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Effects of head-display lag on presence in the Oculus Rift

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Abstract

We measured presence and perceived scene stability in a virtual environment viewed with different head-to-display lag (i.e., system lag) on the Oculus Rift (CV1). System lag was added on top of the measured benchmark system latency (22.3 ms) for our visual scene rendered in OpenGL Shading Language (GLSL). Participants made active head oscillations in pitch at 1.0Hz while viewing displays. We found that perceived scene instability increased and presence decreased when increasing system lag, which we attribute to the effect of multisensory visual-vestibular interactions on the interpretation of the visual information presented.

Disciplines

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Method for estimating display lag in the Oculus Rift S and CV1

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ABSTRACT

We validated an optical method for measuring the display lag of modern head-mounted displays (HMDs). The method used a high-speed digital camera to track landmarks rendered on a display panel of the Oculus Rift CV1 and S models. We used an Nvidia GeForce RTX 2080 graphics adapter and found that the minimum estimated baseline latency of both the Oculus CV1 and S was extremely short (~2 ms). Variability in lag was low, even when the lag was systematically inflated. Cybersickness was induced with the small baseline lag and increased as this lag was inflated. These findings indicate the Oculus Rift CV1 and S are capable of extremely low baseline display lag latencies for angular head rotation, which appears to account for their low levels of reported cybersickness.

CCS CONCEPTS

• Displays and imagers • Visualization design and evaluation methods • Empirical studies in visualization

KEYWORDS

Virtual Reality, VR, Oculus Rift, Display Lag

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1 Introduction

Recent escalation in commercial uptake of HMDs is attributed not just to manufacturer advertising of high refresh rates and high pixel resolution, but also very low display lag – the time delay required to generate a compensatory change in the display for a change in angular head orientation (i.e., motion-to-photon delay). Indeed, high display lag has been found to generate perceived scene instability and reduce presence [Kim et al. 2018] and increase cybersickness [Palmisano et al. 2017].

New systems like the Oculus Rift CV1 and S reduce display lag by invoking Asynchronous Time and Space Warp (ATW and ASW), which also significantly reduces perceived system lag by users [Freiwald et al. 2018]. Here, we devised a method based on a previous technique [Kim et al. 2015] to ascertain the best approach to estimating display lag and its effects on cybersickness in modern VR HMDs.

2 Method

We deconstructed the Oculus Rift CV1 and S by removing the right Fresnel eyepiece of the HMD1, exposing a display panel operating at its native resolution. The head strap and ear pieces were temporarily removed to allow for direct line of sight to the panel. A custom 3D-printed plate fitted with ball bearings was mounted to the base of the headset to provide free movement within the XY plane. One end of a 3D-printed y-bracket was attached to the top of the HMD with the other end connected to a retort stand to constrain its movement to a circle with a radius equivalent to the fore-aft depth of a human head (see Figure 1).

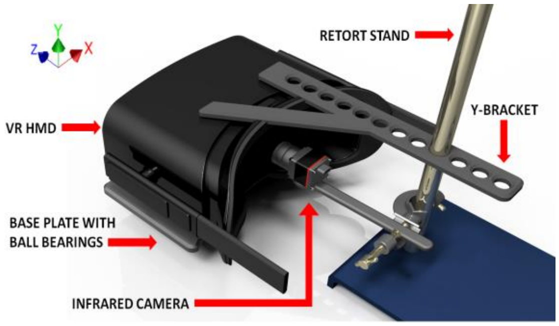

Figure 1: Schematic of the setup and constrained HMD

A custom OVRLib program performed GPU rendering of two small 32p × 32p black patches against a grey background on each display. One patch was rendered at a constant position near the display's centre (reference patch). Another adjacent patch moved linearly along the y-axis as a function of the HMD's yaw

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orientation (delay patch). We used an Earth-fixed digital camera (Blackfly S, FLIR) to optically track both reference and delay patches on the same display. Tracking the relative displacement of both patches in the video provides an estimate display lag independent of the camera's inherent latency. The camera's CMOS sensor has varying sensitivity to different lighting parameters. To test whether this influences lag estimates, we also used reference and delay patches that varied in contrast polarity against the grey background.

A memory buffer was used to artificially increase display lag, and variability in lag was measured over 12 × 2 s sample windows of HMD oscillation. To assess cybersickness, self-motion in depth was simulated on the Oculus Rift S using random-dot flow (18,432 dots). 20 participants were presented with 4 randomised scenes with varying amounts of artificially added display lag. They performed yaw head oscillations (in time with a 1 Hz auditory tone) and then rated their cybersickness using the Fast Motion Sickness (FMS) scale [Keshavarz and Hecht, 2011].

3 Results

Results of mean cross-correlation and 95% confidence intervals (CI) between the measured horizontal motion on the reference patch and vertical motion of the delay patch are shown in Figure 2 for the Rift S. A temporal offset of -2.3 ms was required to minimize the correlation of these inverse signal profiles after cubic spline interpolation of the recorded time-series data.

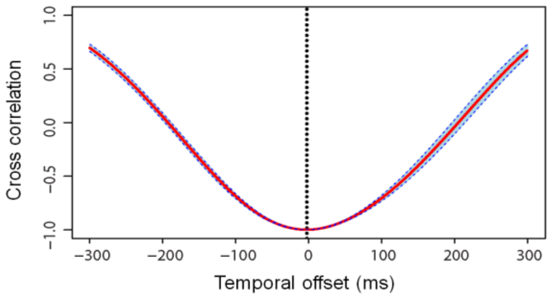

Figure 2: Benchmark latency estimate of the Oculus Rift S

The same method achieved a similar benchmark level of -1.8 ms for the Oculus Rift CV1. Figure 3 shows the result of artificially increasing display lag by increasing the size of a memory buffer to store HMD sensor data for delayed rendering. The patches of inhomogeneous contrast polarity (open points and dashed line) generated inflated estimates of display lag, compared with tracking two dark patches of homogenous contrast polarity (grey points and solid line). When we inflated the buffer size to 40, the display lag estimate increased to 207 ms for homogenous contrast polarity patches. However, the 95% CI for this estimate was approximately 1.5 ms and was not considerably greater than for the benchmark lag (0.4 ms 95% CI), suggesting these systems are highly consistent in their performance output.

Mean sickness severity increased significantly as system latency was added incrementally as shown in Table 1. Even for the benchmark lag, a small amount of cybersickness was still reported on average (1.25) across our cohort of 20 participants, $t(19)=2.84$ ($p < .05$). Reported mean FMS scores are out of 20 (where, 0 = no sickness at all; 20 = frank sickness).

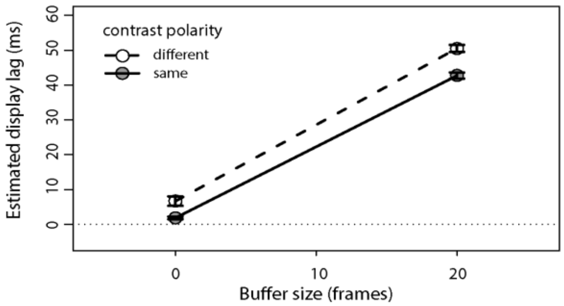

Figure 3: Display lag estimates for the Oculus Rift CV1

Table 1: Cybersickness increases with artificially inflated lag

Lag(ms)	2.68	58	117	176
Mean FMS	1.25*	3.35**	4.40**	4.80***
95% CI	±0.92	±1.66	±1.98	±2.01

$^{*}p < 0.5$ $^{**}p < 0.005$ $^{***}p < 0.001$

4 Discussion and conclusions

The proposed method for estimating display lag in high-performance HMDs was optimal for tracking landmarks of locally dark luminance contrast. This is presumably due to small variations in the photometric response of the CMOS image sensor to different light intensities. The Oculus Rift CV1 and S have relatively low display lags, attributed to the engagement of ATW and ASW inherent in the operation of these systems. However, cybersickness was still reported even at low latencies (albeit very low severity) and increased with display lag. Our findings suggest that under optimal conditions these systems compensate for *angular* head rotations almost perfectly, but their performance for *linear* head translations remains to be determined and perceptually quantified.

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