C. and Beams, R., 2024. Geometric distortion on video see-through head-mounted displays. Journal of the Society for Information Display, 32(5), pp.184-193.