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Evaluating State of the Art Upscaling Technologies: Performance, Image Quality and Gaming Scenario Suitability

Christoph Alexander Mayer

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Contents

Abstract

The advancement of video game graphics has led to an increase in demand of processing power which is typically provided by Graphics Processing Units (GPUs) from major companies like Nvidia, Intel, and AMD. However, the quest for more GPU capabilities is faced by challenges such as transistor scaling limitations and an increase in energy consumption which raises concerns for sustainability and environmental impact.

In order to counter these issues upscaling technologies like Nvidia's Deep Learning Super Sampling (DLSS) utilize Artificial Intelligence (AI) to enhance performance and even the image quality. There are even cases where upscaling techniques can reduce energy consumption which is especially a crucial point for consumers since environmental protection becomes more important and energy prices are on the rise.

This research aims to fill these gaps by conducting a comprehensive comparative analysis of Nvidia DLSS, AMD FSR and Intel XeSS. The primary research objectives revolve around the examination of the performance, image quality and suitability within modern gaming environments.

The research design herby revolves around extensive benchmark tests across all upscaling technologies and multiple graphics cards generations. Important metrics include the frame rate, frame consistency and even the GPU energy consumption. Games of a variety of different genres and game engines are assessed.

Keywords: DLSS, FSR, XeSS, Upscaling Technologies, Gaming Performance

1 Introduction

Nowadays video game graphics are improving constantly. Complex particle physics as well as racy-traced light effects where lighting is rendered in real time as individual rays, have become the standard within the video gaming industry. These effects require lots of processing power. For consumers of video games to run these video games they rely on dedicated hardware known as Graphis Processing Units (GPUs) from one of the three major companies such as Nvidia, Intel, and AMD (Watson, 2020, p. 1).

However, the pursuit of increasing GPU processing power to cope with ever-new great-looking video games is faced with challenges such as the issue that transistors approach atomic sizes. Furthermore, the pursuit of engineering new and more powerful GPUs comes with a huge problem which is an increase in energy consumption. This increased energy demand is not only a challenge for efficient hardware usage but also raises concerns regarding sustainability and the contribution to environmental issues such as the climate change. Therefore, major companies in the industry are exploring innovative solutions, particularly in the area of upscaling technologies. One such technology is Nvidia's Deep Learning Super Sampling (DLSS) technology which uses the power of Artificial Intelligence (AI) in the upscaling process.

The goal of these technologies is to allow the majority of the graphics rendering to run at a lower resolution for increased performance, and then create a higher resolution image from that approximates the same level of detail as if the image had been rendered at this higher resolution. Astonishingly, Nvidia's DLSS can even increase the level of detail and image quality in video games (NVIDIA Corporation, 2023b).

A recent performance test of Cyberpunk 2077, the action RPG developed by CD Projekt RED, showcased impressive results with the utilization of the latest DLSS version, DLSS 3.0. When DLSS is enabled, the frames per second (FPS) skyrocket from a mere 20 to a remarkable 100 (Burnes, 2023). It's noteworthy that anything exceeding 30 FPS is generally considered to be smoothly without stuttering.

Moreover, upscaling technologies can also help to decrease power consumption since they optimize the rendering process of video games. For instance, DLSS 3.0, the latest version of DLSS, can help to reduce power consumption by up to 40 percent (White, 2022).

In addition to DLSS, there are other noteworthy technologies in the gaming world. One of these is XeSS by Intel which uses machine learning for image upscaling. Another technology is AMD FSR which takes a different approach without relying on artificial intelligence.

1.1 Research Objective

The research objective centers around the evaluation and assessment of the three upscaling technologies in form of a benchmark. That problem that comes up when looking at various benchmarks of large video game magazine such as Gamestar is that the focus is often on sole technology such as DLSS without testing the other technologies. As an example, in the technic report of Cyberpunk 2077 the author Nils Raettig solely focused on DLSS as a performance evaluation criterion and did not mention FSR. Furthermore, only the upscaling settings Performance and Quality were considered but not the setting Balanced. Furthermore, there were no tests regarding the GPU efficiency in terms of power consumption when using upscaling technologies (Raettig, 2020).

Another example hereby is Gamer Nexus, a large hardware review channel on YouTube. The review on the Nvidia Geforce RTX 4060 does include the power consumption of the RTX 4060 but does not emphasize whether the usage of upscaling technologies affect the power consumption. What is more, the benchmarks on Cyberpunk 2077 are extensive but does not include a variety of different upscaling technologies nor different graphical settings (Gamers Nexus, 2023).

By recognizing the limitations in current benchmarks and evaluations conducted by entities such as Gamestar or Gamer Nexus, this research aims to resolve these shortcomings by conducting a comprehensive and comparative assessment of the three upscaling technologies – Nvidia DLSS, AMD FSR and Intel XeSS. Unlike previous evaluations, the research objective is focus on all different graphical settings, upscaling settings and also to consider differences in GPU power consumption since energy efficiency is becoming more and more crucial to consumers.

1.2 Research Questions

Research Question:

How do various state-of-the-art upscaling technologies compare in terms of performance, image quality and suitability in the context of modern video games?

The aim of the research is to conduct a comparative analysis of state-of-the-art upscaling technologies. The focus lies on the performance measurement and image quality. Furthermore, a very important aspect is to the assess the suitability for optimal gaming experiences.

Sub Research Questions:

Sub-question 1: What are the key technological differences and underlying mechanisms between Nvidia DLSS, Intel XeSS, and AMD FSR in the context of image upscaling and enhancement for gaming?

This sub question is intended to go deeper into the technological differences and mechanisms among Nvidia DLSS, Intel XeSS, and AMD FSR. It aims to investigate the different approaches for image upscaling.

Sub question 2: How do Nvidia DLSS, Intel XeSS, and AMD FSR impact performance measured in frames per second (FPS) and frametimes across a diverse range of modern video games and different graphics card generations, specifically assessing their combined effect on overall performance and gameplay smoothness?

This sub question seeks to analyze the influence of Nvidia DLSS, Intel XeSS, and AMD FSR on the performance in terms of frames per second and frametimes in different video games and across graphics card generations.

Sub question 3: In what ways do Nvidia DLSS, Intel XeSS and AMD FSR influence the gaming scenario suitability in terms of a smooth gaming experience, image quality and energy consumption?

The third sub question aims to further highlight the gaming separability which can interpreted as the balance between a smooth gaming experience in terms of a high framerate in combination with a solid frametimes and a sharp and flawless image quality. In addition, since high energy consumption is becoming more and more a problem, this sub question also aims to investigate the influence that upscaling technologies have in terms of energy efficiency.

2 Research Background

In this chapter, a systemic literature review was conducted to better understand the image upscaling process as well as the current landscape of state-of-the-art upscaling technologies. The chapter focuses on their functionalities and operational methodologies. Each of these technologies represents up to date approaches in video game graphics enhancement whether it is by using neural networks, machine learning or advanced algorithms as in the case of AMD FSR.

2.1 The Theory behind Image Upscaling Technologies

GPUs were invented in order to meet the demands of parallel computation tasks from computer graphics. In the recent years display devices have developed a lot and displays which offer a 4K or 8K high resolution are not uncommon anymore. In addition, state-of-the-art video games and virtual reality headsets also demand higher resolutions, levels of detail and refresh rates than before. This results in the problem that the hardware power of GPUs has to increase exponentially but GPU can only grow in a linear fashion. That is why it is important to keep rendering at low resolution and obtain high resolution by applying image upscaling technologies (Zhihua et al., 2023, p. 2).

Image upscaling which is also known as super resolution is the process of increasing the resolution of an image to a higher resolution than the original resolution. There are several techniques which are used for image upscaling. Traditional methods such as interpolation for example and more advanced approaches such as machine learning based image upscaling (Zhihua et al., 2023, p. 2).

Traditional methods such as bilinear and bicubic interpolation work by estimating the values of new pixels based on the values of neighboring pixels in the original image. The bilinear approach uses the weighted average of the four nearest pixels. The bicubic interpolation uses a more complex approach. A complex algorithm which involves a large number of neighboring pixels to estimate the new pixel values. These methods are very effective but might result in blurred or low-quality images (Zhihua et al., 2023, p. 4)

In the recent years, machine learning-based approaches such as neural networks have gained attention because of the ability to generate high-quality images. One example for such a machine learning based approach would be Nvidia’s DLSS. These methods involve training a neural network on a massive dataset of low-resolution and high-resolution image pairs. These image pairs allow the network to learn complex patterns and features which enables it to generate realistic high-resolution images from low-resolution inputs. These techniques often produce superior results compared to traditional interpolation methods and are especially effective when it comes to preserving fine details and textures in the upscaled images. This is an important advantage when it comes to video games because this preservation of fine details and textures significantly enhance the immerse experience for gamers and also ensures a high level of visual fidelity and realism in gameplay (Zhihua et al., 2023, p. 4).

2.2 Definition of the State-of-the-Art Upscaling Technologies

In this paragraph the upscaling technologies Nvidia DLSS, AMD FSR and Intel XeSS are explained in detail in order to better understand how these technologies work and operate. These three technologies are the state-of-the-art upscaling technologies and leverage neural networks, machine learning or in the case of AMD FSR advanced algorithms.

2.2.1 Nvidia Deep Learning Super-Sampling (DLSS)

In modern video games the rendered frames are not display directly but rather the frames first endure a post processing image enhancement step which connects the input from multiple rendered frames. This process tries to remove visual artifacts such as aliasing. One of these techniques is called Temporal Anti-Aliasing (TAA) where a shader-based algorithm connects two frames by introducing motion vectors to determine where to sample the previous frame. The problem with such an image enhancement process is that the process is very hard to get in order to create a perfect image (NVIDIA Corporation, 2018, p. 34).

That is why Nvidia came up with an AI based solution called Nvidia DLSS. This solution to the image analysis and optimization problem uses a deep learning approach. Nvidia's deep neural network is called Deep Learning Super-Sampling. In contrast to the previously mentioned TAA approach, DLSS creates a much higher quality output from a given set of input samples and also has the capability to improve the overall performance of the video game in terms of frames per second (FPS). Another very important aspect is that Nvidia's solution allows for a faster rendering process since the algorithm uses lower input samples and then upscales the input to the target resolution (NVIDIA Corporation, 2018, p. 34).

DLSS features various quality presets that users can choose from. These modes provide different balances between image quality and performance. These modes differ by their pixel upsampling rates, with Performance linked to 4x, Balanced to 3x, and Quality to 2x upsampling (Liu, 2020, p. 20).

Another important component of Nvidia's architecture is the Tensor Cores. These Tensor Cores are used for tensor and matrix operations, which are essential computations for the deep learning model. DLSS uses the power these Tensor Cores to efficiently process and combine information from multiple frames, which allows DLSS to reconstruct high-quality images (NVIDIA Corporation, 2018, p. 4).

The convolutional neural network of Nvidia is trained by supercomputers ahead of time and is then delivered to the consumer's GPU through driver updates. In video game applications the pre-trained model which is part of the driver package works together with the GPU during gameplay. The GPU uses the pre-trained model in combination with the Tensor Cores to perform the neural network's computations in real-time (Watson, 2020, p. 4). Additionally, DLSS is an exclusive feature for Nvidia graphics card. DLSS debuted with the RTX 20 and the version 1.0. (NVIDIA Corporation, 2022, pp. 9–11).

The latest version of DLSS is version 3.0. This version which is only available for Nvidia RTX 4000 graphics cards which use an all-new Optical Flow Accelerator and AI frame generation that boosts the frame rates up to 2 times over the previous DLSS 2.0 version while also maintaining or exceeding native image quality. In addition, compared to traditional graphics rendering, DLSS 3 is up to 4 times faster while also offering low system latency (NVIDIA Corporation, 2023a, p. 5).

2.2.2 AMD FidelityFX Super Resolution (FSR)

FSR is a high-quality solution which is designed to produce high resolution frames from lower resolution inputs similar to Nvidia's DLSS. In addition, FSR is an open-source solution, and the source code can be accessed on GitHub (Riley & Arcila, 2022)

FSR does not use artificial intelligence, but the technology uses a spatial upscaler. This upscaler works by taking the current anti-aliased frame at render resolution and upscales it to the display resolution without relying on other data such as frame history or motion vectors (AMD, 2021b).

FSR is an algorithm that detects and recreates high-resolution edges from the source image. According to AMD those high-resolution edges are an utterly critical element which is indeed required for turning the current frame into a super resolution image (AMD, 2021b).

According to AMD, FSR is composed of two main passes:

- EASU (Edge-Adaptive Spatial Upsampling) an upscaling pass which also performs edge reconstruction. In this pass the input frame is analyzed and the main part of the algorithm detects gradient reversal from a set of input pixels (AMD, 2021b).
- RCAS (Robust Contrast-Adaptive Sharpening) is a sharpening pass which extracts details in the upscaled image (AMD, 2021b).

FSR features a variety of different quality modes including ultra quality, quality, balanced and performance. These modes offer different balances between image quality and performance. The difference between the modes is due to the increase of the scale factor between input resolution and output resolution. For example, an output resolution of 1920 by 1080 pixels means that in performance mode an input resolution of 960 by 540 pixels is used while in ultra quality mode an input resolution of 1477 by 831 pixels is used (AMD, 2021a, p. 10).

FSR is not bound to a specific graphics card vendor like Nvidia or AMD but can run on a variety of different GPUs. The technology also supports older GPU architectures (AMD, 2021a, p. 28).

2.2.3 Intel Xe Super Sampling (XeSS)

Intel XeSS is another upscaling technology which boots performance and allows upscaling from 1080p up to 4K. The technology tries to preserve the original image quality. This is even true when the upscaling factor is 2 (Kawiak et al., 2022, p. 3). Similar to DLSS and FSR, XeSS offers different quality modes which differ in performance and image quality, including ultra performance, performance, balanced, quality and ultra quality. The scale factors range hereby from 1.3 when using ultra quality to 2.3 when using ultra performance (Kawiak et al., 2022, p. 24).

XeSS is a deep learning based super sampling technique and replaces the TAA stage in the render stage. Furthermore, XeSS is a cross-platform solution and does not require a per-title training. The super sampling technique uses data the current and the previous frames and also increases the amount of information for the upscales. The technology also treats anti-aliasing and upscaling as a single problem in the process. In addition, XeSS preserver the quality at higher scaling factors when compared to spatial upscaling. FSR uses spatial upscaling for instance (Kawiak et al., 2022, p. 6).

It is worth noting that state-of-the-art super sampling techniques also come with their own issues. For example, ghosting, blurring and even flickering are problems that can occur (Kawiak et al., 2022, p. 6).

The software development kit (SDK) is also open source to developers. The Unreal Engine, which is used by many video games, includes a XeSS plugin for developers (Kawiak et al., 2022, p. 11).

The key difference between DLSS and XeSS is that XeSS supports graphics cards from multiple vendors, while DLSS relies on the usage of Nvidia graphics cards.

According to Sydney Butler (Butler, 2023b) DLSS also provides a better image quality compared to XeSS or even FSR and is present in more games and also offers a unique frame generation option which was introduced in version 3.0 of DLSS.

3 Research Design

The following sections describes the research design employed in the master thesis. The sections thoroughly explain the benchmark process in order to comprehensively evaluate Nvidia DLSS, AMD FSR, and Intel XeSS against native (standard) rendering. This approach aims to assess performance, image quality and gaming scenario suitability across diverse gaming environments.

3.1 Methodology

In order to answer the research questions an extensive benchmark test will be conducted. A benchmark is generally defined as the measure of the quality of something by comparing it with something else.

In this master thesis the benchmark process is serving as a methodical approach in order to test the performance, image quality and gaming scenario suitability of Nvidia DLSS, AMD FSR and Intel XeSS in comparison to native rendering.

The benchmark test will also be conducted by using two different graphics cards of two different generations. In particular, the Nvidia RTX 3060 from the Ampera microarchitecture which supports DLSS 2.0 and the Nvidia RTX 4060 from the Ada Lovelace microarchitecture which supports DLSS 3.0 (NVIDIA Corporation, 2023a, p. 9). The benchmark test is conducted on Nvidia graphics cards since Nvidia supports all three upscaling technologies.

Moreover, the selection of the Nvidia RTX 3060 and the newly introduced Nvidia RTX 4060 for this study finds its validation in the November 2023 Steam Hardware Survey. The RTX 3060 is used by 4.89 percent of all steam users. The RTX 4060 is already used by over 2 percent and growing (Valve, 2023). This justifies the selection of these two graphics cards. The complete experimental setup is mentioned in section 3.5.

The benchmark metrics include the average frames per second (FPS), the 1 % low fps, 0.1 % low fps, frametimes, GPU utilization and GPU energy consumption. These terms are defined in section 3.2.

The game selection spans across various different genres which offers a diverse set of gaming environments for the benchmark tests. The selection includes games such as Cyberpunk 2077, an award-winning action role playing video game developed by CD Project or Call of Duty Modern Warfare III, a first-person shooter game developed by Sledgehammer Games which offers intense and fast-paced combat scenarios. These games, alongside others in the selection support all three upscaling technologies. The complete selection can be found in section 3.3.

The data collection and data processing methodology are explained in section 3.6 and 3.7 respectively. This also involves the usage of various Python to facilitate the large-scale data collection, required for the comprehensive evaluation.

The sections 3.8 to 3.10 explain the process behind the evolution regarding performance, image quality and gaming scenario suitability.

3.2 Benchmark Metrics

Average FPS:

Frames per second is a highly important metric for PC gamers. In the gaming world, FPS and Hertz are often interchanged and misused. Hz is defined as cycles per second and is associated with the monitor. In contrast, FPS is the rate at which the system completes frames. FPS is typically rolling average since frame times are not consistent from frame to frame. In addition, the higher the FPS the smoother animations are. Furthermore, the author mentions an example that shows 240 FPS delivers a way smoother animation compared to 60 FPS (Tamsai, 2019).

1% Low FPS and 0.1% Low FPS:

The term "1 % low FPS" is the lowest frame rates one can experience 1 % of the time during gameplay. Similarly, the term "0.1% low FPS" refers to the lowest FPS one can experience 0.1 % of the time (Butler, 2023a).

These metrics give a more accurate understanding of the gaming experience than just using the average FPS since these metrics give insight into the worst-case scenarios. In addition, they help to identify instances of stuttering or lagging which can significantly impact gameplay even though the average FPS are fine (Butler, 2023a) .

Frametimes:

Frametime is defined by the time which passes between a frame that is rendered and the next frame. It also be defined in more simpler terms as how long a frame is on a screen. For example, if a frametime of a given time duration is 16 milliseconds that means that the last frame has been on the screen the exact period of time (Digital Masta, 2022).

Consistent frametimes have a significant impact on gameplay. The more consistent the frametimes are the less lags and stuttering occurs (Digital Masta, 2022).

In addition, the optimal frametime for 30 FPS is about 33.3 milliseconds and for 60 FPS it is about 16.7 milliseconds (Digital Masta, 2022).

GPU Utilization:

"GPU utilization refers to the percentage of time that a GPU is actively performing computations or processing data" (Ferro et al., 2017, p. 5). Therefore, GPU utilization measures how much of the GPU's processing capacity is used at a given time. High utilization indicates that the GPU is being fully utilized and is operating at its maximum capacity (Ferro et al., 2017, p. 5). This case can often be seen in AAA video games where the utilization is often sitting at 99 percent.

GPU Energy Consumption:

The GPU power consumption is the amount of electrical power consumed by the GPU while performing a specific task such as running a video game or an application. The energy consumption is typically measured in watts (W) and can be affected by various factors such as the workload, temperature and also the utilization of the GPU (Ferro et al., 2017, pp. 2–11).

Energy consumption can be measured through various means. For example, direct measurements such as internal sensor which collect samples to estimate the power consumption during a time interval. There are various third-party tools available to measure power consumption (Ferro et al., 2017, pp. 2–11).

3.3 Benchmark Setup

The experimental setup looks as following:

Benchmark PC Configuration:

- **Central Processing Unit (CPU):** Intel Core I5-10600K (base clock speed of 4.1 GHz, no over-locking applied)
- **CPU Cooler:** be quiet! Dark Rock Slim
- **Mainboard:** Asus Prime Z490-A
- **Random Access Memory (RAM):** Corsair Vengeance LPX 32GB (2x16GB) DDR4 3200MHz
- **Graphics Card 1**: ZOTAC GAMING GeForce RTX 3060 Twin Edge OC (Ampere)
- **Graphics Card 2:** Gigabyte NVIDIA GeForce RTX 4060 AERO OC (Ada Lovelace)
- **Storage:** SanDisk Ultra 3D 1 TB SSD (Internal SSD)
- **Power Supply:** be quiet! Pure Power 11 600 watts

Monitor:

- **Model:** Samsung Odyssey Gaming Monitor C27G73TQSR
- **Resolution:** 2,560 x 1,440 pixels (supports lower resolutions)
- **Panel Type:** VA-Panel
- **Supported Technologies:** AMD FreeSync Premium Pro, G-Sync, HDR
- **Reaction time:** 1 millisecond

Input Device:

To conduct the benchmark tests the Xbox Elite Wireless Controller Series 2 is used for input and control during gaming sessions. The controller is connected via a USB-C cable.

Graphics Drivers:

The same NVIDIA graphics drivers are installed for both the Nvidia Geforce RTX 4060 and Nvidia Geforce RTX 3060 in order to ensure consistent and comparable performance across the two graphics cards during the benchmarking process.

Resizable BAR Support:

Resizable BAR support has been enabled for both graphics cards in the motherboard UEFI settings. This feature allows the GPU to access the system's entire memory which can potentially improve performance in certain scenarios (Archer, 2021).

Operating System:

- Version: Microsoft Windows 11 Home, 64-bit
- Operating Version: 10.0.22361
- Build Version: 22631

3.4 Video Game Selection

In order to perform the benchmark tests the following video games have been selected:

- Call of Duty Modern Warfare III (2023)
- Diablo IV
- Assassin's Creed Mirage
- Cyberpunk 2077 Ultimate Edition
- The Witcher 3

All of these games support Nvidia DLSS, AMD FSR and Intel XeSS. The game selection covers a broad field of different genres including a first-person shooter, adventure games, an action role-playing dungeon crawling game as well as adventure games (PCGamingWiki, 2023). These games are also new, relevant and are played by millions worldwide.

The selection of video games for the benchmark tests is based on a comprehensive evaluation beyond factors just as popularity. Each game was chosen deliberately to include diverse genres, ensuring a comprehensive representation of different gaming experiences and demands.

As an example, Call of Duty Modern Warfare III, a first-person shooter, was chosen since it offers fast-paced gaming while offering incredible graphics. First-person shooters require a high framerate and steady frametimes without stuttering since it could affect a responsive gaming experience and frame stutters can lead to comprised accuracy which impacts the player's ability to hit the target and potentially lose a match. This is especially true for Esports players where high frame rates give these players the competitive edge (Tamsai, 2019).

3.5 Resolution, Graphics Quality Settings and Upscaling Settings

Resolution Testing:

- 1,920 x 1,080 pixels: Testing at the standard Full HD provides insights into the performance on mainstream display configurations. This standard is used by over 60 percent of all Steam users. Steam is a very popular online video game platform (Valve, 2023).
- 2,560 x 1,440 pixels: Since higher resolutions than Full HD are getting more common in the gaming world and the required monitors are also getting more affordable, this resolution is perfect for additional testing. According to the Steam Hardware Survey, 15 percent of all Steam users already use this resolution for their gaming experience (Valve, 2023).

Graphics Quality Settings:

Each game is tested across a spectrum of quality settings, ranging from low to high settings. This range of settings aims to evaluate how the upscaling technologies adapt to different graphical settings and optimize performance across different levels of detail and graphical complexity.

Settings for the Upscaling Technologies:

The upscaling technologies, namely Nvidia DLSS, AMD FSR and Intel XeSS, are tested across multiple preset modes. These preset modes are Performance, Balanced and Quality.

Additionally, investigating how GPU energy consumption varies across different resolutions, graphics quality settings and upscaling settings can yield valuable insight into the efficiency and resource utilization of these technologies.

3.6 Data Collection

During the benchmarking process the following data is collected:

- Average Frames per Second (FPS)
- 1 % Low FPS
- 0.1 % Low FPS
- Frametimes
- GPU Energy Consumption
- GPU Utilization
- Screenshots

The data is collected using various kinds of different third-party software:

- **MSI Afterburner**: This tool is used to collect the average FPS, the 1% low FPS and the 0.1% low FPS.
- **HWInfo:** This tool is used to collect sensory data. This includes GPU utilization, temperatures, core clocks, memory clock speed and GPU power consumption.
- **RTSS (River Tuner Statistics Server):** This tool is to display the data from MSI Afterburner and HW Info as an in-game overlay in order to see the data at first glance.
- **CapFrameX:** This tool is used to capture the frametimes.
- **Intel PresentMon**: This tool is used in order to validate and to confirm the data collected from MSI Afterburner.
- **Nvidia GeForce Experience**: This tool is used to capture the screenshots in order to evaluate the image quality.

3.7 Data Processing

The collected data from MSI Afterburner, HW Info and CapFrameX is processed and cleaned using Python scripts. Python is used as the main programming language here since Python supports a vast number of different libraries. For example. CapFrameX outputs the logs as a JSON file which is perfect for Python's inbuilt JSON library in order to further process the date.

The data cleaning process involves the following steps:

1. Data Aggregation: The Python scripts are designed to aggregate and consolidate the data collected from the various programs into a unified format. This step ensures consistency in the dataset.
2. Quality Check and Cleansing: The scripts perform quality checks to identify and inconsistencies, missing values or even outliers present in the data. This process is crucial for ensuring accuracy and reliability of the further analyses.

The Python scripts also save the processed and cleaned data into Excel (xlsx) files. These files serve as repositories for further analysis and also for graphical visualization.

3.8 Performance Evaluation

The performance evaluation metrics including average FPS, 1 % low FPS, 0.1% low FPS and frametimes serve as the starting point for the evaluation. The Frametimes represent the duration between frames and provide insight into the consistency of gameplay experiences.

This master thesis will also feature various graphs which showcase the performance differences between natively rendered graphics and those enhanced through upscaling technologies in video games. Plus, the thesis also includes graphs which show the consistency of frametimes.

ANOVA Test:

Moreover, to conduct a comprehensive analysis an ANOVA test will be conducted. The ANOVA test enables the comparison of means across multiple samples which allows for a statistical assessment of performance differences among the three upscaling technologies. The ANOVA tests helps to determine if there are statistically significant different among the technologies. It provides insight whether the observed differences in metrics like FPS or frametimes are due to the technology itself or are random occurrences (Newbold et al., 2023, p. 652).

In the ANOVA test the H0, the Null Hypothesis, is that there are no significant differences in performance among the various technologies tested. The H1, the Alternative Hypothesis, is that there is a significant difference in performance among the upscaling technologies (Newbold et al., 2023, p. 652).

The test will be conducted using a 95 % (alpha = 0.05) confidence interval since it is the general rule for researchers (Fein et al., 2022). In addition, the test will be performed using Python libraries such as SciPy which offers functionalities for statistical analysis (Pypi, 2023).

3.9 Image Quality Evaluation

The image quality assessment involves comparing native screenshots captured from the gameplay with their upscaled counterparts.

This approach aims to evaluate sharpness, contrast, brightness, clarity, artifacts and overall fidelity between the natively rendered image and the upscaled images using Nvidia DLSS, Intel XeSS and AMD FSR.

3.10 Gaming Scenario Suitability

The evaluation of upscaling technologies for gaming scenario suitability features various parameters. The first one is robustness which indicates a stable system without crashes or freezes during gameplay. This will be monitored throughout the benchmark tests and every crash or freeze will be logged and analyzed. Another important aspect is efficient hardware. Therefore, GPU power consumption and GPU utilization are part of the benchmark test. The question hereby is to answer to which extent upscaling technologies influence the power consumption of GPUs when compared to native rendering.

What is more, performance metrics such as the average FPS and frametimes are also an important factor to consider when evaluation upscaling technologies. A high average framerate and consistent frametimes are key for a consistent and smooth gaming experience.

3.11 Recommendation

After conducting the benchmark tests where the performance, image quality and gaming scenario suitability is tested for all three upscaling technologies, the next step is to draw conclusion and give recommendations. One important aspect is of course to assess which technology performs decently, meaning increasing the frames per second significantly and keeping steady frametimes. Plus, the image quality should also remain at a high level.

Since energy efficiency is a crucial aspect when it comes to video gaming nowadays, it is important that the upscaling technology offers a significant improvement in terms of energy consumption in conjunction with GPU utilization.

The aim is then to give a recommendation on which upscaling technology is the best.

4 Anticipated Contributions

The anticipated are multifaceted and can significantly enhance the existing knowledge in several ways:

1. **Comparative Analysis:** The aim of the research and more specifically the master thesis is to conduct a comparative analysis of Nvidia DLSS, AMD FSR and Intel XeSS against native rendering. By evaluation performance, image quality and gaming scenario suitability across diverse game genres and settings, this work fills the gap in understanding the upscaling technologies in a real-world evaluation.
2. **Efficiency and Sustainability**: This research project also delves into efficiency aspects of the upscaling technologies regarding energy consumption and resource utilization. By analyzing the GPU energy consumption and performance metrics under various settings, the ecological footprint of these technologies become visible.
3. **Hardware-Specific Insights:** By using two distinct generations of Nvidia Geforce RTX graphics cards, this research aims to shed light on the performance disparity between different GPU architectures. In addition, not only the performance disparity is relevant but also the focus on energy consumption can enhance the existing knowledge.
4. **Enhanced Benchmark Methodology**: The research introduces an advanced benchmarking methodology that extends beyond conventional performance evaluations. The benchmarking methodology includes various graphical settings, various upscaling technologies and settings and even a focus on GPU energy consumption that goes beyond the consumption when applying native rendering techniques but also focuses on the energy consumption when applying upscaling technologies. Furthermore, also various display resolutions are tested.

5 Project management

5.1 Time schedule

1. **Project Initiation**

Description: This phase involves the definition of the research objective, setting up the experimental environment and installing the necessary software for the benchmarking process.

Interdependence: This phase sets the foundation and also provides the infrastructure for conducting the benchmarking process and data analysis.

To be completed by: February 11, 2024

2. **Literature Review**

Description: In this phase there will be a comprehensive literature review to understand the underlying technologies behind Intel XeSS, AMD FSR and Nvidia DLSS.

Interdependence: The outcome of this phase is significant for the results interpretation but also for the data analysis process.

To be completed by: March 3, 2024

3. **Data Collection**

Description: During this phase the benchmarking tests on the various games and across the two graphics card generations will be taking place.

Interdependence: Dependent on the completion of the experimental setup and the successful installation of the necessary software which is done in the project initiation phase.

To be completed by: April 7, 2024

4. **Data Analysis**

Description: This phase involves the analysis of benchmark data, including frames per second, 1 % low fps, 0.1 % low fps, frametimes, energy consumption and also the screenshots in order to judge the image quality.

Interdependence**:** Depends on the completion of the data collection.

To be completed by: April 21, 2024

5. **Results Interpretation**

Description: This phase involves getting insights and drawing conclusion based on the analyzed data.

Interdependence: Depends on the completion of the data analysis

To be completed by: May 5, 2024

6. **Writing of the Master Thesis**

Description: In the phase, the actual writing of the master thesis will take place. This includes the important research findings, analysis and conclusion.

Interdependence: This phase depends on the completion of the results interpretation.

To be completed by: June 2, 2024

5.2 Risk analysis

1. Hardware or Software Failures

Potential Problem: Hardware parts such as graphics, the Random Access Memory or even software systems maybe fail during the benchmarking process which can lead to inaccurate results or even data loss.

Mitigation: Regular back up of data to the Google Drive folder and to the GitHub repository is very important to mitigate these risks. Moreover, I also have spare components such as another CPU cooler or storage devices on hand for a quick replacement. Furthermore, during the benchmarks the software program HW Info is used to check the temperature of the central processing unit and the graphics to guarantee that these components stay below the temperature threshold.

2. XeSS, FSR and DLSS Variability

Potential Problem: Intel XeSS, AMD FSR and Nvidia DLSS are upscaling technologies that might have variability in performance across different video games, versions, and settings. The variability inhibits a challenge in ensuring consistent and reliable benchmarking result as it may lead to discrepancies in performance measurements. Furthermore, inconsistent behavior can make it difficult to draw conclusions and potentially impact accuracy of the research findings.

Mitigation: In order to account for the variability of the benchmarking process there will be a diverse selection of video games used. The selection will be composed of games of different genres and graphic engines as well as visual styles. Furthermore, benchmarking will also be performed across multiple runs to account for fluctuations in performance. Averaging results from several runs provides a more stable performance measurement.

3. External Factors:

Potential Problem: Nowadays almost every video game relies on a permanent internet connection which can cause a problem in cause of an outage of the internet service provider. Moreover, there can also be issues with the server availability of the gaming provider which can lead to disruption in the benchmarking process.

Mitigation: In order to mitigate the risk of internet failure, there will be two separate internet connections available during the benchmarking process. One connection is established using a cable internet connection, while the other utilizes a mobile internet connection. The issue regarding the server availability is beyond my control. Therefore, the server status will be closely monitored, and server outages will be documented should any disruption occur during the benchmarking process.

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7 List of abbreviations

AI	Artificial Intelligence
ANOVA	Analysis of Variance
BAR	Base Address Register
CPU	Central Processing Unit
DLSS	Deep Learning Super Sampling
FSR	Fidelity Super Resolution
FPS	Frames per Second
GPU	Graphics Processing Unit
HD	High Definition
HDR	High Dynamic Range
RAM	Random Access Memory
RTX	Ray Tracing Technology
XeSS	Xe Super Sampling

8 Declaration of authorship

Evaluating State of the Art Upscaling Technologies:

Performance, Image Quality and Gaming Scenario Suitability

I hereby declare that the present paper is entirely my/our own work and without the use of any unauthorised assistance. Any content which has been taken verbatim or paraphrased from other sources has been identified as such. This paper has not been submitted in any form whatsoever to an examining body. Previously published work has been cited as such.

In this paper Artificial Intelligence tools such as ChatGPT, Bard by Google, ChatPDF, or Deepl Write were utilized.

[Christoph Alexander Mayer] [Vaduz, 12/21/2023]