

Cloud VR

Secure Fast and Distributed Virtual Reality Solutions

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2 Abstract

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4 List of Abbreviations

Acronyms

FoV Field-of-View. 12

GPU Graphics Processing Unit. 3, 9, 14

HMD Head Mounted Display. 11, 12

MS Milliseconds. 8, 11, 12

MTP Motion-to-Photon. 11, 12, 14

RGB Red Green Blue. 8

UX User Experience. 11, 14

VR Virtual Reality. 6, 7, 9, 10, 11, 12, 14

5 Introduction

Recent developments in the field of Virtual Reality (VR) offer all kinds of opportunities in the field of training and entertainment. For training purposes, the audiovisual entry into a virtual world is where the biggest value is. The capabilities of artificial environments allow users to manage scenarios and experiences that cannot be simulated in the real world. VR also allows users to access the virtual training at any time and less physical facilities are required for exercises. Examples VR experiences include training maintenance at high altitudes (such as windmills), working under heavy loads weather conditions in construction (Strukton) or maintenance on naval ships (Thales).

6 Preliminary Problem Statement

One of the essentials for a good Virtual Reality (VR) experience is a powerful computer system to render semi-realistic worlds. However, there are two problems here. First, this type of system is not available in every location. Certainly if realistic images have to be rendered in the simulation, it requires specialized and expensive machines that are difficult to move.

The second problem is that for rendering the VR training scenario, all kinds of data about the scenarios need to be available on the system. This can pose a problem when it concerns sensitive information, for example about all kinds of information defense systems or business sensitive information.

Focusing on these problems will lay the foundation for future research, to make CloudVR streaming a mature technology.

The aim of this project is to investigate the feasibility of a streaming based VR approach with current cutting edge technology. Qualitative research methods will be used to gain in-depth insights about existing solutions and the current state of research into this topic. The data will be contextualized via a literature review of recent research papers and an analysis of the capabilities of existing solutions when applied to the research problem.

7 Problem Analysis

Together with the companies from the Industrial Reality Hub mentioned in the Introduction, Saxion wants to investigate how virtual reality can be rendered in the cloud in a safe and efficient manner. This involves looking at state-of-the-art technology in the field of virtual reality, cloud computing, rendering and machine learning for one complete CloudVR pipeline. There are four research objectives here:

7.1 Architecture for a cloud system

One of the questions to be answered is what the CloudVR architecture should look like in terms of hardware and software. This not only concerns the servers, but also whether there are local ones rendering is required (see the next point).

7.2 Latency

Current market players such as Google Stadia (Google, n.d.-b), GeForce Now (Nvidia, n.d.-b) and Xbox xCloud (XBox, n.d.) already offer cloud gaming services that stream games over the internet. Powerful servers are used for rendering games that are then streamed to users in real time. A bottleneck with this technology is the latency (delay). This is because user input is first sent to a server, which renders these new images, after which they are sent back to the users, all without disturbing them. The mentioned platforms all use network optimization. Low latency is very important for VR, where head movements should be converted to images in under 20 Milliseconds (MS), to prevent motion sickness. The research for techniques for reducing latency is one of the spearheads of the CloudVR project. The following research directions are relevant here:

Network optimization As with the platforms described above, network optimization is one of the techniques which needs to be investigated. The question is to what extent an optimized network can reduce latency and how it relates to the quality of the network connection.

Two-step rendering One of the options to bypass latency is to render in two steps. The delay is not so much reduced, but avoided. The server renders next to RGB also positions and BRDF variables for each pixel. Afterwards, the user, on less powerful hardware, adjustments are made so that the image corresponds to the current position of the user.

Behavioral prediction Another possibility to reduce latency is by predicting user input through machine learning. This will mainly revolve around it analyzing head movements to find out what behavior can be expected. With this information we can render any part of the virtual world before it is viewed

by users. If this information is then forwarded from the cloud to the location of the VR experience, what information is displayed can be selected on the spot.

7.3 Multi-user experiences

One of the questions with a CloudVR solution is how to deal with multi-user VR experience where users at another location share a VR experience via a network. The interaction with each other and the environment are a point of attention.

7.4 GPU scaling

One of the advantages of cloud rendering is that in theory it gives the possibility of unlimited computing capacity. This gives the opportunity to all kinds of touristic feats (graphic), and interaction (physics). It is therefore interesting as part of the CloudVR pipeline to investigate how techniques such as NVLink and NVSwitch 5 could be used for high-quality VR experiences.

8 Theoretical Framework

In order to thoroughly understand the aim and subject of the research, it is important to explore different existing solutions and literature. Therefore, the subjects that will be discussed in the following theoretical framework are Cloud Streaming/Cloud Computing and Virtual Reality. Within this theoretical framework, definitions of the subjects will be given as well as current insights into these subjects. The topics reflect knowledge needed to understand the problem space. Together all of the topics make up the 360 scan.

8.1 Cloud Streaming/Cloud Computing

8.1.1 Definition

According to Armbrust et al. (2010) Cloud computing is defined as follows: "Cloud computing refers to both the applications delivered as services over the Internet and the hardware and systems software in the data centers that provide those services." (Armbrust et al., 2010) We can then further define Cloud streaming as the applications that are delivered over the internet as a service.

8.1.2 Existing Solutions and Technology

Several commercial gaming Cloud streaming services already exist, such as Google Stadia (Google, n.d.-b), Xbox XCloud (XBox, n.d.) and Nvidia GeForceNow (Nvidia, n.d.-b). The start of 2020 also saw the first experimental cloud VR streaming development kits, such as Nvidia's CloudXR (Nvidia, n.d.-a). There is also a variety of Infrastructure-as-a-service (IaaS) platforms, such as Amazon's AWS (Amazon, n.d.), Microsoft's Azure (Microsoft, n.d.) and Google's Cloud Platform (Google, n.d.-a). For more information about these applications and technologies, please refer to the Literature Analysis.

8.1.3 System Architecture (for a cloud system)

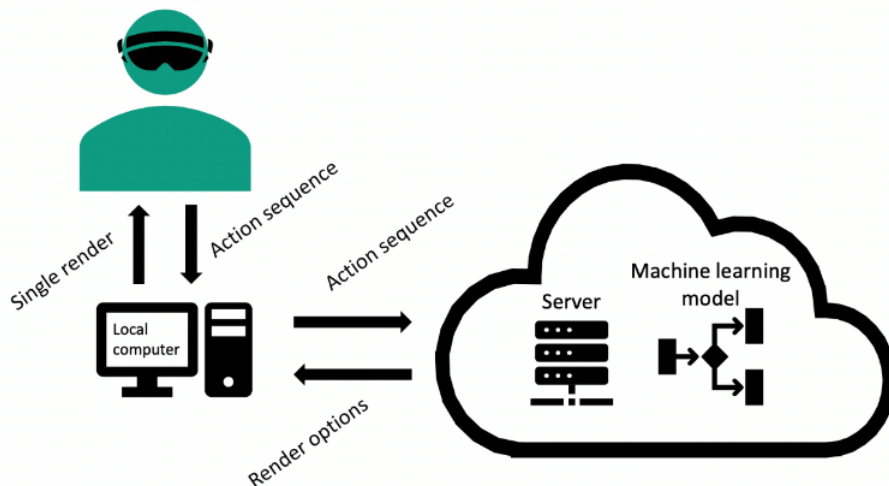
8.1.4 Latency

8.2 Virtual Reality

8.2.1 Definition

Early works, such as the 1996 article "Virtual Reality in Scientific Visualizations" or the 2003 book "Virtual Reality Technology", define Virtual Reality as: "The use of computers and human-computer interfaces to create the effect of a three-dimensional world containing interactive objects with a strong sense of three-dimensional presence." (Bryson, 1996) or "A Simulation in which computer graphics is used to create a realistic looking world. Moreover, the synthetic world is not static, but responds to the users input. This defines a key feature of Virtual Reality, *real-time interactivity*" (Burdea & Coiffet, 2003).

Figure 1: Example System Architecture



8.2.2 Physical Constraints

As mentioned before, when developing a VR application, there are a few physical constraints that developers need to be aware of. The most important threshold to know is the 20 MS Motion-to-Photon (MTP) delay. Upon input from the Head Mounted Display (HMD), the developer has to display a new rendered image within an average of 20 MS to avoid motion sickness for users. The more this threshold can be undercut, the better the chances to have an acceptable gameplay experience without motion sickness. Interaction input, such as the input from the controllers, can safely be processed at delays of >100 MS without any negative repercussions in terms of User Experience (UX). For more information, please refer to the Literature Analysis.

9 Literature Review

9.1 Modern (<5 years old) research and technology

Within the last decade the cloud computing space has expanded rapidly and with it the possibilities. Today, even individuals can set up an experimental cloud Virtual Reality (VR) streaming solution from pre-made components (TayoEXE, n.d.), such as the service from cloud computing company Shadow (Shadow, n.d.). The most recent years have also seen the rise of commercial cloud streaming for gaming services, such as Google Stadia (Google, n.d.-b), Xbox XCloud (Xbox, n.d.) and Nvidia GeForceNow (Nvidia, n.d.-b), but not without problems, as the services were quickly overwhelmed on launch. However no commercial products for cloud VR streaming exist at the time of writing, hence the need for this research paper. Modern video compression codecs, like the AV1 codec introduced in 2018 (for Open Media, n.d.), are getting better and better at compressing high-resolution video streams and together with an application like WebRTC (Google, n.d.-c) which offers latency optimizations via peer-to-peer networking and more, they lay the foundation for modern cloud streaming applications. With ever increasing performance and optimizations, the feasibility of cloud VR streaming is just a matter of time.

Research Papers like the ones from Liu et al., 2018 or from Shi, Gupta, Hwang, and Jana, 2018 demonstrate the viability and technical feasibility of cloud VR streaming . They developed innovative solutions to achieve and undercut the 20 Milliseconds (MS) Motion-to-Photon (MTP) delay barrier while streaming VR content. 20 MS is the agreed upon threshold a frame should have, from receiving the input to displaying the frame on the Head Mounted Display (HMD), to avoid inducing motion sickness. One such solution is a low latency control loop that streams VR scenes containing only the user’s Field-of-View (FoV) and a latency adaptive margin area around the FoV. This allows the clients to render locally at a high refresh rate to accommodate and compensate for the head movements before the next motion update arrives. (Shi et al., 2018). Another angle of attack leverage’s the power of parallel rendering, encoding, transmission and decoding, together with a Remote VSync Driven Rendering approach to minimize MTP latency (Liu et al., 2018). The prototype for this experiment was based on commodity hardware, which further demonstrates the feasibility of cloud VR streaming.

10 Final Problem Statement

11 Research Questions

Main Question 1:

What is the current state of cloud Virtual Reality (VR) streaming?

Sub Question 1: What cloud streaming solutions are already existing?

Sub Question 2: How effective are existing solutions when applied to the cloud streaming VR context?

Sub Question 3: What research has been done on the shortcomings from question 2?

Sub Question 4: Which issues still require the most research?

Main Question 2:

What are the best practices when building a cloud streaming VR pipeline?

Sub Question 1: What are the most important considerations when designing an Architecture for cloud VR streaming?

Sub Question 2: What is the most efficient way to reduce Motion-to-Photon (MTP) Latency?

Sub Question 3: What is the best practice for multi-user experiences?

Sub Question 4: Does GPU scaling improve User Experience (UX)?

12 Methodology

13 Experiments

14 Results

15 Discussion

16 Conclusion

References

- Bryson, S. (1996). Virtual reality in scientific vizualisation. *Communications of the ACM*, 39(5).
- Burdea, G. C., & Coiffet, P. (2003). *Virtual reality technology*.
- Armbrust, M., Fox, A., Griffith, R., Joseph, A. D., Katz, R., Konwinski, A., ... Zaharia, M. (2010). A view on cloud computing. *Communications of the ACM*, 53(4), 50–58. doi:<https://dl.acm.org/doi/fullHtml/10.1145/1721654.1721672>
- Liu, L., Zhong, R., Zhang, W., Liu, Y., Zhang, J., Zhang, L., & Gruteser, M. (2018). Cutting the cord: Designing a high-quality untethered vrsystem with low latency remote rendering. *Proceedings of MobiSys ACM '18*. doi:<https://doi.org/10.1145/3210240.3210313>
- Shi, S., Gupta, V., Hwang, M., & Jana, R. (2018). Mobile vr on edge cloud: A latency-driven design. *MMSys '19*. doi:<https://doi.org/10.1145/3304109.3306217>
- Amazon. (n.d.). Amayon web services (aws) - cloud computing. Retrieved from <https://aws.amazon.com/>. ((accessed: 12.05.2020))
- for Open Media, A. (n.d.). Av1 features. Retrieved from <https://aomedia.org/av1-features/>. ((accessed: 12.05.2020))
- Google. (n.d.-a). Google cloud computing services. Retrieved from <https://cloud.google.com/>. ((accessed: 12.05.2020))
- Google. (n.d.-b). Stadia - one place for all the ways we play. Retrieved from <https://stadia.google.com/>. ((accessed: 11.05.2020))
- Google. (n.d.-c). Webrtc. Retrieved from <https://webrtc.org/>. ((accessed: 12.05.2020))
- Microsoft. (n.d.). Cloud computing services — microsoft azure. Retrieved from <https://azure.microsoft.com/en-us/>. ((accessed: 12.05.2020))
- Nvidia. (n.d.-a). Nvidia cloudxr sdk. Retrieved from <https://developer.nvidia.com/nvidia-cloudxr>. (accessed: 13.05.2020)
- Nvidia. (n.d.-b). Your games. your devices. play anywhere. Retrieved from <https://www.nvidia.com/en-us/geforce-now/>. ((accessed: 11.05.2020))
- Shadow. (n.d.). Transform your device into an gaming pc1. Retrieved from <https://shadow.tech/usen>. ((accessed: 08.05.2020))
- TayoEXE. (n.d.). Test: No vr-ready pc required, cloud pc vr streaming via shadow and virtual desktop quest. Retrieved from https://www.reddit.com/r/OculusQuest/comments/c5xnux/test_no_vrready_pc_required_cloud_pc_vr_streaming/. ((accessed: 08.05.2020))
- XBox. (n.d.). Project xcloud. Retrieved from <https://www.xbox.com/en-US/xbox-game-streaming/project-xcloud>. ((accessed: 11.05.2020))

17 Appendices