Q-VR: System-Level Design for Future Collaborative Virtual Reality Rendering

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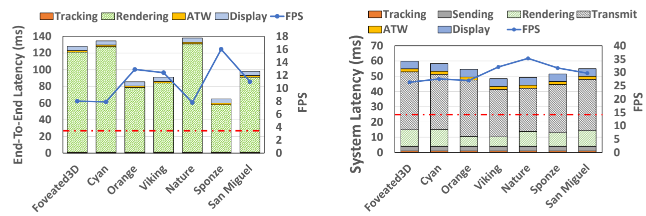
1. Motivation

Since the release of the movie *Ready Player One*, consumers have been longing for a commercial VR product which could provide a truly immersive experience without mobility restriction and periodical motion anomalies. In other words, users require exceptional visual quality from an *untethered* mobile-rendered head-mounted displays (HMDs) that is equivalent to what high-end tethered VR systems (e.g., Oculus Rift [15] and HTC Vive [7]) provide. Although the current mobile's processing capability has been significantly improved [1,16], they still cannot fully process heavy VR workloads under the stringent runtime latency constraints. With the development of high performance server technology, server-based realtime rendering of Computer Graphics has been introduced by the recent architecture studies [8, 10, 23, 24] and major cloud vendors [5, 14]. However, under the current network conditions, remote servers alone cannot provide realtime low-latency high-quality VR due to the dominating communication latency. Fig.1 shows the breakdown of the *end-to-end latency* (i.e., from tracking to display) for executing several high-quality VR applications under two commercial mobile VR designs: *local-only rendering* and *remote-only rendering*. The blue lines represent the frame rate (FPS) achieved on the VR HMD while the red dash lines illustrate VR system latency restriction (i.e., commercial standard of 25ms). The figure shows that the performance on the integrated GPU is the key bottleneck for local-only rendering, while the transmission latency in remote-only rendering contributes to approximately 63% of the overall system latency. Thus, neither local-only nor remote-only rendering can satisfy the latency requirements for high-quality mobile VR: there is a clear mismatch between hardware's raw computing power and desired rendering complexity.



(a) Local-only rendering (b) remote-only rendering

Figure 1: System latency and FPS when running high-end VR applications on two types of mobile VR system designs.

2. Limitations of the State of the Art

To address the latency and bandwidth challenges of today's dominant mobile rendering models, it seems reasonable to utilize mobile VR hardware's computing power to handle part of the rendering workload near the display HMD to trade off for reduced network communication, while letting the remote system handle the remaining workload. But how to design such VR systems to reach the latency and perception objectives is still an open problem. Recent studies [3, 9, 11–13] proposed a static collaborative software framework that renders the interactive objects locally while offloading the background environment to the remote servers. However, after a thorough qualitative investigation into its architecture-level rendering pipeline and a quantitative latency bottleneck analysis (Sec.2.3), we observe that this naive rendering scheme faces several challenges. First, interactive objects have to be narrowly defined by programmers on each hardware platform to satisfy the "worst case" scenario during VR development which significantly limits the design possibilities for high-quality interactive VR environments and burdens programmers to accommodate all the realtime constraints during the development cycle. It is labor intensive and impractical. Second, since the remote rendering workload remains unchanged, this scheme cannot drastically reduce the communication latency. Third, it loses the flexibility to dynamically maintain the balance between the local and remote rendering latency under realtime uncertainties: unpredictable user inputs (e.g., interaction and movements) and environment changes (e.g., hardware and network). Finally, it suffers from high composition overhead by requiring more complex collision detection and embedding methods [3, 9], directly contributing to resource contention on mobile GPU(s).

3. Key Insights

Unlike the previous pure software solutions, we explore how to build an efficient collaborative rendering pipeline for high-quality VR through a thorough workload characterization and a qualitative VR execution pipeline analysis (Sec.2.3). We summarize the following key design goals: (1) reducing the overall communication data size to decrease the global impact from remote rendering and transmission latency; (2) dynamically balancing local and remote rendering latency based on realtime constraints for optimal resource utilization and rendering efficiency; and (3) significantly reducing or even eliminating realtime hardware contention on the execution pipeline to further improve FPS. To reach these goals, we argue that the best strategy should be a *soft-hardware co-design solution* that transforms this complex VR execution problem into a cross-layer system design and optimization problem. To achieve (1), we propose a software framework design (Sec 3) based on two key insights: (a) human visual acuity falls off from the centre (called *fovea*) to the *periphery* [17, 19] and different acuity level requirements of human visual system naturally generate a new workload partitioning mechanism for collaborative VR rendering; (b) modern mobile SoCs are capable of dynamically rendering a range of workloads (or fovea sizes) with fine details and high resolutions, determined by realtime constraints. To achieve (2) and (3), we propose two novel hardware component designs. For (2), we discovered that there is a strong correlation between VR motion features and realtime hardware-level intermediate data, which can be leveraged to describe the scene complexity change and help dynamically build a strong mapping between environmental conditions and rendering workload (Sec.4.1). For (3), we observe that the major pipeline contention is caused by the resource competition on GPU(s) from the following concurrent executions: rendering, composition and asynchronous timewarp (ATW). We further discover that there is an algorithmic-level similarity between composition and ATW so that we can combine them through execution pipeline reordering to enable an asynchronous execution with GPU(s) for further improving the overall FPS (Sec.4.2).

4. Main Artifacts

In this paper, we propose a novel *software-hardware co-design for low-latency high-quality collaborative mobile VR*, named *Q-VR*, which effectively leverages the processing capability of both local and remote rendering hardware. At the software level, new interfaces and programming model are designed and integrated to Q-VR so that it can leverage the foveation effects of the human vision system [6, 18, 20–22] to enable a dynamic collaborative rendering framework for fine-grained rendering workload tuning and network latency reduction, while maintaining user perception (Section 3). The software-layer design also transforms this complex global collaborative rendering problem into a workable framework so that deeper hardware pipeline-level optimizations are possible. Specifically, at the hardware layer, based on the key insights above, we design a *lightweight interaction-aware workload controller* (Sec.4.1) and a *unified composition and reprojection unit* (Sec.4.2), to achieve two optimization objectives: (1) quickly reaching the local-remote latency balance for each frame to achieve the optimal rendering efficiency; and (2) further optimizing the global collaborative rendering pipeline for better architecture-level parallelism. To implement and evaluate the proposed Q-VR hardware design, we extend ATTILA-sim [2], a cycle-accurate rasterization-based GPU rendering simulator. Specifically, we implement simultaneous multi-projection engine in ATTILA-sim to support two-eyes VR rendering similar to [23] and reconfigure it by referencing the ARM Mali-G76 [4], a state-of-the-art high-end mobile GPU. Refer to Sec.5 for the detailed evaluation methodology.

5. Key Results and Contributions

As Sec.6.1 demonstrates, Q-VR achieves an average of **2.2x** (up to **3.1x**) end-to-end performance speedup and a **4.1x** frame rate improvement over the static collaborative rendering design. The runtime traces and sensitive study in Sec.6 show that Q-VR is able to help the system quickly reach local-remote balance under different user inputs and realtime environment constraints. Furthermore, Q-VR achieves an average of 73% energy reduction over the local rendering design. To summarize, the paper makes the following contributions:

- We design the first software-hardware co-designed collaborative rendering architecture to tackle the mismatch between VR hardware processing capability and desired rendering complexity from a cross-layer systematic perspective;
- We identify the fundamental limitations of the state-off-the-art collaborative rendering designs and quantify the major bottleneck factors via detailed workload characterization and VR execution pipeline analysis;
- By leveraging the foveation features of human visual system, we explore the software-level flexibility to reduce the network limitation via a fine-grained dynamic tuning space for workload control while maintaining user perception;
- Based on our key observations on VR motion correlations and execution similarity, we design two novel hardware components to support software-layer interfacing and deeper pipeline-level optimizations.

6. Why ASPLOS

Future collaborative mobile VR is a system design and optimization problem, requiring aggressive co-optimization of graphics algorithms, networking, vision, architecture and wireless. Necessarily there is no single expert on every aspect of it; in this paper we capture the current system level constraints and see what role jointly modifying the hardware and software can play, which makes perfect synergy with ASPLOS's long efforts on multidisciplinary ground-breaking research. From the the perspective of research scope, Q-VR is a quintessential ASPLOS paper, representing the intersection between software-hardware co-design and emerging applications. It also includes case studies of real-world experimental systems.

7. Citation for Most Influential Paper Award

In this work, authors propose the first software-hardware co-designed collaborative rendering architecture to tackle the mismatch between VR hardware processing capability and desired rendering complexity, from a cross-layer systematic perspective. Their solution has provided a possible pathway to design future low-latency high-quality mobile VR systems and paves the road for other research in computer system/architecture to be proposed for this very important area.

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