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MAIN STAGES OF RENDERING AND THE DEVELOPMENT PROSPECTS OF ITS SOFTWARE COMPONENTS

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Introduction. The productivity and realism level of three dimensional images formation significantly depends on the peculiarities of rendering algorithms and methods. Rendering is the process of creating an image from a geometrical model using a computer program. To increase the efficiency of images visualization, the improvement of rendering algorithms is constantly being carried out, as a result, the new promising rendering directions are emerging.

Aim. The analysis of main rendering stages and the overview of rendering development prospects.

Materials and methods. The analysis of scientific literature and rendering textbooks.

Results and discussion. The main stages of rendering [1] are modeling, texturing, lighting settings, animation, camera settings, actual rendering, post-processing. The modeling stage lies in creating 3D models of scene's objects. This includes specifying the shape, structure, and dimensions of each object. Object modeling can be done using polygons, splines or NURBS (Non-Uniform Rational B-Splines), depending on the needs of the project. Most often, the triangles [1] are used to represent the surfaces of objects, they are the simplest polygons and provide a guaranteed decomposition of the surface. The usage of splines requires the development of special algorithms. NURBS curves [2] involve the usage of weighs to specify the shape of the curve and are characterized by flexibility for representing various surface shapes. At the texturing stage [1], the textures are mapped to the model to add detail, color and visual effects. Textures can represent realistic materials like leather, metal, wood, and more. In addition to textures, materials play an important role in determining how a surface interacts with light, considering reflections, transparency, and roughness. The lighting adjustment stage involves setting the scene's light sources that define shadows, brightness and contrasts. Lighting [3] can be simple (one source), complex (a combination of different sources), point (unidirectional lighting from a point), spotlight (conical lighting in a given direction), planar (illumination from a plane like a screen), solar (from infinite remote source), global (the reflection, refraction and scattering of light reflected from other objects is additionally taken into account). An animation stage [2] occurs if the scene is dynamic. Developers animate objects by setting trajectories of movement, rotation directions and other dynamic characteristics. The main four approaches [2] to animation are the use of key frames, procedural animation (based on mathematical procedures), the use of physically-based techniques (solving equations), motion capture (registration of the movement of real objects). The camera setting stage lies in determining the position, orientation and parameters of the camera. This includes choosing the angle of view, depth of field and other camera parameters.

Actual rendering [1] is the stage at which the computer calculates how the light interacts with objects and textures in the scene in order to create final image. The stage is characterized by the fact that it contains 60-80% [4] of calculations for the three-dimensional image formation. The rendering process may vary from simple rasterization to complex methods like ray tracing. Rasterization converts 3D models to 2D images by transforming the vertices and finding the pixels that should be shaded. At the same time, the shading methods are used [1]. The method of flat shading lies in shading a polygon with one color, the Gouraud method [1] lies in linear interpolation of color intensities between the vertices of a polygon, Phong method [1] lies in the interpolation of the normals between the polygon's vertices. Ray tracing, on the other hand, simulates the real world physical processes of light reflection and refraction, which produces more realistic images but requires more computational resources. The final stage of post-processing can include color correction, adding special effects such as blur , glows, integration with other images and general improvement of visual quality of the formed image. Anti-aliasing algorithms are used to eliminate the jagged edges effect [5]. For example, multisampling works by computing multiple samples for each pixel and averaging those samples to create a smoother image.

Each of these stages requires specific knowledge and may take some time depending on the project's complexity and the chosen rendering technology. Let's consider the approaches to rendering optimization and latest technologies in this area.

Real-time rendering [5] faces unique challenges because it requires high data processing speed and quick system responses. For this, the special shaders, which allow to programmatically control how the points, edges and surfaces are processed and visualized, and advanced graphics processors (GPU), which can process large amounts of data in parallel, significantly improving rendering speed, are used. Although raytracing technology is already used in games and visual applications, its real-time implementation still requires significant computational resources. Research is aimed at optimizing raytracing algorithms to reduce the hardware requirements, which will allow the technology usage on a wider range of devices.

Deferred rendering [6] is a technique that allows more efficient processing of a large number of light sources in a scene. It lies in dividing the rendering process into two stages: firstly, the parameters of the materials and geometry of each pixel are recorded in the G-buffer (geometric stage), and then, in a separate pass, the deferred characteristics of light interaction are calculated (lighting stage). At the same time, only those polygons that have passed the depth test are processed during the second pass. This increases efficiency when there are many lighting effects.

The technique of physically-based rendering (PBR) is based on the physical laws of interaction of light with surfaces, which allows to achieve the high realism of the images. The roughness of the surface and its microfacet representation [5], the wave-particle nature of light, surface reflectance models [7, 8], diffraction models, Fresnel formulas for light reflection and refraction, and subsurface scattering of light can be taken into account. The improvements of physical models, such as more accurate modeling of fluid environments, soft bodies, and complex materials, can greatly enhance the realism of scenes. These techniques play a key role in scientific visualization, game development, and cinematography.

The adaptive rendering technique [9] is used to optimize the rendering process by dynamically changing the visualization quality in different parts of the scene depending on the need. The optimal level of detail (LoD) of the object is determined. For example, less important parts of an image may be rendered in lower detail, while key points may be rendered in higher detail. Objects close to the camera are modeled in more detailed way than distant objects. At the same time, the image rendering quality shouldn’t be significantly reduced. The technique allows better usage of computational resources and improves the performance of object visualization.

Perspective-correct rendering [10] is a technique that ensures the correct representation of textures on three-dimensional objects in perspective, so that they look natural and realistic, in particular, when viewed from different angles. The main aspects of perspective-correct rendering are interpolation of texture coordinates considering the perspective, texture correction and taking into account Z-depth. Interpolation of texture coordinates is carried out by taking into account the depth (Z-buffer value) of each point on the polygon. Texture correction is carried out through the usage of mathematical methods. Points closer to the viewer represent the bigger parts of the texture, while points farther away represent the smaller parts. As a result, the texture coordinates are not distorted in perspective and provide a more realistic representation. Considering Z-depth is important for determining which parts of an object should be visible and which parts should be hidden behind other objects. The advantages of perspective-correct rendering are the creation of more realistic and immersive 3D scenes, the natural appearance of textures from any viewing angle, which is critically important for interactive applications. The challenges are computational complexity and the need to optimize the method for different hardware. This is especially relevant for mobile devices where resources are limited.

Artificial intelligence (AI) and machine learning are gradually integrated into rendering processes, helping to automate and optimize many tasks [11], including determining the optimal level of detail of object's polygonal model, simplifying a polygonal model, automatically improving texture quality, predicting the intensity of pixel colors, improving the quality of the rendered image, generating realistic facial animations and character emotions. AI can also be used to simulate physical phenomena such as fluid interactions, providing a high level of detail without the need to manually model every detail. Further merging of rendering with fields such as artificial intelligence, big data, Internet of Things may lead to fully integrated systems that can respond and adapt in real time to changes in their environment.

As VR [5] and AR continue to gain popularity, there is a need for specialized rendering techniques that can optimize and enhance the visual experience in these environments. In particular, reducing latency, improving spatial interaction, and implementing accurate lighting and shadows are critical to providing an immersive experience. Technologies that integrate sensory information (sound, touch) into the visualization process can significantly enhance the immersiveness of virtual realities and open up the new opportunities for interactive applications.

Cloud technologies allow rendering on powerful servers instead of local systems, which is especially useful for projects with high quality requirements, such as animated films or complex scientific visualizations. A significant advantage of using cloud technologies is the parallelization of the formation of graphic scenes on different remote machines. This allows to approximately reduce the cost of equipment and electricity by three times, makes rendering more accessible to a wider audience and provides the ability to scale the computational resources.

With the increasing of size and complexity of data in modern projects, the efficient processing of large volumes of information becomes important. The development of rendering systems that can be scaled and efficiently process large datasets is critical for many industries, including scientific research, big data visualization, and realistic simulation of the surrounding world. Advanced ways of representing data, including voxels and point clouds, provide high accuracy and detail, which is crucial for analyzing large volumes of information.

Although quantum computing is still in its early stages of development, it has the potential to revolutionize the field of rendering, especially in computationally demanding tasks such as real-time ray tracing and simulation of large systems. Quantum technologies can significantly speed up the calculations that require significant resources, and allow the creation of more detailed and complex visual effects today. For example, on the basis of neural radiancee fields (NeRF), the concept of quantum radiance fields (QRF [12]) was introduced. Color intensities and transparency levels are predicted for surface points, based on which quantum volumetric rendering is applied. At the same time, the speed of visualization is hundreds of times higher [12] than during the neural networks usage.

The advances in rendering personalization can provide users with unique visual experiences that adapt to their individual preferences or usage conditions. This may include adapting color schemes for visually impaired people or customizing interfaces depending on the context of use, such as in a dark environment.

Conclusions. Three-dimensional rendering lies in forming an image based on a geometric model of the scene. The stage is characterized by the biggest computational complexity during the scene visualiztion. The development of real-time, perspective-correct, deferred, physically-based, adaptive directions of rendering is promising. It is appropriate to combine the rendering process with the technologies of machine learning, quantum computing, cloud computing, and virtual reality.

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