Cloud Rendering-based Volumetric Video Streaming System for Mixed Reality Services

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ABSTRACT
Volumetric video is an emerging technology for immersive representation of 3D spaces that captures objects from all directions using multiple cameras and creates a dynamic 3D model of the scene. However, rendering volumetric content requires high amounts of processing power and is still a very demanding task for today’s mobile devices. To mitigate this, we propose a volumetric video streaming system that offloads the rendering to a powerful cloud/edge server and only sends the rendered 2D view to the client instead of the full volumetric content. We use 6DoF head movement prediction techniques, WebRTC protocol and hardware video encoding to ensure low-latency in different parts of the processing chain. We demonstrate our system using both a browser-based client and a Microsoft Hololens client. Our application contains generic interfaces that allow easy deployment of different augmented/mixed reality clients using the same server implementation.

CCS CONCEPTS
• Information systems → Multimedia streaming; • Human-centered computing → Ubiquitous and mobile computing systems and tools; • Networks → Cloud computing.

KEYWORDS
volumetric video, augmented reality, mixed reality, edge cloud, cloud rendering

1 INTRODUCTION
Recent technical advances in capturing and displaying immersive media sparked a huge market interest in virtual reality (VR) and augmented reality (AR) applications. Although the initial focus lay on omnidirectional (360°) video applications, with the advancements in volumetric capture technology as well as availability of mobile devices that are able to register their environment and place 3D objects at fixed places, the focus has started to shift towards volumetric video applications [14].

Volumetric videos capture an object or scene with multiple cameras from all directions and create a dynamic 3D model of that object [15]. Users can view such content using an AR device (e.g. an optical see-through AR display) with accurate six-degrees-of-freedom (6DoF) positional trackers, or on a 2D screen albeit in a less immersive fashion. Volumetric video is expected to enable novel use cases in the entertainment domain (e.g. gaming, sports replay) as well as in cultural heritage, education, and commerce. For example, capturing spaces for documentation of historical events, virtual lectures and classrooms, virtual museum visits and field trips are among the envisioned future use cases. Commercial applications such as real estate preview, industrial production monitoring, repair and maintenance tasks are among future use cases that can be implemented in a more immersive fashion using volumetric video [3, 15].

Despite the significant increases in computing power of mobile devices, rendering rich volumetric videos on such devices is still a very demanding task. Especially, presence of multiple volumetric objects in the scene can increase the rendering complexity significantly. Furthermore, efficient hardware implementations for decoding of volumetric data (e.g. point clouds or meshes) are still not available, and software decoding can be very demanding in terms of battery usage and real-time rendering requirements.

One way to reduce the processing load on the client is to send a 2D view of the volumetric object that is rendered according to the actual user position, rather than sending the entire volumetric content to the client. This is achieved by offloading the expensive rendering process to a powerful server and transmitting the rendered views over a network to less powerful client devices. This technique is typically known as remote (or interactive) rendering [16]. Another advantage of this approach is that network bandwidth requirements are significantly reduced because only a 2D video is transmitted instead of full 3D volumetric content. The rendering server can also be deployed within a cloud computing platform to provide flexible allocation of computational resources and scalability based on changes in processing load.

Recently, the reduced network latency enabled by the emerging 5G networks fostered a resurgence of interest in cloud rendering applications, especially in the domain of cloud gaming [9]. Nvidia has released an SDK called CloudXR [12] which aims to deliver advanced graphics performances to thin clients by rendering complex immersive content on Nvidia cloud servers and streaming only the result to the clients. Google Stadia [5], a cloud gaming service operated by Google, has already been launched in November 2019.
Microsoft is also expected to launch a similar cloud gaming service for Xbox in 2020 under the name Project xCloud [10]. While cloud-based rendering helps to reduce the processing load on the client side, a major drawback is the added network latency which is not present in systems that perform rendering entirely on the end device. In addition to the added network latency, rendering and encoding on the server side also contribute to the increase in the end-to-end latency [6]. Degraded user experience and motion sickness are known to be common consequences of a perceivable motion-to-photon latency [1, 2]. Therefore, it is crucial to employ latency reduction techniques in every element of the processing chain.

One way to reduce latency is to serve the volumetric content from a geographically closer server, thereby reducing the network latency [8]. Also, deployment of recent real-time communication protocols such as WebRTC is crucial for meeting the demands of interactive low-latency streaming applications [7]. In terms of video encoding latency, the use of fast hardware-based video encoders (e.g. Nvidia NVENC [13]) is critical for reducing video compression latency while maintaining good quality and compression efficiency. Finally, the system should predict the future position of the user using various prediction algorithms to further minimize the perceived end-to-end latency [4].

In this work we present a system for low-latency volumetric video streaming using the cloud rendering concept that comprises a server and two different client implementations. To ensure low latency streaming, we utilize 6DoF head movement prediction techniques as well as the WebRTC protocol together with Nvidia hardware encoder (NVENC). Our system provides generic interfaces such that any client implementation can be deployed using the same server implementation. For our demonstration, we have implemented a client application for Microsoft Hololens (both 1st and 2nd generation) and another browser-based client that can be run on different browsers.

2 SYSTEM ARCHITECTURE
This section describes the key components of our cloud-based rendering volumetric video streaming system as well as the dataflow and interfaces between the components.

2.1 Server side architecture
An overview of the overall system architecture is shown in Figure 1. Our server implementation consists of a volumetric video player and a generic cross-platform cloud rendering library that can be integrated into different applications.

The volumetric video player is implemented using Unity. The player is able to play volumetric sequences stored in a single MP4 file which consists of a video track containing the compressed texture data, and a mesh track containing the compressed mesh data. Before the start of the playback, the player registers all game objects (e.g. a volumetric object stored in a MP4 file or a virtual camera) that are to be controlled by the cloud rendering library and/or the client. After registration, the player can start playing the MP4 file by demultiplexing and feeding it into the corresponding video and mesh decoders. Then, each mesh is synchronized with the corresponding texture, and a rendered view of the volumetric object (represented as a Unity RenderTexture [17]) is passed to the cloud rendering library for further processing. The player concurrently asks the library for the latest positions of the previously registered game objects and updates the rendered view accordingly.

The cloud rendering library is a cross-platform library written in C++ that can be readily integrated into different applications. In our Unity application, we integrated it as a native plugin into the player. The library contains various modules for application control, media processing, and the communication interfaces between the server and the client. The main modules of our library are the WebSocket Server, GStreamer module, Controller, ObjectPool and Prediction Engine. Each module runs asynchronously in its own thread to achieve high performance.

The WebSocket Server is used for exchanging signaling data between the client and the server. Such signaling data includes Session Description Protocol (SDP), Interactive Connectivity Establishment (ICE) as well as application-specific metadata for scene description. The WebSocket connection is also used for transmission of the control data in order to modify the position and orientation of any registered game object or camera. Our system also allows the usage of WebRTC data channels for control data exchange after a peer-to-peer connection is established. Both plain WebSockets and Secure WebSockets are supported which is important for running the system in real use cases.

The Gstreamer module contains the media processing pipeline which takes the rendered texture as input, compresses it as a video stream, and transmits it to the client using WebRTC. Specifically, the Unity RenderTexture is inserted into the pipeline using the appsrc element of Gstreamer. Since the texture is in RGBA format, it has to be passed through a videoconvert element to bring it to the I420 format accepted by the encoder. We use Nvidia encoder (NVENC) to compress the texture in H.264 format but it is also possible to encode in H.265/HEVC format using NVENC, or replace the encoder block with a different encoder e.g a software encoder such as x264. Finally, the resulting compressed bitstream is packaged into RTP packets, encrypted, and sent to the client using the WebRTC protocol.

The ObjectPool is a logical structure that maintains the states of all registered objects (IDs and positions) enabling the client to position virtual objects correctly. The Controller contains the application logic and controls the other modules depending on the application state. For example, it closes the media pipeline if a client disconnects, and re-initializes the pipeline when a new client is connected. The controller also describes the object states in a JSON file and sends that to the client to inform the client about the existing objects and their positions.

The Prediction Engine implements a 6DoF user movement prediction algorithm to predict the future head position of the user based on her past movement patterns. Based on the client interaction and the predictions output by the Prediction Engine, the Controller updates the positions of the registered objects accordingly such that the rendering engine renders a scene matching to the predicted user position that will be attained after a pre-defined prediction interval. The prediction interval is set to be equal to the estimated motion-to-photon latency of the system. Currently, an autoregressive model (as described in [6]) is implemented but the module allows integration of different kind of prediction techniques e.g. Kalman filtering [4].
2.2 Client side architecture

Our client-side architecture is depicted on the left side of the Figure 1 and essentially consists of the following modules: WebSocket Connection, Video Decoder, Application Logic, and the client application: a browser client or a native client for Microsoft Hololens.

Before the streaming session starts, the client establishes a WebSocket connection to the server and asks the server to send a description of the rendered scene. The server responds with a list of objects and parameters. After receiving the scene description, the client replicates the scene and initiates a peer-to-peer WebRTC connection (RTCPeerConnection) with the server. The server and the client begin the WebRTC negotiation process while sending SDP and ICE data over the previously established WebSocket connection. Then, the peer-to-peer connection is established and the client receives a video stream over RTCPeerConnection that contains the rendered view of the 3D scene corresponding to the (predicted) user pose. The client can use the WebSocket connection (or optionally RTCDatChannel) and send control data back to the server to modify the rendered view. For example, the client may signal the changes in user’s pose, or it may rotate, move or scale any volumetric object in the scene based on the user interaction.

We implemented both, a web browser player and a native application for the Microsoft Hololens. While our browser application targets use cases in which the volumetric content is viewed on a 2D screen such as a tablet or computer display, our Hololens client targets AR/MR applications that potentially offer better immersion and more natural interactivity.

Browser client. Our browser client is implemented in JavaScript and it uses the three.js [18] library that allows to interact with the volumetric object using a mouse, keyboard or touchscreen. Specifically, the user can move the camera around, drag the object to change its position and use range sliders to change the orientation or scaling of the object. The client application has been tested on different web browsers such as Chrome, Firefox, and Safari.

Hololens client. Our Hololens application is built as Universal Windows Platform (UWP) application with Unity. We build separate applications both for x86 and ARM architectures since Hololens 1 executes applications on an x86 processor whereas Hololens 2 uses an ARM processor. On the server side, the renderer designates the user as a camera in Unity 3D space and moves the camera according to the user’s position. The renderer positions the camera such that it always views the object ensuring that the object is always visible in the AR environment.

Due to the properties of the optical see-through display used in Hololens, black pixels are seen fully transparent while white pixels are seen as increasingly opaque [11]. This display property can be exploited to remove the background of the volumetric object inside the video stream such that the volumetric object is perceived to be overlaid onto the real world. To achieve this, the background pixels (already rendered with a solid color on the server) are set to black in Hololens using a shader which leads them to be perceived as transparent by the user.

The Hololens app renders the 2D scene onto a plane orthogonal to the user’s point of view in the world space (see Figure 2). When the user changes her position and a new matching view is rendered on the server, this plane is always rotated towards the user. In this way, the user perceives the different 2D views rendered onto the orthogonal plane as though a 3D object were present in the scene.

3 Demonstration

We will demonstrate our volumetric video cloud rendering system on the web browser client as well as the Hololens client. In reality,
we are able to deploy our server application at a 5G edge server as well as on the AWS instance. However, due to possible limitations in Internet connectivity, we will connect both clients over WiFi to a local area network using a router.

Users will be able to interact with the volumetric content using both the browser and Hololens clients. In both cases, users may scale, rotate, and move the object. While using the browser client, the user will also be able to measure the motion-to-photon latency using our custom-built latency measurement tool [6]. This tool sends pre-defined textures (known by the client) depending on the control data received from the client. As soon as the client detects the corresponding texture based on its previous input to the server, it stops the timer and computes the overall motion to photon latency. Running the server on the Amazon EC2 instance in Frankfurt and the WiFi connected client in Berlin we are measuring latencies around 60ms.

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Figure 2 shows the implementation of our Hololens client where the transmitted 2D scene is rendered on the orthogonal plane as shown in the figure. After receiving and decoding the 2D video, the renderer detects a certain range of RGB values in the fragment shader and adjusts the plane background in Figure 2(b) to the transparent background as in Figure 2(a). The user can then move the object to any desired position using spatial gestures designed for scaling and dragging 3D objects in Hololens.

As supplementary material, we provide a video describing the overall system architecture and showing the functionality of our browser and Hololens clients.

4 CONCLUSION

In this paper, we presented a low-latency cloud rendering-based volumetric streaming system. Our system utilizes a powerful server for rendering of volumetric videos and decreases processing requirements and battery usage in end devices. Also, by avoiding the streaming of full 3D data, required bandwidth is significantly reduced. To reduce the increased motion-to-photon latency due to the added network latency, we use 6DoF movement prediction techniques, low latency streaming protocols (WebRTC) and low latency hardware video encoders (NVENC).

Based on the developed volumetric streaming system, our future work will include investigation of the effect of latency on the user perception in AR environments as well as development of more effective prediction techniques for prediction of user movement in 6DoF environments.

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