

A Comprehensive Crosstalk Characterization Method for Autostereoscopic Visualization

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Abstract

Minimizing crosstalk is essential for high-quality 3D visualization. This study proposes a dynamic protocol for crosstalk assessment of autostereoscopic visualization (ASV) that considers workspace-wide viewing effects, shifts in point of rendering (POR), and interpupillary distance (IPD) variations. Results show that the proposed method provides insights that could guide lens design optimizations and aid future advancements in 3D viewing quality.

Author Keywords

display; crosstalk; characterization; autostereoscopic visualization; lenticular lens.

1. Introduction

Autostereoscopic visualization (ASV) enables glasses-free three-dimensional (3D) visualization, omitting the need for wearable equipment (1). Instead, in these displays an embedded eye-tracking system calculates the 3D coordinates of the user's eyes that are transmitted to a 3D weaving algorithm. This algorithm mixes the left and right images of stereo pairs into a composite image. This image is then projected to the user through a lenticular lens sheet laminated in front of the display panel. This optical layer consists of plano-convex lenses that direct pixel light in certain directions (2). By knowing which pixel light ends up in which eye, the algorithm composes the image such that the left and right images are only visible to the respective eyes, creating depth perception (1-2).

Achieving high-quality 3D experience in (auto)stereoscopic displays may be significantly impacted by crosstalk. Crosstalk refers to the leakage of light, where pixels intended for one eye (partially) become visible to the other (1,4). This phenomenon can reduce perceived depth, degrade visual quality, and cause visual discomfort and ghosting (1,3,4). Crosstalk is the ratio of undesired to desired light measured in luminance for each eye at a given position. To maintain high 3D quality, crosstalk should be kept below 2% (1,4). Consequently, each lens design defines an optimal viewing zone relative to the display, where crosstalk is below this threshold.

However, in this viewing zone, crosstalk can arise from several factors, including incorrect lens lamination, eye-tracking errors, and variations in interpupillary distance (IPD) (5). For instance, improper lamination of the lenticular lens sheet can lead to misalignment between the pixels and their corresponding lenses, resulting in incorrect projection. Similarly, inaccuracies in the eye-tracking system can cause the display to miscalculate the position of the user's eyes, leading to increased crosstalk in the actual viewpoint. Furthermore, displays are typically designed for an average IPD of 65 mm (5). A person with a different IPD might experience an increase in crosstalk at the same viewpoint.

Understanding the effect of these potential sources of crosstalk is crucial for optimizing lens designs and 3D rendering. A comprehensive characterization protocol could help to assess systematically the 3D quality and the viewing experience of users.

2. State-of-the-Art in Crosstalk Measurement

Several studies have investigated the characterization of crosstalk to better understand its underlying mechanisms and mitigate its impact on viewer experience (4,6-9). Current measurement methods can be categorized into subjective and objective assessments. Subjective evaluations involve psychophysical experiments via user observation, where participants rate perceived crosstalk using test charts and Likert scale (4,7,9).

In contrast, objective measurements typically involve analyzing the spectral properties of light emitted by the display to quantify crosstalk artifacts (4,6). These procedures involve capturing images of the display while showing stereoscopic content, with the aim to quantify the leakage of light from the other image. In general, a camera or luminance meter is positioned in front of the display at a specific distance and angle to simulate the position of a viewer. Luminance meters can directly measure the light output of the display, while cameras need to be calibrated to be able to measure luminance. The captured images are then analyzed to quantify crosstalk by comparing the measured light intensity with the intended light intensity.

Standardized guidelines exist, including those from the International Standards Organization (ISO 9241-306: Ergonomics of Human-System Interaction), VESA (Flat Panel Display Measurements Standard (FPDM), Version 2.0) and the Society of Motion Picture and Television Engineers (SMPTE ST 2084 & ST 428-19). However, the limitations of these standards are that they primarily measure crosstalk at the optimal viewing point, neglecting variations that occur in real-world applications where users move around. This might suffice for displays intended for desktop use, where users are expected to remain relatively stationary. However, ASV can be used in dynamic environments, such as healthcare applications, where users may move around and view the display from varying positions.

Therefore, this paper proposes an automated and comprehensive characterization methodology that evaluates crosstalk throughout the viewing zone. Moreover, it enables characterizing how crosstalk changes when users move away from the rendered viewpoint. These findings can also provide crucial requirements for the accuracy of the eye-tracking system, enhancing the overall user experience. The overall requirements can be derived by measuring the allowed movement from the rendered viewpoint before exceeding the lower crosstalk threshold. Lastly, the proposed method allows the assessment of the effect of IPD variation across different users. The proposed methodology is demonstrated by conducting measurements on an autostereoscopic display with lenticular lens technology.

3. The Proposed Characterization Methodology

Measurement Setup: The characterization setup consists of an 4K, 27" autostereoscopic display (Barco NV, Kortrijk, Belgium), a PC, and an XYZ robotic system, as shown in Figure 1.

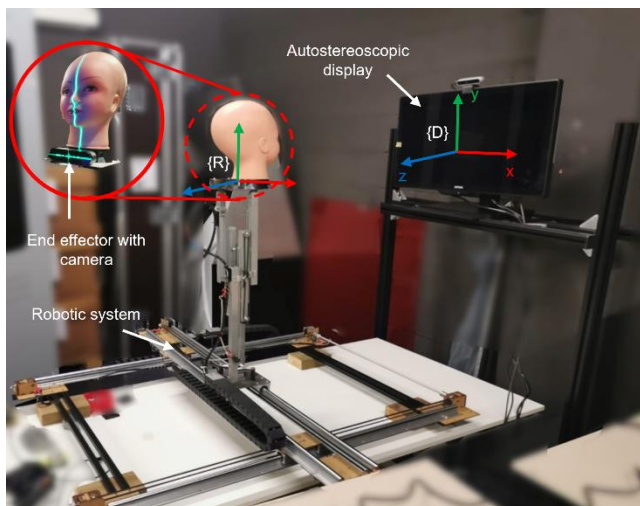


Figure 1. Overview of the characterization setup.

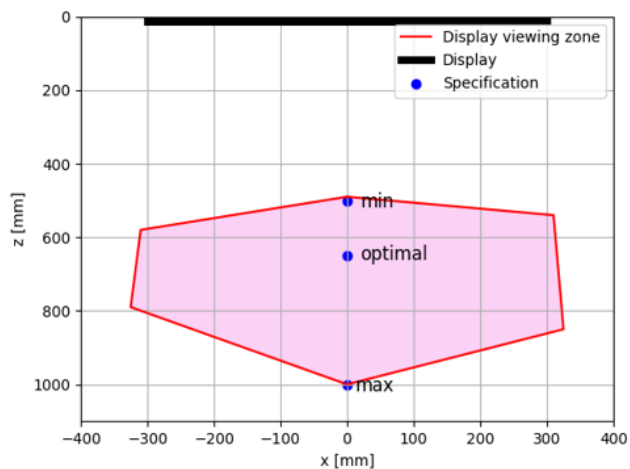


Figure 2. Optimal horizontal viewing zone of the investigated display.

The display had a minimum, optimal, and maximum viewing distance of 500, 650, and 1000mm, respectively. The width of the horizontal viewing zone was 600mm, as shown in Figure 2.

The robotic system can move its end effector in 3D space to a desired position while providing real-time positional feedback. The motion is actuated by stepper motors. The end effector is a Logitech Brio 4K camera (Logitech International S.A., Lausanne, Switzerland), that captures the visualized images across the viewing zone. The axes of the robot coordinate system $\{R\}$ are aligned with those of the display coordinate system $\{D\}$. The position of the end effector is determined by counting the steps taken by the stepper motors relative to a starting point p_0 . The origin p_0 of $\{R\}$ is defined at $[0, 0, 750]$ mm in the display coordinate frame $\{D\}$, coinciding with the center of the camera sensor. The range of motion for the end effector along the X, Y, and Z axes of the display coordinate frame $\{D\}$ is between $[-450, 450]$, $[-250, 250]$, and $[350, 1100]$ mm, respectively.

The data communication and collection were handled by a PC (Dell Precision 7550, Intel i7-10875H CPU, 32GB RAM, NVidia Quadro T1000 GPU). The PC could set the desired and read the current robot positions in real time through a custom developed Teensy 4.0 based controller board that was connected via a USB (VCOM) port to the PC. It could also set the point of rendering

(POR) for the display via another USB (VCOM) port. The camera was connected via a USB-C port to the PC.

Camera Calibration: Traditional luminance meters are typically limited to close-range measurements, making them inadequate for assessing crosstalk at greater distances. Therefore, the setup used an RGB camera. During calibration, a lookup table was created to convert RGB to luminance values, using a Barco LCD sensor (Barco NV, Kortrijk, Belgium) (9). The calibration procedure was done using custom software that displayed single-color images and recorded values from a luminance meter in the Yxy color space (10). Four image sets were registered, where the first contained grayscale images from black to white; the other sets modified the R, G, or B channels. The luminance meter was centrally positioned on the display, generating a lookup table of reference RGB and corresponding Yxy values. The camera was then placed at $[0, 0, 750]$ mm to capture the same images and calculate the mean RGB value of the image, allowing the creation of a table to convert captured RGB images to luminance.

When capturing grayscale calibration images close to pure white, saturation occurred, with the camera registering maximum RGB values of $[255, 255, 255]$ for input values higher than $[225, 225, 225]$, indicating limited dynamic range. To address this, a neutral density filter was applied to reduce light intensity without altering color. However, this led to saturation in darker values, necessitating an increase in camera gain to enhance resolution for darker shades. As the camera was positioned in the left eye's position, this adjustment allowed measuring with higher resolution in darker values, assessing whether crosstalk exceeded the maximum allowed 2% threshold. The camera settings were kept constant during the measurements.

Measurement Protocol: The measurements were conducted in a dark room to minimize ambient light interference. The visualized stereo image pair comprised of a single color black and white image, the former being projected to the left, while the latter to the right eye. The camera was always at the left eye's position, while the right eye coordinates were set with a constant offset, simulating the average IPD of 65mm. The Y coordinate of the camera was kept at 0, in the display's horizontal mid-plane.

The proposed measurement protocol is shown in Figure 3. The measurements are made at multiple positions by moving the camera using the robotic system, with position offsets that can be as small as the resolution of the actuator. For demonstration purposes, in this study the camera was positioned at fixed distances along the Z-axis, ranging from 500mm to 1000mm, with a step size of 50mm. At each of these distances, the camera was then moved along the X-axis, from -250mm to 250mm, with stops every 50mm to capture data at each position.

While mean crosstalk levels at various viewpoints provide useful data, eye-tracking errors can cause discrepancies between the display's POR and the actual eye position. To analyze how crosstalk changes with deviations from the correct POR, the width of the view projection lobe at the POR can be measured. Therefore, at each position the camera was kept stationary, while the POR was swept along the X, Y, and Z axes. First, the POR was swept along the X-axis from -65mm to 130mm relative to the camera, based on the standard IPD, to visualize crosstalk for both eyes. This sweep along the X axis also allowed for the assessment of crosstalk for different IPDs. Next, the POR was swept along the Y and Z axes from -200mm to 200mm relative to the camera, for a comprehensive measurement of crosstalk. A 5mm step size was used along all three axes.

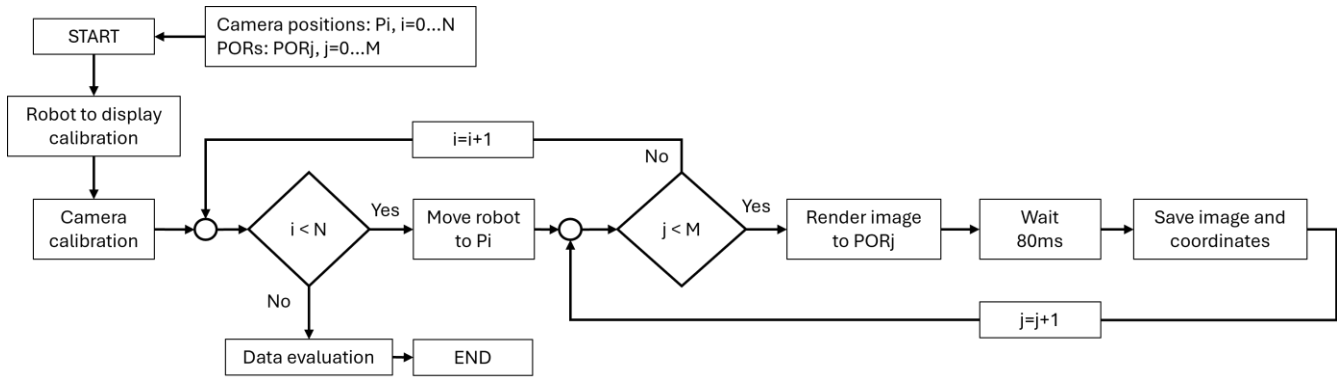


Figure 3. Flowchart of the measurement protocol.

Data evaluation: Through the sweeping of the POR, a crosstalk curve at each camera position is obtained along the three axes, showing how crosstalk changes as the eye of the user moves away from the POR. An example is shown in Figure 4. Based on this obtained data, three key aspects can be assessed, namely i) crosstalk, ii) width of projection lobe and allowed eye-tracking error along each axis, and iii) effect of IPD.

The measurements are only made at positions where the whole display area is visible on the camera image. The display area is segmented from the images and the mean RGB value is calculated. This RGB value is then converted to mean luminance using the look-up table, with linear interpolation applied between the nearest available values. Then crosstalk c is calculated as

$$c = \frac{L_{mean}}{L_{max}} 100 \quad (1)$$

where L_{mean} is the mean luminance of the segmented image and L_{max} is 350 cd/m^2 , the maximum luminance from the look-up table, corresponding to a fully white image.

Based on the crosstalk curves, the allowed eye-tracking error can be determined, by identifying the displacement at which crosstalk exceeded the 2% threshold. As the width of the lobe increases with increasing distance, the requirement is determined where the width of the lobe is the smallest, which is at the minimum viewing distance at 500mm.

Furthermore, while measurements are based on an IPD of 65mm, it can vary among individuals and can also shift dynamically within a user. For instance, eye convergence or divergence due to fatigue or changing gaze depth can subtly alter IPD. Such variations may affect the perceived 3D image quality, potentially impacting crosstalk levels. Based on the crosstalk curves, the effect of deviations from the IPD of 65mm can be observed. By moving left or right along the curve, crosstalk can be determined for smaller or larger IPDs, respectively. This data allows for determining the optimal viewing zone for different IPDs, by identifying where crosstalk remains below the acceptable threshold at different distances for a given IPD.

4. Results

Figure 4 shows a crosstalk curve illustrating the sweeping of the POR along the X axis. In this specific example, the camera is positioned at $[0, 0, 600]$ in mm along the X, Y and Z axes, respectively. When the POR coincided with the position of the camera, crosstalk was 0.7%. When setting the POR towards the left or the right of the camera position, crosstalk increased. When

setting the POR for example 65mm away from the camera, crosstalk was converging to 100%, as the image of the other eye became fully visible. The figure shows the captured images of the display at the three examples in the bottom row.

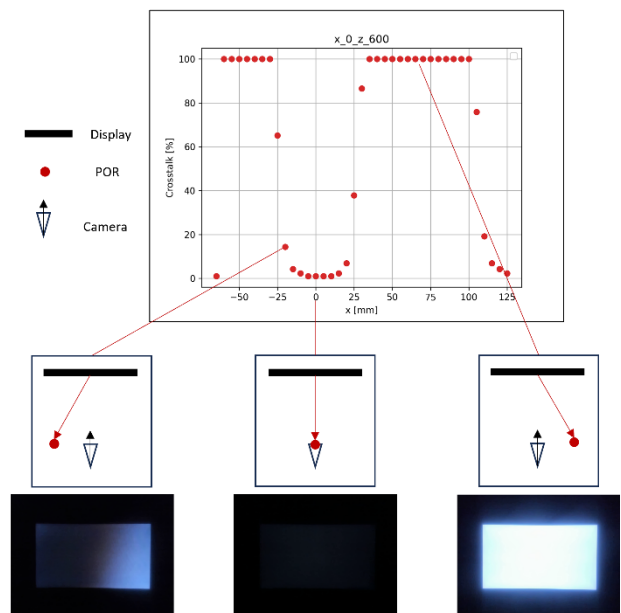


Figure 4. An example crosstalk curve illustrating the sweeping of the POR along X axis at 600mm distance.

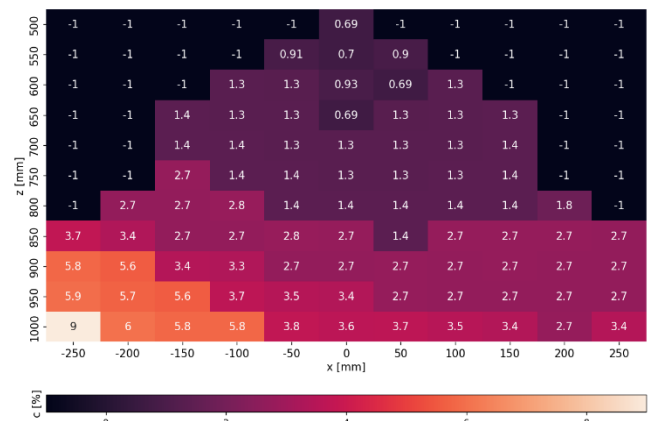


Figure 5. The crosstalk heatmap in the measured positions.

Figure 5 shows the resulting heatmap of the crosstalk characterization. The values represent when the POR coincided with the camera position. The graph shows the measured crosstalk levels in the horizontal workspace of the display, which is marked with the dashed green lines. The values -1 represent measuring points, where the display was not fully visible in the captured images, thus crosstalk was not assessed. It is visible that crosstalk is the lowest around the optimal viewpoint at 650mm. As the user would move further, crosstalk increases.

Effect of the IPD on the optimal viewing zone is shown in Figure 6. The display is designed for an IPD of 65mm. As the IPD decreases, the maximum viewing distance also decreases, and the optimal viewpoint shifts towards the display. In case of an IPD of 52mm, the maximum viewing distance becomes 700mm. When the IPD increases from 65mm, the minimum viewing distance increases to 600mm.

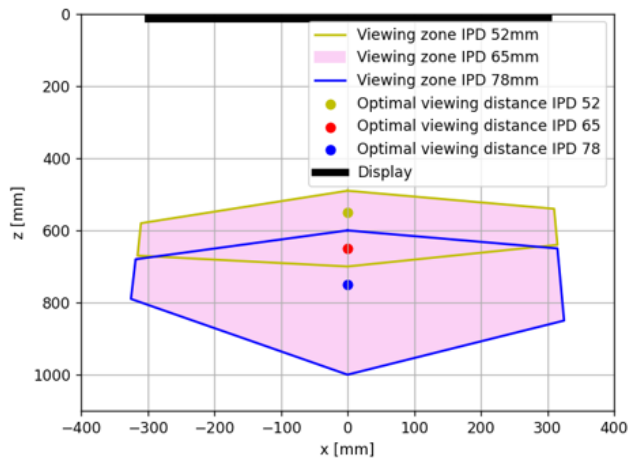


Figure 6. Change in optimal viewing zone for different IPDs.

5. Discussion

Overall, a novel crosstalk characterization methodology was proposed for autostereoscopic visualization. The measured crosstalk patterns aligned closely with the design parameters of the investigated display. As observed in the sweeping assessment along the X, Y, and Z axes, the shift in the minimal crosstalk point with respect to distance was in line with expectations, validating the reliability of the developed protocols. Although eye-tracking technology is used to increase the viewing zone of the display by re-rendering the view to the specific viewpoint, optimal viewing conditions were still observed around the ideal viewpoint. Therefore, in dynamic settings, where display positions may vary during use, it is required to highlight the importance of correct display positioning.

In comparison to state-of-the-art methods and industry standards, the primary advantage of the proposed multi-axis sweeping methodology is its comprehensive crosstalk analysis across the display's entire workspace. This approach allows for assessment of crosstalk behavior at various positions. By performing this sweeping assessment along multiple axes, the methodology effectively measures factors such as allowed eye-tracking error and the effect of IPD variations. These factors are crucial for maintaining visual quality across diverse user profiles and dynamic viewing positions.

A limitation of this analysis is the assumption of ideal viewing conditions in a completely dark environment, overlooking potential environmental factors that could impact crosstalk perception in

real-world settings. Another limitation of the measurements was the camera used, as it could not capture the full dynamic color range, leading to a compromise to have high resolution for dark values but saturation in near white values. Future work should also involve the measurement of crosstalk dynamics introduced by system latency. System latency is the overall delay from capturing the image of the user until the visualization of the image to the specific viewpoint. In case the user moves fast to a new viewpoint, this overall latency could affect the perceived image with increasing crosstalk. Lastly, the camera's and the display's Z axes were kept parallel during the measurements, which may differ from real-world scenarios where the viewing angle can vary, potentially affecting the perceived crosstalk. In a next step, the effect of viewing angle should be assessed by rotating the end effector about its vertical Y axis.

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7. References

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