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A survey of real-time rendering on Web3D application

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Abstract: Background In recent years, with the rapid development of mobile Internet and Web3D technologies, a large number of web-based online 3D visualization applications have emerged. Web3D applications, including Web3D online tourism, Web3D online architecture, Web3D online education environment, Web3D online medical care, and Web3D online shopping are examples of these applications that leverage 3D rendering on the web. These applications have pushed the boundaries of traditional web applications that use text, sound, image, video, and 2D animation as their main communication media, and resorted to 3D virtual scenes as the main interaction object, enabling a user experience that delivers a strong sense of immersion. This paper approached the emerging Web3D applications that generate stronger impacts on people's lives through "real-time rendering technology", which is the core technology of Web3D. This paper discusses all the major 3D graphics APIs of Web3D and the well-known Web3D engines at home and abroad and classify the real-time rendering frameworks of Web3D applications into different categories. **Results** Finally, this study analyzed the specific demand posed by different fields to Web3D applications by referring to the representative Web3D applications in each particular field. **Conclusions** Our survey results show that Web3D applications based on real-time rendering have in-depth sectors of society and even family, which is a trend that has influence on every line of industry.

Keywords: Web3D; Real-time rendering; Virtual reality; Cloud rendering; Mobile Internet

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1 Introduction

With the growth of web technologies, including HTML5 and WebAssembly, in the mobile Internet era, the concept of "Web+" is gradually taking root in all industries and exerting a profound impact on people's lives. Be it travel, shopping, learning, or entertainment, several the activities in our daily lives can now be performed through a web browser. Meanwhile, human perceptions have gradually extended from the real world to the

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virtual world of the internet. This has, in turn, created an even higher expectation for Web technologies, that is, Web technologies should not only realize the various application needs of users but also fulfill their demand for perceptual experience at the same time. However, most current web applications still use text, sound, image, video, and 2D animation as their main communication media. These traditional forms have limitations which make them unable meet growing needs for a multi-sensory experience of high interactivity and immersion in the virtual world. With this background, 3D visualization technology has started to integrate into the web and has become a new major trend.

With the rapid development of Internet and 3D visualization technologies, sustained progress has been made in web-based 3D visualization technology. Today, web-based 3D visualization technology known as "Web3D" has enabled the display of 3D virtual scenes on mainstream web browsers, setting off new possibilities for next-generation web services based on visualization. According to Zhao Qingping of the Chinese Academy of Engineering, Web3D exerts a transformative and disruptive impact on existing browsers and email systems and even becomes a new gateway to the Internet[1]. In recent years, a number of Web3D applications have emerged in various industries, with typical examples including Web3D online tourism, Web3D online architecture, Web3D online educational environments, Web3D online medical care, and Web3D online shopping.

In all these applications, real-time rendering technology plays a key role: it not only affects the rendering effect and quality but also determines the quality of user experience and future development of these applications. Therefore, it is necessary to examine the relationship between real-time rendering and Web3D applications and take a closer look at the real-time rendering technologies, tools, and frameworks used in Web3D applications.

2 Web3D real-time rendering tools

2.1 Web3D graphics API

The key to Web3D is a set of browser-based 3D graphics APIs that not only allow for GPU-accelerated usage of physics and the processing of 3D graphics but are also compatible with all types of web browsers. Driven by the rapid development of HTML5, real-time 3D rendering applications have migrated from the client side to the web, with the core principle being the invocation of rendering techniques inside various Web3D graphics APIs to realize the design and display of 3D visualization scenes. Currently, there are several mainstream 3D graphics APIs for the web, including Stage3D, WebGL, WebGPU, and WebXR (Table 1).

Stage3D is an API for the real-time rendering of interactive 3D graphics created by Adobe for its proprietary 3D technology on the web, Flash3D. Using ActionScript as its writing language, Stage 3D relies on Adobe's Flash Player plug-in, with a great market occupation. Only when the plug-in is activated can Stage3D run properly on the web. Apart from this, Stage3D also uses the Adobe Graphics Assembly Language (AGAL)[2] for writing shaders in Stage 3D. This is a very low-level assembly language that lacks flexibility and extensibility compared to high-level shader compilation languages such as GLSL (OpenGL Shading Language) or HLSL (High-Level Shading Language). At that time, the development of Web3D online systems and mobile games could be realized using Stage3D technology[3,4].

WebGL 1.0, was released in 2011 by Khronos in collaboration with major browser vendors, including Apple (Safari), Google (Chrome), Microsoft (Edge), and Mozilla (Firefox). WebGL 1.0 is a JavaScript API that's based on "OpenGL ES 2.0" the mobile version of "OpenGL," which is a widely-used PC-class graphics API. WebGL can be used to render 3D and 2D graphics within most mainstream web browsers without plug-ins. This API enables GPU-accelerated graphics processing, and WebGL elements can be mixed with other HTML elements. Currently, most Web3D engines are designed based on WebGL API[5].

Table 1 Web3D APIs

API	Corporation	Release year	Features
Stage3D	Adobe	2011	Hardware acceleration supported by Flash player
WebGL	Khronos Group	2010	Hardware acceleration without plugins
WebGPU	W3C Working Group	2017	Closer to desktop graphics API
WebXR	Mozilla	2018	Designed for AR/VR/XR applications on the website

As a new 3D graphics API for the Web, “WebGPU” was first introduced by the W3C Working Group in 2017. To create an underlying API that is truly cross-platform, WebGPU was developed based on Vulkan, Metal, and Direct3D 12. Compared to WebGL, WebGPU has certain advantages in terms of rendering and computation and provides better support for multi-threading. The computational efficiency of the API was enhanced by bringing GPU acceleration to the web. W3C formally confirmed this standard in 2020[6]. In terms of low overhead rendering, it exhibits almost the same performance as Vulkan[7].

WebXR is a graphics API introduced by the Mozilla team in 2018 for VR(virtual reality), AR (augmented reality), and XR(extended reality) applications. This API was intended to replace “WebVR,” which was introduced by the team in 2014. Compared with WebVR that was designed solely to support VR, WebXR provides support for both VR and AR on the web, and can be used within a variety of hardware and software platforms including VR devices (Oculus Rift, HTC VIVE), browsers (Chrome, Edge, Internet) and Web3D engines (A-Frame, Babylon.js, Three.js). WebXR brings a brand-new experience to Web3D applications[8], and with the help of this API, many VR/AR applications have good realistic and immersive experiences on the web side[9,10]. WebXR has more typical applications in many fields, such as architectural design[11] and educational reading[12].

2.2 Web3D real-time rendering engines

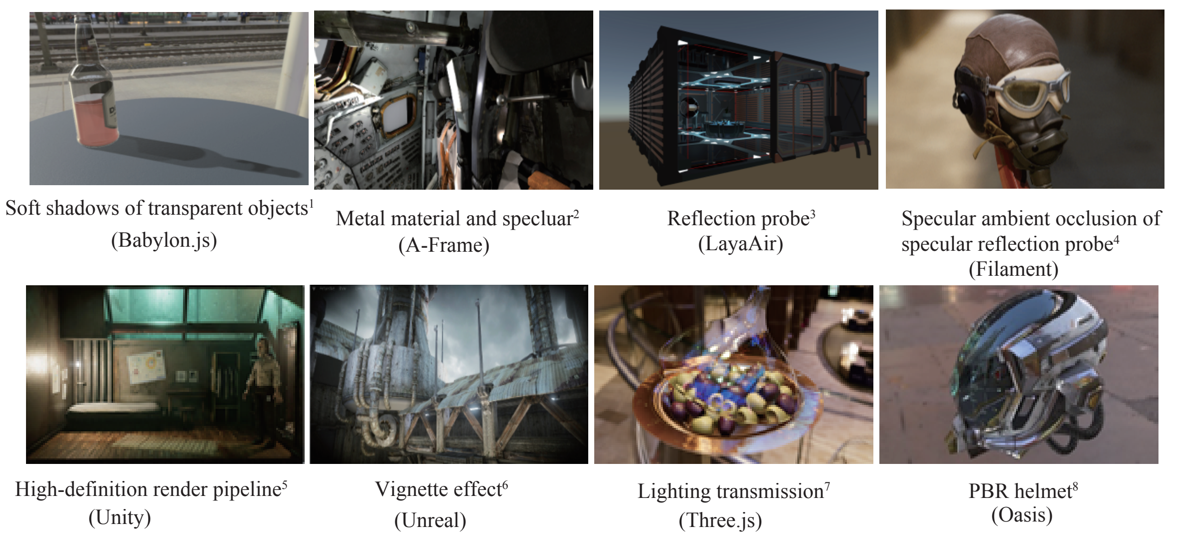
Web3D real-time rendering engines (Web3D engines) are a set of software frameworks based on Web3D graphics APIs, which serve as the foundation to enable real-time interactive rendering of virtual scenes in 3D. Web3D engines are mainly used for developing Web3D applications, with core functions including rendering engine (“renderer”) for 2D or 3D graphics, physics engine, particle system, sound, scripting, animation, network, streaming media, memory management, threading, and localization support[13]. Currently, there are a number of available Web3D engines, with typical examples including Away3D, Three.JS, Babylon.js, Oasis Engine, LayaAir, A-Frame, and Filament. Each of these engines exhibits distinctive features owing to the different Web3D graphics APIs on which they are based (Table 2 and Figure 1).

Away3D is an open-source 3D engine based on Flash3D, developed in 2007 by Alexander Zadorozhny and Unk Bateman. Away3D uses ActionScript 3.0 as its writing language and in the 4.0 version, it made use of the Stage3D API of Flash and achieved GPU acceleration of 3D graphics. Moreover, the rendering efficiency was improved through load balancing between the CPU and GPU. In terms of rendering, CSM (Cascaded Shadow Maps), rim lighting, global lighting, per-pixel lighting, and other features have become available. Away3D supports the particle system and post-processing and is a typical representative of the Flash3D engine.

Three.js is a web-based 3D JavaScript graphics library launched in 2010 by Ricardo Cabello. This engine is a JavaScript open-source framework designed based on the WebGL API[14,15]. Given that WebGL is relatively difficult to use, Three.js produces an easy-to-use graphics library by encapsulating and simplifying the WebGL interface and simplifies the details of 3D rendering without compromising WebGL flexibility[16]. In terms of function, Three.js provides a rich variety of cameras and scene graphs, navigation modes, several pre-programmed shaders and materials (along with the function to program custom shaders), level-of-detail mesh loading and rendering, and animation components that allow skeletal and deformation animation[17]. Owing to its strong compatibility, scalability, and open-source nature, three.js has become the current mainstream real-

Table 2 Web3D engines

Engine	Company/team	Release year	Supported API	Plugin	Supported languages	Features
Three.js	Ricardo Cabello (Mr.doob)	2010	WebGL, WebXR	NO	JS	Simple interface
Babylon.js	Microsoft	2013	WebGL, WebXR, WebGPU	NO	JS, TS	Rich resource library and powerful model support
A-Frame	MozVR	2015	WebGL, WebXR	NO	JS	Designed for AR/VR/XR applications on the Web-side
Filament	Google	2018	WebGL, Vulkan, Metal, OpenGL	NO	C++, Java, JS	Excellent PBR(physically based rendering)material
Oasis	Ant Group	2017	WebGL	NO	TS	Excellent microkernel architecture
LayaAir	LayaBOX	2016	WebGL	NO	AS3, JS, TS	Excellent performance optimization
Away3D	Away Studios	2007	Stage3D	YES	AS3	Excellent representative of Flash3D
Unity3D	Unity Technologies	2005	DirectX, OpenGL	YES	JS, C#, Boo	Excellent cross-platform commercial game engine
Unreal	Epic Games	1996	DirectX, OpenGL, OpenGL ES, Vulkan	YES	C++	Excellent high-realistic commercial game engine



Soft shadows of transparent objects[1] (Babylon.js)
Metal material and specluar[2] (A-Frame)
Reflection probe[3] (LayaAir)
Specular ambient occlusion of specular reflection probe[4] (Filament)
High-definition render pipeline[5] (Unity)
Vignette effect[6] (Unreal)
Lighting transmission[7] (Three.js)
PBR helmet[8] (Oasis)

Figure 1 Performance in Web3D Engines.

time rendering engine for Web3D visualization applications.

Babylon.js is a WebGL-based Web3D engine driven by Microsoft Corporation. This engine offers a wide array of functions, including a complete scene graph with lighting, material library and mesh, collision engine, animation engine, physics engine, optimization engine, and audio engine. It supports two programming languages, JavaScript and Typescript, and runs on all the browsers that support WebGL or WebGPU. In his research on the rendering of 3D scenes in web applications, Pakkanen also mentioned that Babylon.js is a convenient and lightweight engine on WebGL, with impressive performance and powerful scene rendering capabilities[18]. The latest version “Babylon.js 4.2” has introduced the Babylon Native framework, which

[1]https://www.babylonjs.com/
[2]https://math.nist.gov/~SRessler/aframe/ebd/projects/apollo/
[3]https://layaair.ldc.layabox.com/demo2/?language=zh&category=3d&group=Advance&name=ReflectionProbeDemo
[4]https://google.github.io/filament/Materials.html
[5]https://unity.com/cn/srp/high-definition-render-pipeline
[6]https://docs.unrealengine.com/4.27/en-US/RenderingAndGraphics/PostProcessEffects/Vignette/
[7]https://threejs.org/examples/#webgl_loader_gltf_transmission
[8]https://oasisengine.cn/0.6/examples

provides more PBR(Physically Based Rendering) support and can render soft transparent shadows for transparent objects. Compared with Three.js, Babylon.js is more intended for game development, with a relatively small memory overhead[19,20], a powerful and diverse library, and strong compatibility that requires no additional plug-ins to deliver a rich VR experience[21]. Babylon.js provides a fairly immersive experience on the Web, iOS, Android, and other platforms, however, owing to its focus on game development, Babylon.js has a higher level of encapsulation and is difficult to expand[22].

Oasis Engine is the mobile-first open-source Web3D engine released by the Ant Group in 2017 and supports languages, such as TypeScript. Adopting a microkernel architecture in the overall design, the Oasis Engine is an easy-to-use and lightweight engine that offers 3D rendering capabilities, audio, physics, VR/AR, 2D, 3D, and other functions. In addition, based on component development (CBD), the Oasis Engine has a simple and clear structure with a high code reuse rate, which effectively solves the problems in traditional (OOPct-oriented programming OOP() development. Oasis Engine v0.5 introduced image-based lighting (IBL) and spherical harmonic lighting[23] and improved the diffuse reflection design of ambient light, which delivers a better rendering effect while improving the rendering performance. In terms of animation, the Animator component was redesigned to support BlendShape animation and enable better animation performance.

LayaAir is an HTML5 open-source game engine that was developed independently by LAYABOX. First released in 2016, LayaAir has unique advantages in terms of performance and 3D space and supports three developmental languages: AS3, JS, and TS. In terms of rendering, LayaAir supports WebGL and Canvas rendering. With LayaAir, products developed using the same language can be released onto multiple platforms including HTML5, APP (Android and iOS), and WeChat mini-games at the same time and also has an excellent extension mechanism to support access to third-party libraries. The updated version LayaAir2.0, introduced the Box2D physics engine and added support for componentization. In terms of texture, LayaAir2.0 which introduced more texture parameter configurations (such as mipmap, format, and filtermode) and added functions, including GPU texture compression. LayaAir is a streamlined and high-performance API game engine that is lightweight, easy to use, and free of charge. It offers a complete range of API functions and a highly efficient toolchain and supports multi-language development and multi-version releases.

A-Frame was released in 2015 by the MozVR team, the initiator of WebVR. A-Frame is a web development framework that focuses on web VR applications[24]. In terms of programming structure, A-Frame provides an extensible, declarative, and entity component system based on the framework idea of Three.js[25]. In the latest version, 11.0, the engine has introduced several core functions, including hand tracking, immersive navigation, hit test, and support for Chrome and Oculus browsers. In terms of hardware devices, A-Frame supports mainstream VR headsets, including HTC Vive, Oculus Rift, Daydream, GearVR, and Cardboard. In addition, A-Frame can also be used in augmented reality (AR). In his study of web-based virtual reality, Neelakantam et al. mentioned that the various components and building blocks of A-Frame can effectively improve performance during resource caching and deliver better scene quality[26]. Pathak et al. proposed an adaptive resolution scheme for VR (ARS-VR), which indicates that A-Frame has improved the frame rate and frame latency of VR during the use of the device[27]. Baruah describes the rich extensibility of A-Frame and its use for creating VR applications on the Web[28]. He also identified the true advantage of A-frame as the ability to apply the system to the scene, arguing that using A-frame to load 3D models in XR and AR can give users an experience of highest enjoyment. Markman et al. believe that the future of the Internet cannot be built without A-Frame, which enables human beings to establish molecular models, reconstruct historical spaces, design stages, scenes for performing arts, and so on[29].

Filament, developed by Google, is a real-time physically based rendering (PBR) engine written in C++ and supports APIs including WebGL 2.0, Vulkan, Metal, OpenGL 4.1, and OpenGL ES 3.0. As a substitute for OpenGL, Vulkan was also developed by the Khronos Group to improve API performance while balancing

CPU and GPU loads. As the graphics API is tailored by Apple for its own products, metal accommodates both graphics and general-purpose computations and has excellent performance on Apple products. The languages that A-Frame can support include C++, Java, and JavaScript. Filaments are available on a wide range of platforms including WebGL, iOS, Windows, and Android. In particular, the filament provides Android developers with a set of APIs as well as extensible frame graphs and pipeline rendering tools, which allow developers to easily achieve high-quality real-time 2D and 3D rendering through special optimizations.

Unity3D and Unreal are two representative game development engines with fairly high market share. Compared to the Web3D engines mentioned above, these two engines are characterized by their strong rendering capability, high extensibility, low program development complexity, and cross-platform flexibility. Although neither of these engines falls under the category of Web3D engines in the strict sense, Unity3D enables demonstration in mainstream browsers with its exclusive plug-in “Unity Web Player”[30], while Unreal 4.0 uses the plug-in “Pixel Streaming” to push 3D content to the Web front-end and provides a consistent runtime environment for Web3D applications[31]. Therefore, these two engines are also included in this chapter for a more comprehensive comparison of Web3D engines.

3 Real-time rendering in Web3D application

3.1 Real-time rendering framework of Web3D applications

As the core unit of Web3D applications, real-time rendering frameworks are responsible for model parsing, code passing, real-time rendering, and final display of all 3D virtual scenes. Each Web3D application has a real-time rendering framework with unique characteristics. Based on the “side” where the rendering task occurs, all real-time rendering frameworks are classified into three categories, namely web-based real-time rendering frameworks, server-based real-time rendering frameworks, and end-cloud collaborative real-time rendering frameworks.

3.1.1 Web-based real-time rendering frameworks

Under these frameworks, the primary rendering task is placed on a web browser. The server transfers the 3D model, textures, and other stored resources to the web front-end without participating in the rendering task at all (Figure 2a). This type of framework is the mainstream rendering framework for Web3D applications and, unless specifically handled, these applications developed with the above Web3D engines will use this type of rendering framework by default.

Compared to remote rendering frameworks (cloud rendering frameworks and collaborative rendering frameworks), this type of framework orients its rendering tasks directly to the user front-end. This has shortened the latency of real-time interactions for Web3D applications. However, owing to the limited rendering capability of web browsers, the rendering quality of Web3D applications based on these frameworks is unsatisfactory. In addition, the workload on both sides of these frameworks is quite unbalanced; the web side is overloaded with rendering tasks that exceed its capacity, while the server side is idle. That said, this type of framework only requires a lightweight network architecture, as the resources are transferred only once to the front-end over the network prior to Web3D application rendering.

3.1.2 Server-based real-time rendering frameworks

These rendering frameworks place the main rendering task on the server and then transfer the rendering result to the web in the form of an image stream. The web front-end (i.e., web client) is used only to display the rendering result without participating in the rendering task (Figure 2b). This type of framework can achieve a higher level of security with stronger support for compute-intensive rendering and fewer resource require-

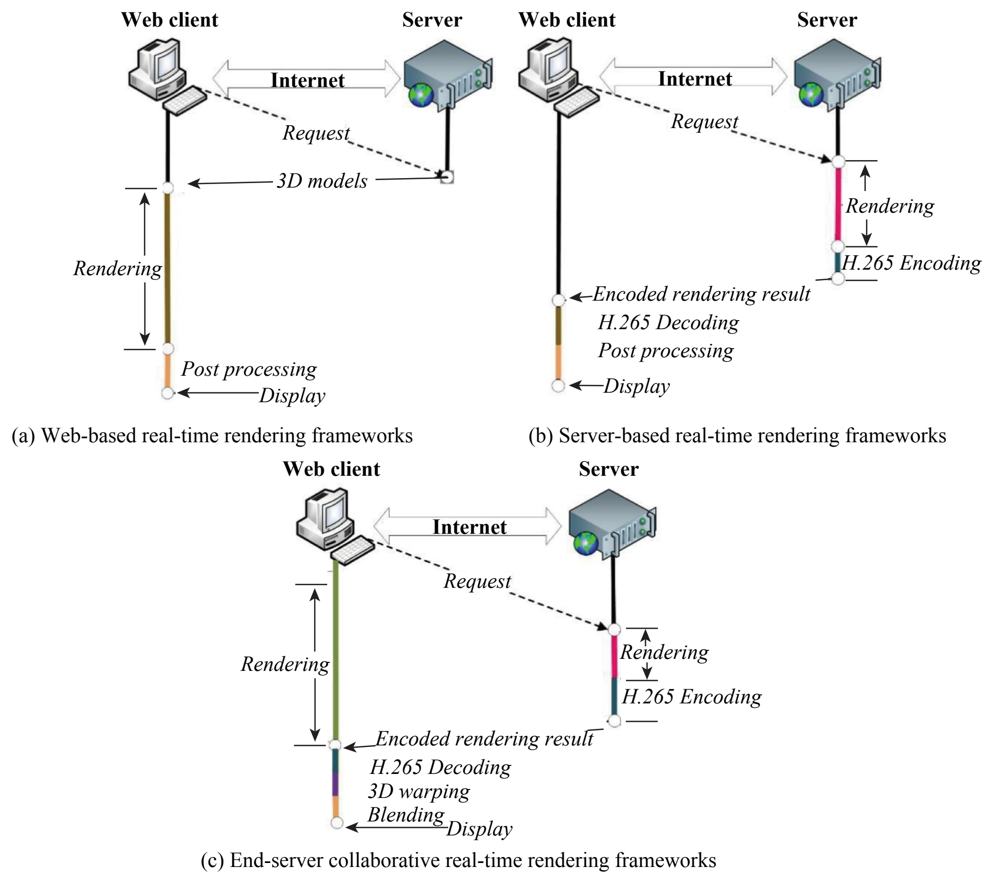


Figure 2 **Real-time rendering framework.**

ments posed to the web front-end. Due to these advantages, server-based real-time rendering frameworks are commonly used for applications that require high rendering quality on the web front-end or a high level of security, such as cloud gaming[32] and high-quality 3D model display applications[33]. Thus, it is evident that server-based real-time rendering frameworks have fully exploited the rendering capabilities of the remote server. With the help of the well-developed mobile Internet today, they have made it possible to achieve high-quality rendering for visualization applications on weak client-sides, such as web browsers.

Compared with web-based real-time rendering frameworks: 1) These frameworks require a more complicated rendering architecture that deals with the request and transmission of rendering at over 30 frames per second. 2) The problem of workload imbalance on both sides still exists, as the rendering task is completely placed on the server side, while the web side is only used to receive and display the rendered results, with its rendering capacity being completely abandoned. Under such circumstances, a collaborative rendering system architecture that can effectively invoke the rendering capabilities of the remote server while fully exploiting the rendering capabilities on the web side has long been expected by researchers.

3.1.3 End-server collaborative real-time rendering frameworks

Given that server-based rendering is largely restricted by the conditions of server hardware and bandwidth, while the rendering effect of web-based frameworks is far worse than that of server-based frameworks owing to the limited rendering capability of Web3D rendering engines, a collaborative rendering framework has emerged as a combination of web-based and server-based frameworks, which combines the advantages of the two and allows for simultaneous rendering on both the web client-side and server-side as shown in Figure 2c. Currently, most applications of collaborative frameworks are still in the research stage[34], however, with the continuous advancement of technologies, including edge computing, cloud computing, and real-time rendering, collaborative rendering frameworks are bound to become the mainstream rendering framework for Web3D applications in the era of the mobile Internet.

Compared with the above-mentioned two types of rendering architectures, both sides of the end-cloud collaborative rendering framework perform the rendering tasks within their capabilities and achieve a good load balance. In addition, with the end-cloud collaborative rendering framework, the rendering resources that need to be sent from the server are much fewer than in the case of cloud-based rendering frameworks. This results in a lower network transmission load, which, in turn, leads to better real-time interactivity of Web3D applications under such frameworks. Therefore, the end-cloud collaborative real-time rendering framework has drawn on the merits of other rendering frameworks and eliminated their flaws. Thus, it has achieved greater compatibility and scalability and is a major direction for future real-time rendering frameworks. See Table 3 for comparison of real-time rendering frameworks in Web3D application

Table 3 Comparison of real-time rendering frameworks in Web3D application

	Web-based	Server-based	Collaboration
Transmission bandwidth cost	low	high	medium
Transmission request frequency	low	high	medium
Rendering computation cost	lightweight	heavy	medium
Render effects performance	general	excellent	excellent
Hardware cost	cheap	expensive	medium

3.2 Web3D applications and cloud rendering

Server-based real-time rendering frameworks of Web3D applications fall under the category of remote rendering, which is intended at migrating rendering tasks onto remote servers to enable high-quality graphics display even on "thin" clients like Web[35]. With the support of cloud computing technology, rendering tasks in remote rendering frameworks have migrated to cloud servers, leading to the emergence of cloud rendering technology[36]. Currently, mobile-based and web-based online XR applications, as well as web-based online cloud games that are targeted at high-quality rendering and fast interactive response, have become the main application areas of cloud rendering technology in Web3D applications[37].

In recent years, driven by mobile Internet technology, great achievements have been made in cloud computing technology, with remote rendering frameworks gradually evolving from "end-server" frameworks into "end-cloud" frameworks. Meanwhile, "end-server" collaborative rendering frameworks have also turned into "end-cloud" collaborative rendering frameworks. The collaborative mechanism of the "end-cloud" rendering framework is embodied in the sharing of the rendering tasks. This mechanism makes full use of the rendering capabilities of the front-end and reduces the rendering load on the back-end, allowing the framework to achieve a certain level of load balancing. These rendering frameworks typically rely on decomposition of the rendering equation. One example is "Cloud Baking", a collaborative scene illumination framework for Web3D scenes proposed by Liu et al., which places the simple task of direct illumination on the web front-end and moves the heavy task of global illumination to the cloud back-end. The final rendering results were then blended and delivered on the web front end[38]. To optimize this framework, the team built a pre-rendering mechanism based on the lightmap tree[39], and recently proposed a dynamic real-time illumination cloud rendering framework for Web3D scenes based on device performance[40], which further subdivides the rendering tasks on both sides of the "end/cloud". Viewpoint-dependent multiside collaborative rendering frameworks are highly sensitive to interaction latency, which inevitably leads to inconsistency between front-and back-end viewpoints and creates distortions in the rendering output that relies on the blending of results from both sides. Therefore, frameworks typically rely on viewpoint correction[41] to address the output distortion caused by latency.

The collaborative light-rendering framework proposed by Shao et al. generally follows Liu's rendering task sharing model, except for the different processing of global light on the cloud, with the former using ambient occlusion based on scene voxelization, whereas the latter uses the Lightmap algorithm based on sparse voxelization[42,43]. Both algorithms are viewpoint-independent. Such frameworks are more tolerant to interaction latency, but this inevitably leads to more light information images being stored on the loud. Therefore, when choosing between these two frameworks, a balance must be reached between their interactivity and storage consumption. Generally, the higher the space occupation of the sharing mechanism, the greater the demand for cloud computing capacity, and the stronger the support for weak front-ends.

In addition, with the integration of edge computing into the "end-cloud" Web3D collaborative rendering frameworks, the rendering approach of these frameworks will change dramatically. Compared with cloud servers, edge servers are closer to the front-end. Therefore, offloading the compute-intensive rendering tasks from the front end to the edge can reduce the network latency and bandwidth consumption[44]. This represents the future development direction for real-time rendering frameworks.

4 Application of Web3D in various fields and real-time rendering technology

Ultimately, all advancements in Web3D technologies would have to come down to the application of Web3D in everyday life. This chapter will discuss the application of Web3D in the fields of tourism, architecture, education, medical care, and business to analyze the changes brought by real-time rendering technology to traditional fields.

4.1 Web3D online tourism and real-time rendering technology

Web3D online tourism is a type of real-time interactive Web3D application oriented towards the 3D reproduction (reconstruction) of tourist attractions (Figure 3). Currently, most of these applications apply distributed real-time rendering technology, which allows users to engage in real-time interactions with large-scale 3D virtual tourist scenes. Compared with traditional real-time rendering applications, these applications have adopted the techniques of mesh compression and stream transmission, which have effectively addressed the problem of slow user access owing to overly large render scenes. By leveraging real-time rendering technology, these applications allow users to have an immersive experience in reconstructed virtual tourist scenes on a web browser without even leaving their desk. Tourist scenes can be either natural views or cultural relics that currently exist around the world, or historic sites that have long disappeared in the river of history[45,46]. Virtual tourist scenes can be presented in various forms, either panorama spliced together with filmed images[47] or hyper-realistic 3D models reconstructed by Unreal/

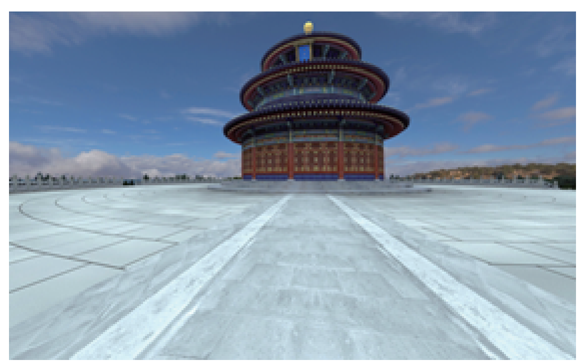


Figure 3 Web3D online smart travel application[9].

Figure 4 Virtual building in Web3D[10].

[9]https://www.web3di.com/article-889.html

[10]https://www.proginn.com/w/1352727

Unity3D[48,51]. As WebXR technologies become increasingly mature, experience forms of virtual tourism have migrated from 3D scenes displayed on web browsers to various types of VR/AR headsets that enable an immersive experience of roaming through 3D scenes, which provides users with a much stronger sense of reality and immersion[52,53].

4.2 Web3D online architecture and real-time rendering technology

Web3D online architecture is a type of online real-time interactive Web3D application based on 3D reconstruction of architectural models (Figure 4). They typically have higher requirements for real-time interactivity and multiparty collaboration. Taking advantage of real-time rendering, these applications seek to achieve real-time visualized sharing for both users and designers through a web browser so that they can collaborate and create an architectural solution in real time. In recent years, complicated building information modeling (BIM) has become an industry standard for electronic data in the construction field, creating a strong demand for web-based presentations of such models in the industry[54]. However, owing to their 4V attributes (volume, variety, velocity, and value), this dataset is very large and difficult to display on the web. Therefore, lightweighting is the key to the online visualization of BIM in web browsers. Currently, there are two types of mainstream methods for BIM lighting: 1) the semantic deduplication method, which scans and analyzes the content and references of the entire BIM file from the semantic level to identify and remove all redundant information with semantic duplication. This is also the method adopted by many lightweighting tools including Solibri IFC Optimizer[11], IFCCompressor[55], and BIMSeek[56,57]. 2) The geometric deduplication method, which deduplicates BIM building units with similar shapes to a certain extent and generates a lightweight geometric description. Lightweighting tools including LBSF[58], LPM[59], and LitStreamingIFC[60] are based on this method. Instanced rendering with the help of the Three.js engine can enable the online web visualization of BIM scenes to reach the GB level[61].

4.3 Web3D online educational environment and real-time rendering technology

The Web3D online education environment is a type of online real-time interactive 3D learning environment built with the help of Web3D technology that enables a strong sense of reality and immersion (Figure 5). It provides users with interactive virtual reality services with the help of real-time rendering technology and the mobile Internet. The Web 3D online education environment provides interactive VR services through the Internet and can reach a large number of potential learners at any time and anywhere around the world. In this learning environment, learners are allowed to interact with various virtual objects, which helps stimulate their learning interest and increases learning efficiency[62]. Web3D online education environments can solve many challenges in traditional teaching: 1) Web3D online education environments can help deal with the limited supply of experimental instruments in teaching, reduce the risk from experimental operations, and solve the problem of insufficient experimental sites[63]; 2) Web3D online education environments can enable the teaching of certain subjects with scenes that cannot be reproduced in the real world owing to distance, cost, or danger, for example, geocentric measurement, deep-sea research, and space research[64,65]; and 3) Web3D online education environments show

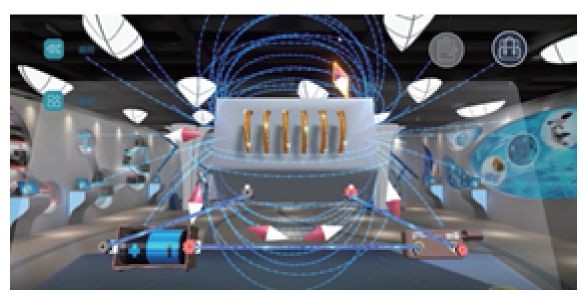


Figure 5 Virtual physics teaching in Web3D[12](maglcloud).

[11] http://www.solibri.com/

[12] http://www.magicloudedu.com/wlxl/show/55.html

greater efficacy in helping learners understand knowledge points that are more complicated[66–69].

4.4 Web3D online medical care and real-time rendering technology

Web3D online medical care is a type of real-time interactive Web3D application that provides comprehensive 3D visualization assistance for all types of medical activities (Figure 6). By enabling real-time interactive 3D visualization simulation and emulation of key medical behaviors or medical objects in medical activities with the help of real-time rendering technology, these applications are designed to assist healthcare professionals in developing skills, determining patient conditions, predicting surgical risks, and constructing treatment plans in real-world medical environments. First, such applications have made major contributions to the high-quality rendering of human organs, with rich outcomes achieved in assisting volume rendering. Currently, most volume datasets of human organs in the medical field are stored in DICOM files (including CT and MRI images) in the form of volumetric data obtained through the sampling of two-dimensional images. With the development of cloud computing and cloud storage technologies, the processing of volumetric data of patients is carried out more often on cloud platforms, and Web3D visualization applications can provide more convenient and faster access to 3D imaging for this purpose[70–73]. In addition, online simulation of 3D virtual surgeries and interactive training is another highlight of such applications, with tremendous help offered to medical workers, especially beginners, by enabling an immersive 3D virtual training experience that covers all stages, from gross anatomy to delicate surgery[74,75].

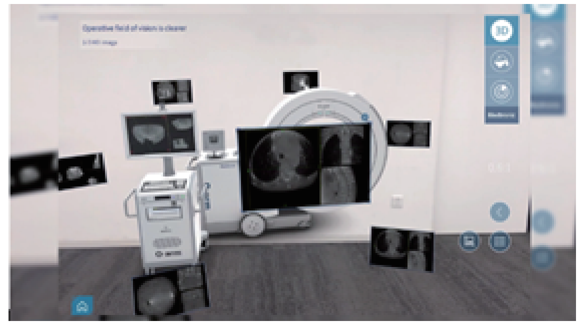


Figure 6 Online medical AR showroom[13](sight plus).

4.5 Web3D online shopping and real-time rendering technology

Web3D online shopping is the most sophisticated segment in the e-commerce sector. Unlike traditional online shopping websites that display 2D images and videos to buyers, these applications enable the real-time interactive virtual 3D display of various merchandise with the help of real-time rendering technology and the web platform. Web3D online shopping leverages an interactive 3D immersive experience and highlights personalized customization. McQueen et al. integrated WebXR technology into 3D scanning technology and delivered Web3D online virtual try-on applications to buyers[76]. Furthermore, Zhu et al. implemented a Web3D online clothing customization application using VR and Unity3D[77], which delivers a completely immersive online clothing shopping experience from try-on to customization. With the help of cloud computing, remote rendering, and Web3D technologies, virtual household supply manufacturers led by Kujiale have enabled a one-stop personalized customization experience of household supplies that goes all the way from Web3D online design to online price offers and online purchases (Figure 7). Through

Figure 7 Web3D furniture design[14](kujiale).

[13]http://www.sightp.com/solution/medical.html

[14]https://www.kujiale.com/dwork/column/3FO4K4W1OV8K?kpm=9V8.34711515e20587d6.2ca

Web3D applications, Dat et al. made online virtual modification of cars possible, which laid a solid foundation for the personalized customization of cars[78]. Web3D online shopping applications integrate various types of information and consolidate relevant correlations based on customer needs so that users can interact with visual solutions more efficiently and obtain the needed information quickly and accurately to make their consumer decisions. Web3D online shopping has relieved the cognitive load for users while raising the quality of the user experience, which ultimately translates into higher shopping efficiency[79].

4.6 Web3D online CAD and real-time rendering technology

Computer-aided design (CAD) is a technology that aids or optimizes the design of various projects with the help of the computer and is widely applied in several industries, including mechanical manufacturing, automotive design, shipbuilding, and architectural design (Figure 8). Commercial CAD software on PC represented by AutoCAD, Vectorworks, and CATIA offers impressive user experience with excellent design performance and a massive number of design functions. However, the refined design functions offered by commercial CAD software on PC inevitably result in a complex design model. Emphasis on the refinement of individual work has led to the neglect of collaboration between designers. Online real-time CAD applications based on real-time rendering technology and web platforms have focused on lightweight models, design collaboration, and scalability of the software itself while ensuring the refinement and accuracy of the design model[80]. Recently, these applications have emerged in large numbers. Soares et al. proposed a collaborative web-based CAD application that enabled simultaneous design and communication between multiple engineers[81]. Lee et al. proposed a web-based collaborative design system that can support files from multiple CAD systems and retain reusable design drawings[82]. Simões et al. proposed a Web3D-based CAD data interaction system that further emphasized the cross-platform nature of Web3D online CAD applications[83]. Kado et al. integrated WebXR into CAD applications and enabled an immersive VR experience of CAD models on the Web[84].

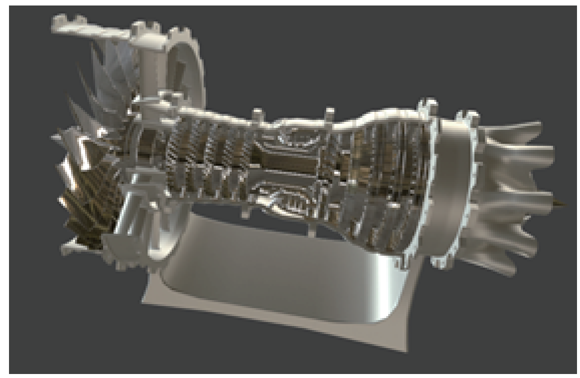


Figure 8 Online CAD design[15] (3D interactive network).

5 Conclusions and future outlook

In the mobile Internet era, web browsers, an interactive platform with an extremely large user base, have begun to gain the ability to produce 3D visualization applications (Web3D applications) that deliver a strong sense of reality and immersion with the support of 3D graphics APIs including Stage3d, WebGL, WebGPU, and WebXR. Driven by the development of mobile Internet technology, Web3D online applications are emerging in many fields, including tourism, architecture, medical care, education, and shopping, while exerting a greater influence on people's lives. To simplify the development of Web3D applications, several Web3D engines have emerged, including Three.js, Playcanvas, Babylon.js, and Filament. Various Web3D engines have promoted the prevalence of Web3D applications.

With concepts such as metaverse and Web 3.0 gaining popularity, the entire Web3D online application industry is expected to undergo tremendous changes. In particular, online VR applications based on WebXR

[15]https://www.d-d-d.cn/engine/index.html

technology have continued to provide users with experiences that deliver a stronger sense of reality and immersion through web platforms and VR/AR headsets, making it a major development direction for Web3D applications. In addition, with the growing popularity of WebGPUs, the integrated solution of WebAssembly +WebGPU is expected to become one of the mainstream underlying technological solutions for complex online 3D scenes, which also contributes to a better real-time rendering effect.

Declaration of competing interest

We declare that we have no conflict of interest.

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