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High dynamic range rendering of virtual 3D scenes

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Abstract
This bachelor's thesis covers the topic of High Dynamic Range (HDR), specifically various HDR techniques that are widely used in the field of computer graphics. Additionally, it covers the Vulkan API and its application for HDR rendering of virtual 3D scenes. The practical part of this thesis is a 3D rendering application, which purpose is to demonstrate the practical implementation of the described HDR techniques, such as global tone mapping operators (photographic, filmic and ACES-based), dynamic eye adaptation, spatially-variant tone mapping based on bilateral filter, exposure fusion, and an advanced bloom effect.

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1. Introduction

This bachelor's thesis delves into the topic of High Dynamic Range (HDR), which is a crucial technology in the computer graphics field, that helps to overcome the limitations of traditional rendering methods by faithfully capturing and reproducing the complexities of light and color.

The thesis explores different methods commonly used in the field and demonstrates how they can be utilized for HDR rendering of virtual 3D scenes. The practical goal is to develop a 3D rendering application to showcase the implementation of the described HDR techniques, specifically: *global tone mapping operators (photographic [1], filmic [2], [3], and ACES-based [4]), dynamic eye adaptation [5], [6], [7], spatially-variant tone mapping with bilateral filtering [8], exposure fusion [9]*, and an advanced *bloom effect* [10], [11]. After the implementation is described, each individual technique is accessed in terms of *visual quality* and *effectiveness*.

2. Research

Because HDR monitors are still not exactly common to have in modern days, I have first started my research by exploring the methods of mapping HDR images to Standard Dynamic Range that could be displayed on practically any device. This can be achieved by using *tone mapping operators*. Simpler operators are *global (or uniform)* ones, which are essentially just mathematical functions, that are applied in the same way for the color of every pixel of the image. Such operators can be efficient and easy to implement, but they might not be enough to achieve better and more realistic visual quality of the image.

So my next step in the research was to find a more elaborated solution to the problem, so I started to explore the field of *local (or spatially-variant)* tone mapping operators. These are usually more taxing in terms of performance and definitely harder to integrate into the rendering pipeline, as their implementation often consists of several post-processing steps to achieve the desired outcome. Nonetheless, such operators have become increasingly popular in the last $20-25$ years as the performance of personal computers has significantly increased. In this thesis, I have chosen to explore one of them that I have found to be relatively efficient and simple enough to be integrated into the demo application. This operator was invented in 2002 [8], and is based on *bilateral filter*, which is also described in this thesis.

Additionally, in this thesis, I have also explored the topic of *dynamic eye adaptation* [5]. The eye adaptation process can be simulated by computing the *average luminance* of the scene (*using a luminance histogram* [7]) and later adjusting the luminance of the next frame based on the computed average and elapsed time, using an *inverse exponent* function.

By further exploring the field of HDR, I have stumbled upon a more recent and more elaborate technique which is named *exposure fusion* [9]. This technique is able to produce incredible visual results that are unmatched in terms of preserved luminance range. It works by blending different exposure levels of the same image based on several weights that are computed for each pixel. The images are blended on different spatial frequencies, which allows for smooth transitions between differently-lit areas of the image while also avoiding noticeable halos.

The research part of this thesis is concluded with the bloom effect implementation. Two approaches for the effect are reviewed and compared, with the latter one (*from the year 2014* [10]) being more realistic and visually appealing. The more realistic approach is later implemented in the demo application.

3. Implementation

The practical outcome of this thesis is the 3D rendering demo application created using the Vulkan graphics API and C++ programming language. It allows the user to load different 3D scenes and HDR skyboxes to assess different HDR post-processing effects. The effects can be turned on/off and combined arbitrarily.

4. Experiments

Demo application was tested on *2* devices with different technical parameters. Specifications of individual test setups are listed in Table 1. *Second device* also has a monitor with HDR support connected.

Device	D1	D2
GPU	Nvidia GTX1650	Nvidia RTX 4090
CPU	I-I Core i7 9750H	AMD R-n 9 7950X3D
Monitor	DELL P2422H	*DELL AW2723DF*
OS	Win 10	Win 10

Table 1. Specifications of testing device setups.

Table 2 contains estimated performance on different testing device setups. Performance is listed as *Frames per second (FPS)*, which indicates how many times per second the application was able to update the content of the window (i.e. to render the scene and redraw the UI). FPS was measured for the interval of *15 seconds*, while rapidly moving around the scene to ensure that the measurement is not restricted to a specific camera view.

From the table it is clear that *global tone mapping* operators are the most efficient in terms of performance, next by efficiency is the *eye adaptation*, which is also expected as this effect doesn't require any complex computations. *Bilateral filter tone mapping*, however, is less efficient, most likely because of bilateral filter itself, which is doing a lot of computations (especially if bigger *radius* is set). Next comes the *bloom effect*, which is expected to be hard on performance, because the *downsampling, upsampling* and *blur* is executed for each mip level. And by far the most performance-heavy effect is *exposure fusion* because of how many processing stages it requires to achieve the result.

	FPS	
Effect	D1	D2
No effect	185.26	1040.33
Global TMO	178.33	1027.6
Eye Adaptation	165.60	982.4
Bilateral TMO	153.06	937.133
Bloom	140.33	883.333
Exposure Fusion	109.13	819.0

Table 2. Performance of individual effects on different test setups.

There is no doubt that there is room for optimizations for every effect, but it would require more proficiency and time for experiments.

5. Conclusions

By assessing individual implemented HDR techniques, I came to a conclusion that *exposure fusion* effect provides the best visual results compared to other tone mapping methods. But it requires bigger computational power and correctly setting individual exposure levels for each scene.

The eye adaptation effect is generally working as expected, but it usually requires some previous configuration (i.e., setting *min* and *max* luminance for the histogram, histogram bounds, etc.).

The bloom effect produces very good visual results, but it has a minor flaw, which is the *stair-step artifacts*, that may be visible at a lower scale. A solution to that problem may be to change or improve the method of how the texture is sampled during the downsampling or upsampling process.

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