Quest 3S Immersive Display with High Visual Fidelity

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Abstract
In October 2024, Meta introduced the Meta Quest 3S mixed reality headset, providing the same display resolution as Quest 2 while prioritizing visual fidelity enhancements. These advancements include: 30% rendering resolution improvement, 14% latency reduction, advanced display imaging algorithms for contrast improvement, and 350% higher pass through resolution with an enhanced color experience.

Author Keywords
Meta Quest 3S, Immersive Display, Mixed Reality, Virtual Reality, LCD, Visual Fidelity, Pass through

1. Introduction
Meta is at the forefront of developing the metaverse, a groundbreaking digital realm that converges virtual and augmented realities to redefine human interaction and connectivity.

A fundamental pillar of the metaverse is the immersive display, which plays a vital role in elevating user experience by seamlessly merging the virtual and real worlds. This fosters unparalleled engagement and fundamentally reshapes our perception and interaction with digital environments.

In 2020 and 2022, Meta released the Quest 2 [1] and Quest Pro [2] devices, followed by the Quest 3 [3], all of which integrate effortlessly with Meta's vision for the metaverse. These devices offer users an immersive gateway to a transformative digital world where connectivity, interaction, and exploration reach unprecedented heights. Building upon the successes of its predecessors, the Quest 3 boasts cutting-edge features, unparalleled performance, and a commitment to redefining virtual and mixed reality.

In 2024, Meta launched the Quest 3S [4], expanding the success of mixed reality to a broader audience with a more affordable price point while maintaining high display performance and visual fidelity. With the Meta Quest 3 and Quest 3S, Meta is leading the charge in shaping the future of the metaverse, empowering users to explore new dimensions of virtual reality (VR) and mixed reality (MR).

This paper delves into the technical details of the Quest 3S Immersive Display system, focusing on enhancements that improve visual fidelity. By pushing the boundaries of display technology, Meta continues to revolutionize the metaverse experience, unlocking new possibilities for users worldwide.

One of the fundamental pillars of the metaverse is the immersive display. The immersive display plays an important role in enhancing user experience by seamlessly blending the virtual and real worlds, fostering unparalleled engagement, and fundamentally reshaping our perception and interaction with digital environments.

Figure 1. Meta Quest 3S

2. Quest 3S Display System Architecture
The Quest 3S leverages the proven display and optical design of the Quest 2, featuring a single high-resolution liquid crystal display (LCD) paired with two separate backlights (one for each eye) and two distinct Fresnel lens systems. Table 1 lists the major display specification comparison between Quest 2, Quest 3S and Quest 3.

Specifications	Quest 2	Quest 3S	Quest 3
Display type	Fast-Switch (FS) LCD		
Pixel density per eye	1832x1920	1832x1920	2064 RGB x 2208
Display resolution	773 PPI | 20 PPD	773 PPI | 20 PPD	1218 PPI | 25PPD
Optics	Fresnel lens	Fresnel lens	Pancake lens
Pass through	Mono color,, 4PPD	Full color, 18PPD	Full color, 18PPD
Color gamut	sRGB	sRGB	sRGB

Table 1. Specifications of Meta Quest 2, Quest 3, and Quest 3S Displays

To deliver exceptional immersive VR and MR experience, We optimize the Quest 3S display systems by prioritizing several key aspects: enhancing display clarity, reducing artifacts, minimizing motion-to-photon latency, and achieving a seamless MR passthrough experience.

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One significant improvement is the display clarity enhancement. By utilizing Qualcomm SoC XR2 Gen2's computational capabilities, Quest 3S achieved a 30% increase in display rendering resolution, compared with Quest 2. This substantial boost in image clarity further elevates the overall visual fidelity of the Quest 3S.

3. Visual Fidelity Improvement

Building on the Quest 3S display system architecture, Meta has optimized the display system from the following four perspectives, to further refine the immersive visual performance.

(a) Display ghosting

For the VR/MR HMDs, dynamic motion artifact attracts a lot of attention, one of the types is the display ghosting (also called "Motion blur"). Display ghosting is a visually perceivable artifact that manifests as double images or trailing effects when users rapidly move their heads or observe fast-moving objects without corresponding head movements. This occurs when the display fails to refresh pixels quickly enough to keep pace with images in motion, resulting in a smeared appearance.

In LCD HMDs, display ghosting arises when the backlight turns on before liquid crystal is fully settled, or the duty cycle is too high; while in µOLED HMDs, it occurs when the display's duty cycles (persistence) are too high [5]. To mitigate display ghosting in LCD HMDs, several optimization strategies can be employed: reducing panel scan time and backlight on-time, minimizing display response time, and optimizing backlight timing.

In the Quest 3S HMD, we have successfully mitigated display ghosting by implementing two key optimizations: reducing backlight on-time and fine-tuning backlight timing. These adjustments enable a smoother visual experience, free from the distracting effects of display ghosting.

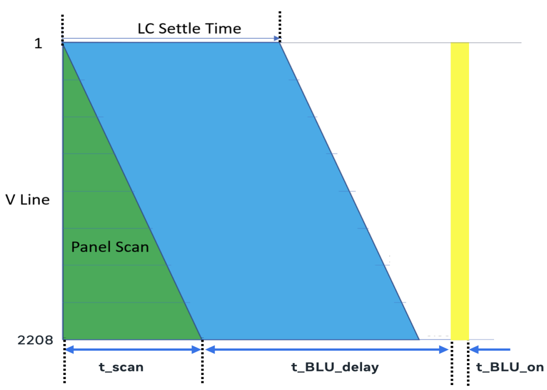

Figure 2. Typical display timing scheme in LCD HMDs

Display ghosting is further optimized via temperature-dependent backlight control. This technique involves tuning the BLU timing with temperatue. , as depicted in Figure 3.

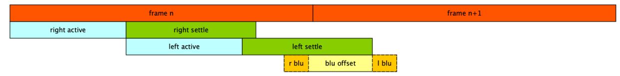

Figure 3. Quest 3S BLU timing

In order to maintain user comfort, the left-right disparity between the flash time for each eye (the 'BLU offset') should be constrained. The maximum left-right backlight disparity and the temperature-to-BLU-delay functions were determined. A virtual temperature sensor was implemented to update the backlight timing accordingly.

(b) Content adaptive duty control (CADC)

LCDs inherently exhibit limited contrast ratios due to backlight leakage, a fundamental limitation of the technology. In VR devices, this issue is further exacerbated by light reflection and scattering between the displays and lenses, resulting in an even more pronounced degradation of contrast. We developed an algorithm called content adaptive duty control (CADC), concept. The algorithm dynamically adjusts the pulse width modulation (PWM) of the backlight depending on content. the algorithm was carefully implemented to ensure uniform optical performance frame to frame.

With the content adaptive duty control algorithm implemented, the HMDs could achieve higher perceived contrast while reducing the power consumption. The algorithm saves more power when input images are darker.

(c) Motion to Photon latency

In VR/MR, an immersive experience is paramount, aiming to create a sense of physical presence in a digital world with minimal delay. One Important parameter for achieving immersion is motion-to-photon latency (MtPL). From a user's perspective, MtPL refers to the time elapsed between their head movement and the corresponding display output reflection on the HMD.

MtPL plays a vital role in ensuring visual comfort during extended usage of MR HMDs [6]. Ideally, this latency should be below the human perception threshold, rendering it imperceptible. However, due to the complexity of the VR/MR pipeline, real-world systems often exhibit significantly longer MtPL. Consequently, there is a pressing need to reduce latency from the end-user experience standpoint, thereby enhancing overall immersion and comfort.

In the Ref [3], knobs to reduce the MtPL in LCD HMDs were discussed. In Quest 3S, based on the unique display architecture, we reduce the latency by (1) reducing BLU on time, (2) optimizing GPU rendering, and (3) applying temperature-dependent BLU timing as described above to the single-panel dual-BLU architecture. By applying these techniques, we achieved an improved latency performance compared to both Quest 2 and Quest 3.

As discussed in section (a), with longer LC settle time, display ghosting performance is better, and inherently increases the latency. Given the physical nature of liquid crystal, the response time is faster at high temperature, so we introduced the temperature dependent BLU timing feature, to optimize the LC settling time at different display temperatures. This feature could achieve latency reduction, while maintaining imperceivable display ghosting.

(d) MR passthrough performance

For MR see-through applications, besides the display HW, cameras resolution and MR rendering pipeline are crucial to provide a more immersive environment for a greater number of users. In Quest 3S, we used the same camera set as Quest 3, to achieve high passthrough MR resolution, and full color experience.

Intrinsically, both the display and camera subsystem have device and device color variation, and such variation can cause degraded color performance for both VR and MR experience. To tackle this problem, both the display and camera subsystems have gone through module level calibration and system calibration, respectively. . The thermal impact has been taken into consideration during the calibration process. With this calibration, the display subsystem ensures a pleasing visual experience for both VR and MR user scenarios.
For the camera subsystem, disparity between left and right are measured and compensated. Beyond the display and camera calibration, image quality tuning is carried out on the HMDs to guarantee the MR visual experience for the customers.

4. Specification and Performances

(a) Display ghosting

Display ghosting performance was carefully evaluated through the UXR study. The optimized BLU on time, and BLU timing was proven to achieve unperceivable display ghosting, even at cold start.

(b) CADC performance

With the algorithm, we achieve the display backlight power save up to 35% compared to Quest 2. More importantly, the algorithm improves contrast up to 50%, which appears as significant perceived contrast enhancement as shown in Figure 4.

Figure 4. Quest 2 without CADC (left) vs. Quest 3S with CADC (right)

(c) Latency performance

Although the Quest 3S uses the same display system design as Quest 2, by HMD level optimization, and BLU timing optimization, we have achieved the latency performance 14% better than Quest 2. Also, the latency performance of Quest 3S is 8% better than Quest 3.

(d) MR passthrough performance

With all the display/camera calibration and image quality tuning we have done, Meta Quest 3S features the same MR experience as Quest 3, and a leap from black and white passthrough to color passthrough compared to Quest 2.

5. Conclusion

The VR and MR landscapes are evolving towards wearability, with a focus on expanding the user base and enhancing overall experience. Display technology is making significant advancements in resolution, refresh rate, visual fidelity, as well as eye comfort, to support this trend.

This paper presents a suite of cutting-edge technologies designed to achieve high visual fidelity, seamless MR passthrough, and low-latency display, ultimately providing an immersive experience on the Quest 3S.

As our display technology continues to push boundaries, we are committed to bringing next-generation display innovations to life for Meta's future VR/MR products. By harnessing these advancements, we aim to further blur the lines between the physical and digital worlds, redefining the possibilities of immersive experiences.

6. Reference

[1] Kim C., Klement A., Park E., Han J., Rao L. and Zhuang J. (2022), High-ppi Fast-Switch Display Development for Oculus Quest 2 VR Headsets. SID Symposium Digest of Technical Papers, 53: 40-43. https://doi.org/10.1002/sdtp.15410

[2] Rao L., Park Y., Klement A., Kang C., Park E., Zhuang J., Kim C., Chiu H., Ning R., Wang D., Shen S. (2023), Infinite Display for Meta Quest Pro. SID Symposium Digest of Technical Papers, 54: 32-35. https://doi.org/10.1002/sdtp.16480

[3] Lee, A., Chiu, H., Xiang J., Klement A., Park Y., Varel C., Lin W., Sulem F., Huh B., Malachi N., Fulghum M., Zhu X., Rao L., Choi J., Zhuang J., (2024), 90-1:Invited Paper:Quest 3 Immersive Display with High PPI and Hybrid Backplane Technology. SID Symposium Digest of Technical Papers, 55: 1258-1261. https://doi.org/10.1002/sdtp.17772

[4]Meta homepage: https://www.meta.com/quest/quest-3s/

[5] Zhao, C., Kim, A.S., Beams, R. et al. Spatiotemporal image quality of virtual reality head mounted displays. Sci Rep 12, 20235 (2022). https://doi.org/10.1038/s41598-022-24345-9

[6] Wagner D., “Motion To Photon Latency In Mobile AR And VR,” https://medium.com/@DAQRI/motion-to-photon-latency-in-mobile-arand-vr-99f82c480926, [Online; accessed 2022-10-14