REAL TIME VOLUMETRIC RENDERING OPTIMIZATION APPROACH FOR CLOUDSCAPES IN VIRTUAL ENVIRONMENT

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DEDICATION

This thesis is dedicated to my beloved parents, wife, kids, siblings, and friends.

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ABSTRACT

There is a great demand for visualizing natural atmospheric clouds in a real-time environment. However, the challenge is maintaining the cloud visualization system performance due to the high computational cost, high sampling cost, intensive main memory consumption, and the deterioration of system performance. Therefore, this research aimed to optimize the rendering performance of a real-time atmospheric cloudscape visualization system via a set of efficient methods considering the volumetric cloud data as the input, the fly-through navigation as the user interaction, and the realistic real-time features as the output of the generated image. First, the volumetric-based path tracing method was enhanced by reducing the number of ray castings during the intersection test and determining the new pixels via the frame-to-frame coherence mechanism. Second, the multiple light scattering method was improved by limiting the maximum number of sampling steps during the light bouncing procedure when calculating the lighting effects in the virtual environment. Third, the new hybrid visibility acceleration method was proposed. It took into account the view-dependency and multi-resolution cloud level of detail, focusing on distance-based view volume segments and the optimized view frustum culling method to remove the invisible regions of clouds in a real-time environment. Based on the experiment conducted, the proposed approach in the prototype system was capable of achieving about 3.83 to 18.58 times faster computational time. This showed an increase of approximately 2.53 to 19.21 times in rendering speed and consumed about 20.63% of the total computer's main memory space compared to previous systems. Furthermore, all the domain experts have reviewed and verified that the prototype system has effectively produced high visual realism of the generated images. Based on the results of this study, an improved real-time volumetric cloudscape rendering optimization approach has been successfully developed to address the inability of real-time rendering used in previous methods.

ABSTRAK

Terdapat permintaan yang besar untuk memaparkan awan atmosfera semula jadi dalam persekitaran masa-nyata. Walau bagaimanapun, cabarannya adalah untuk mengekalkan prestasi sistem pemaparan awan yang disebabkan oleh kos pengiraan yang tinggi, kos pensampelan yang tinggi, penggunaan ruang ingatan utama yang intensif dan kemerosotan prestasi sistem. Oleh itu, kajian ini bertujuan untuk mengoptimumkan prestasi perenderan sistem pemaparan landskap awan atmosfera masa-nyata melalui satu set kaedah yang efisien dengan mengambil kira data awan volumetrik sebagai input, navigasi melalui-penerbangan sebagai interaksi pengguna dan ciri-ciri masa-nyata realistik sebagai output imej yang dijana. Pertama, kaedah penjejakan laluan berasaskan volumetrik telah dipertingkatkan dengan mengurangkan bilangan penyebaran sinar semasa ujian persilangan dan menentukan piksel baharu melalui mekanisme pautan bingkai-ke-bingkai. Kedua, kaedah penyelerakan cahaya berganda telah ditambah baik dengan mengehadkan bilangan maksimum langkah pensampelan semasa prosedur pemantulan cahaya apabila mengira kesan pencahayaan dalam persekitaran maya. Ketiga, kaedah pemecutan keterlihatan hibrid baharu telah dicadangkan. Ia mengambil kira perincian kebergantungan-pandangan dan awan berbilang-resolusi, memfokuskan pada segmen isi padu pandangan berasaskan jarak dan kaedah penyingkiran ruang lingkup pandangan bagi membuang wilayah awan yang tidak kelihatan dalam persekitaran masa-nyata. Berdasarkan eksperimen yang dijalankan, pendekatan yang dicadangkan dalam sistem prototaip berupaya mencapai kira-kira 3.83 hingga 18.58 kali lebih pantas masa pengiraan. Ini menunjukkan peningkatan kira-kira 2.53 hingga 19.21 kali pertambahan dalam kelajuan perenderan dan menggunakan kira-kira 20.63% daripada keseluruhan ruang ingatan utama komputer berbanding sistem sebelumnya. Tambahan pula, semua pakar lapangan telah menyemak dan mengesahkan bahawa sistem prototaip telah menghasilkan realisme visual yang tinggi terhadap imej yang dijana. Berdasarkan hasil kajian ini, pendekatan pengoptimuman perenderan landskap awan volumetrik masa-nyata yang dipertingkatkan telah berjaya dibangunkan bagi menangani ketidakupayaan perenderan masa-nyata yang digunakan dalam kaedah sebelumnya.

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LIST OF ABBREVIATIONS

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LIST OF SYMBOLS

θ_{fov} : [illegible]

c : [illegible]

d : [illegible]

g : [illegible]

L_{comp} : [illegible]

L_e : [illegible]

L_i : [illegible]

L_o : [illegible]

M_{pmc} : [illegible]

M_{usage} : [illegible]

n_{frame} : [illegible]

n_{ray} : [illegible]

n_{sample} : [illegible]

$\hat{n}$: [illegible]

ρ_{HG} : [illegible]

P_{color} : [illegible]

R : [illegible]

s^2 : [illegible]

$t_{complete}$: [illegible]

t_{start} : [illegible]

$t_{current}$: [illegible]

$\hat{w}_i$: [illegible]

$\hat{w}_o$: [illegible]

X : [illegible]

v_n : [illegible]

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Overview

Computer graphics play an important role in visualizing compelling virtual environments (Sobota and Mattová, 2022). A virtual environment refers to any system that implements, organizes, and controls multiple virtual instances in a scene, as opposed to being in the real world (Souza et al., 2021; Slater et al., 2002). Technically, the virtual environment provides the illusion of presence in a place different from one's current physical surroundings, potentially a non-existent or a real place situated at a different physical location or a point in time (Lee and Park, 2022; Stanković, 2015). It can be a computer-based model to bring the actual environment to life in digital form using computer graphics methods, especially in three-dimensional (3D) spaces (Marto et al., 2022; Toumi et al., 2021; Schroeder, 2008; Ellis, 1994). The virtual environment can display various 3D scenes in indoor, outdoor, or mixed of both scenes. Therefore, virtual environment visualizations have reached a wide range of applications, including video games, movie productions, visual simulations, scientific visualization, and many more (Palacios, 2022; Raateland et al., 2022; Yapp and Kim, 2022; Keil et al., 2021; Kraus et al., 2021; Rambach et al., 2021; Knight and Munro, 1999). Moreover, advanced virtual environment methods are currently available and have become the hot topics trending in the computer graphics research community. These include collaborative virtual environments, mobile platform-based virtual environments, immersive virtual reality, augmented reality, photorealistic special effects, virtual humans, and acceleration methods.

Natural phenomena visualization is one of the crucial branches of scientific visualization in the virtual environment to visualize the outdoor scenes. In general, this phenomena visualization is essential for realizing the Digital Earth and understanding its elements using computer technologies (Betts, 2022; Boyd et al., 2022; Greinert et al., 2022; Bauer et al., 2021; Xian et al., 2021; Liu et al., 2020). This research categorizes the visualizations of natural phenomena into three types: (i) atmospheric, (ii) ground, and (iii) aquatic phenomena. These categories are based on the basic information provided by the previous works (Ahrens, 2022; Rudenko et al., 2022; Ma et al., 2021; Hendrix et al., 2020; Heidorn and Whitelaw, 2010; Wolff and Yaeger, 1993). Figure 1.1 shows the hierarchy of natural phenomena visualization in the virtual environment and its related subcomponents.

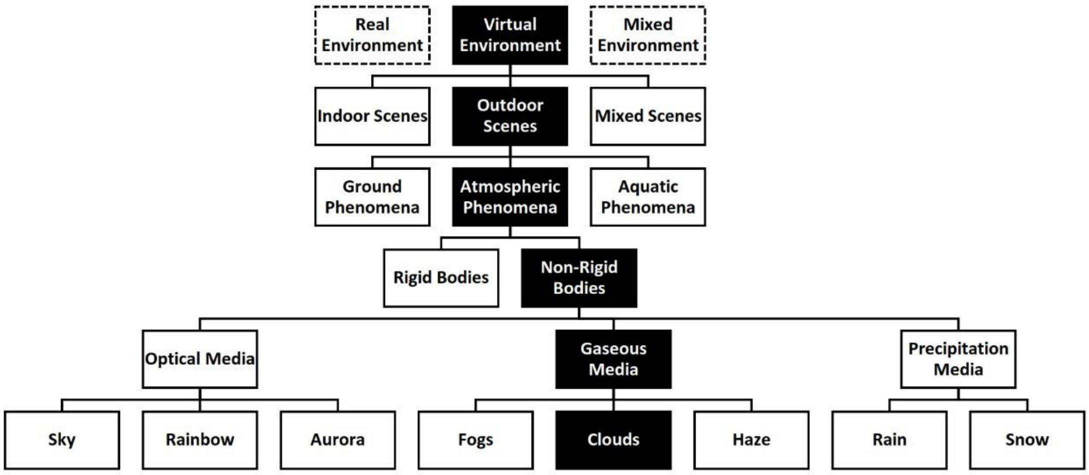

Figure 1.1 Hierarchy of natural phenomena visualization in the virtual environment (black-filled rectangles represent the focused components of this research).

Atmospheric phenomena visualizations become essential features in creating a realistic imitation of the natural environment. Non-rigid bodies (non-solid objects) represent the atmosphere’s structure due to its fuzzy and complex representations (Chen et al., 2022; Blaettler, 2021; Exline et al., 2008). In computer graphics, “participating media” is used to represent the atmospheric components. The subcomponents of the participating media contain gaseous media (clouds, fogs, haze, and hurricane), optical media (sky, rainbow, and aurora), and precipitation media (rain and snow) (Wu et al., 2022; Hendrix et al., 2020; Heidorn and Whitelaw, 2010; Wolff and Yaeger, 1993). In recent years, an increase in numerical model resolutions, the number of simulated parameters, and diversity of data sources has resulted in increased complexity of the related problems and, hence, higher challenges for 3D visualization (Fraboni et al., 2022; Rautenhaus et al., 2018).

Visualizing the atmospheric clouds in the virtual outdoor environment is vital in order to produce a realistic visual appearance of the atmosphere (Mirbauer et al., 2022; Rolnick et al., 2022; Satilmis et al., 2022; Goswami, 2020; Rimensberger et al., 2019). Atmospheric clouds are omnipresent in the Earth atmosphere, where they are significant actors in weather, hydrology, climate, and air chemistry (Spänkuch et al., 2022). Besides, the atmospheric clouds are natural science components that can represent the mood of an environment (Pennonen, 2020). In meteorological studies, a cloud is a hydrometeor comprising of tiny particles of liquid water droplets or ice crystals or both, suspended in the atmosphere and typically not touching the ground (Odugo, 2018). Furthermore, the clouds are classified based on their height (or altitude), shape, and appearance. Due to its attractive appearance and myriad of shapes, the atmospheric cloud visualization is scientifically challenging to be developed because the cloud formation requires both knowledge about the large-scale meteorological environment as well as knowledge about the microphysical processes involved in cloud droplet and ice crystal formation (Lohmann et al., 2016).

In video games, the clouds are frequently used to create a more believable 3D world. Recent advances in computer hardware technologies and computation capability have triggered the use of more detailed, realistic, and interactive representations of the cloud models (Kivi et al., 2022; Patry, 2021; Silvennoinen, 2021; Goswami, 2020; Ge et al., 2019; Hendrikx et al., 2013; Chandrasekar, 2010). Figure 1.2 illustrates the hierarchy of the atmospheric cloud visualization system and its related areas of research focus. The divisions of each area are formulated from several previous works (Zhang et al., 2021; Goswami, 2020; Dobkin and Teller, 2017; Slater et al., 2002). In recently published works, the term “cloudscape” has often appeared to solve issues regarding large cloud formations involved in modeling, rendering, and animation of the atmospheric clouds (Sharma et al., 2021; Goswami, 2020; Webanck et al., 2018; Schneider, 2018; Schneider and Vos, 2017; Toft et al., 2016; Webb et al., 2016).

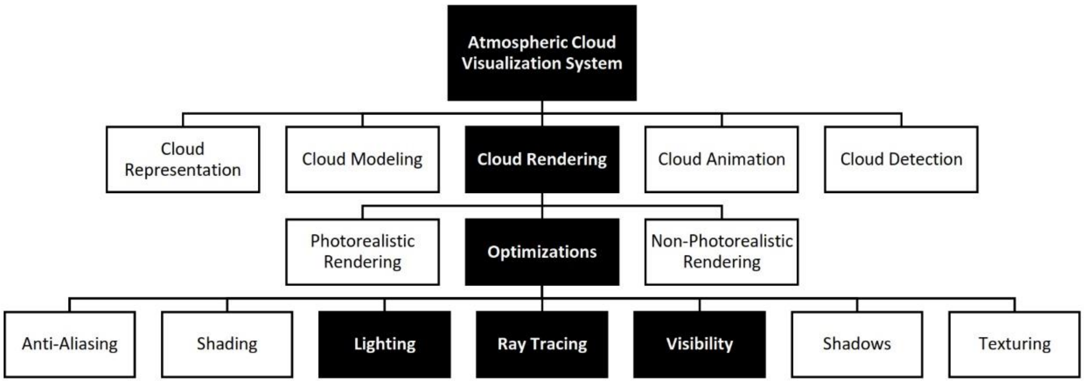

Figure 1.2 Areas of research focus on implementing the atmospheric cloud visualization system (black-filled rectangles represent the focused areas of this research).

Atmospheric cloud rendering is the most critical process and contributes to the atmospheric cloud visualization system. This process is the final stage of determining the color of each pixel on the screen. It generates a two-dimensional (2D) image in the form of a photorealistic or non-photorealistic appearance after assigning all the materials and graphic effects required to the cloud model (Mirbauer et al., 2022; Satilmis et al., 2022; Hempe, 2016). Several cloud rendering methods have been proposed for solving issues related to visual quality (e.g., Sde-Chen et al., 2021; Yu, 2020; Zhang et al., 2020), performance (e.g., Wu et al., 2021; Bittner, 2020; Jiménez de Parga and Gómez Palomo, 2019) or both of them (e.g., Hofmann et al., 2021; Nair, 2020). Real-time atmospheric volumetric cloud rendering is a hot topic in the computer graphics community to solve advanced issues in interactive graphic applications (Wu et al., 2022; Huo and Yoon, 2021; Akenine-Möller et al., 2018). However, real-time rendering and volumetric rendering are two different aspects that are very challenging tasks to be executed. Combining these aspects increases the difficulty in the context of computer hardware and computation capabilities to yield high real-time rates and high image quality.

Therefore, there is an excellent need to render optimizations to tackle the problems mentioned earlier. The purpose of implementing the rendering optimizations is to accelerate the system performance by simplifying the complexity of the existing cloud rendering methods to the level that the system can maintain high frame rates while producing a visually plausible image quality simultaneously (Czerninski and Schechner, 2021; Ronen et al., 2021; Sde-Chen et al., 2021; Toft et al., 2016). Ray tracing, lighting, and visibility of atmospheric clouds are three potential computer graphics methods that have high opportunities to be optimized because they are the major components contributing towards achieving efficient and effective quality of the volumetric clouds.

Ray tracing (ray-based model) is a modern rendering approach (Marrs et al., 2021; Haines and Akenine-Moller, 2019). Classic ray tracing, ray casting, ray marching, and path tracing are examples of the ray-based model. Previously, cloud visualization commonly exploited the traditional scanline approach (raster-based model) (e.g., Ang et al., 2018). The raster-based model transforms all geometry in the 3D world into pixels to determine the final colors on the screen. In contrast, the ray-based model starts shooting rays from each pixel of camera view to all geometry in the 3D world, detecting intersections between rays and geometry, and accounting for the light source to obtain the final colors (Hofmann et al., 2021; Peddie, 2019; Begbie and Horga, 2019). Rasterized rendering is a quicker way of creating 3D imagery. However, it comes at the cost of image quality. Ray-traced rendering could provide high visual fidelity. Nevertheless, it is more computationally demanding (Kivi et al., 2022; Haines and Akenine-Möller, 2019). Interestingly, the transition from the traditional scanline approach to the modern ray tracing approach occurred due to NVIDIA's revolutionary technology on the graphics processing unit (GPU). The related industry players are expected to shift rapidly towards parallel computing using a ray tracing approach to gain far higher performance (Marrs et al., 2021; Azultec, 2019).

Illuminating the atmospheric clouds in the 3D virtual environment is very important in order to produce convincing visual results (Brinck et al., 2021; Wright, 2021). The cloud lighting method is necessary to partner with the ray tracing method in realizing the realistic illumination model for atmospheric clouds. Atmospheric cloud lighting computations range from simple local illumination methods (e.g., Blinn, 1982; Bouthors et al., 2006) to more sophisticated global illumination methods such as ray tracing (e.g., Panin and Nikolenko, 2019) and path tracing (e.g., Hofmann et al., 2021; Max, 2021). However, implementing a multiple volume light scattering effect on the clouds is a difficult task due to its highly repetitive computations in nature (Kivi et al., 2022; Wu et al., 2022; Goswami, 2020). Several researchers proposed their methods (e.g., Mirbauer et al., 2022; Satilmis et al., 2022; Shihan et al., 2020; Kallweit et al., 2017) to optimize the scattering processes. However, the real-time rate is hard to achieve due to computational overhead. Hence, there is space for improvement.

In computer graphics, visibility determination is vital because only a small portion of the virtual scene (or world) is visible from a given viewpoint (Dang et al., 2022; Koch and Wimmer, 2021; Hu et al., 2020; O'Rourke, 2017; Cohen-Or et al., 2001; Hornung, 1984). Without visibility optimization, unnecessary computations inefficiently happened. There is a need for faster solutions to solve visibility-related problems. Visibility culling methods are ways to avoid processing the unnecessary objects that contribute nothing to the rendered image (Sicat et al., 2021; Mattausch et al., 2015; Cohen-Or et al., 2001). Recently, due to the rapidly increasing complexity of three-dimensional data sets, the investigation of suitable methods to control and adjust a given data set's level-of-detail (LOD) has been an active research area (e.g., Karis et al., 2021; Takikawa et al., 2021; Marcus, 2017; Jabłoński and Martyn, 2016). Incorporating visibility optimization into atmospheric cloudscape rendering would give a better real-time performance in time and space complexity.

To sum up, this research attempts to solve the rendering optimization problems regarding the ray tracing, lighting, and visibility of the atmospheric cloudscapes. The research requires to account for the real-time and volume rendering aspects in the 3D virtual environment in order to achieve high-performance results.

1.2 Problem Background

This section explains several related research problems involved in rendering the atmospheric clouds. Rendering virtual atmospheric clouds is a long-standing problem in computer graphics. It is not always an easy task and has been researched for over 40 years. Based on the recent research works, the rendering of atmospheric clouds is highly demanded and exploited in video games (e.g., Patry, 2021; Hillaire, 2020; Nair, 2020; Pettersson, 2020; Ang et al., 2018; Babić, 2018; Hu et al., 2018; Häggström, 2018; Hasegawa et al., 2017), visual simulations (e.g., Röber et al., 2021; Sde-Chen et al., 2021; Wu et al., 2021; Jiménez de Parga and Gómez Palomo, 2019; Webanck, 2019; Duarte and Gomes, 2017), meteorological studies (e.g., Pałubicki et al., 2022; Rudenko et al., 2022; Hädrich et al., 2020; Xie et al., 2020), virtual reality (e.g., Zhang et al., 2021; Wright et al., 2019), and animated movies (e.g., Wu and Fu, 2022; Hanrahan and Catmull, 2021; Junede and Asp, 2020; Goswami, 2019).

For example, atmospheric clouds are one of the essential elements in producing visual effects in filmmaking. Based on the statistic of the visual effects breakdown from 2010 to 2013 (see Figure 1.3), there are six key elements that were frequently employed in realizing the desired visual effects (Museth et al., 2019). These include hero effects (character-related effects), destruction, dust (or smoke), fire, liquids, and clouds. Even though the percentage of exploiting the cloud elements is small, it still contributes to the successful making of the visual effects in terms of convincing visual appearances, particularly for outdoor scenes. Besides, the importance of atmospheric clouds can be observed in the development of the weather system. Based on the flight simulation community survey conducted by Navigraph (2021), Figure 1.4 shows that most of the respondents chose that the weather, including clouds, is very important in terms of the realistic weather experience (visual quality) and visually exciting experience (perception and presence).

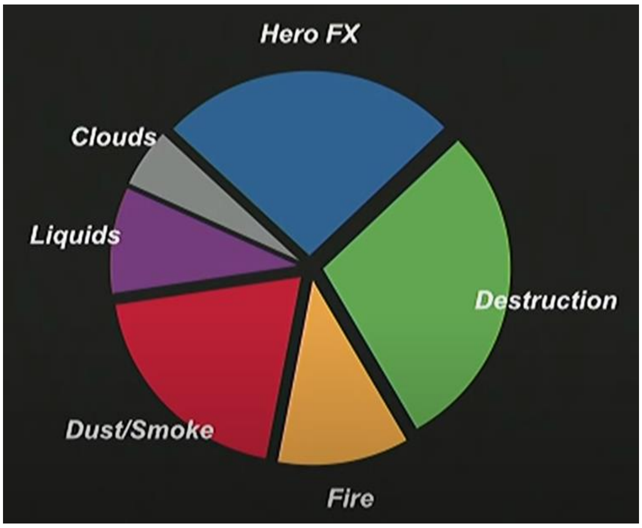

Figure 1.3 Main elements in visual effect productions (Museth et al., 2019).

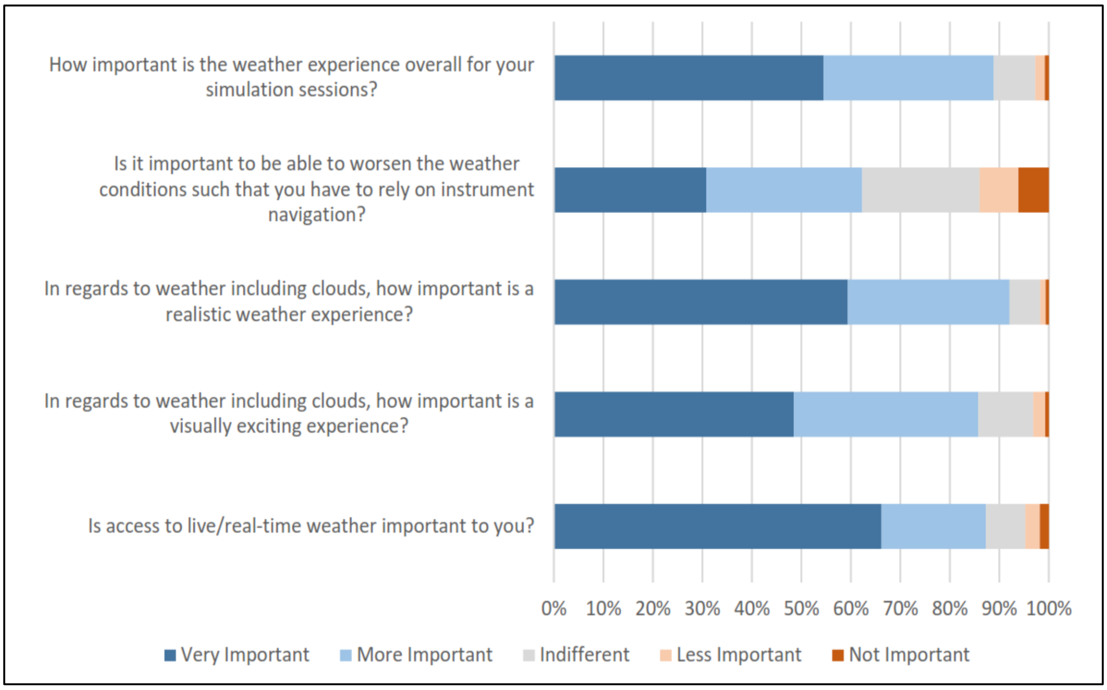

Figure 1.4 Importance of weather simulation (Navigraph, 2021).

The cause-effect diagram in Figure 1.5 illustrates the category breakdown of the issues (causes) regarding the unoptimized atmospheric cloud rendering problems (effect). The issues are divided into five main factors that contributed to the rendering problems of the atmospheric clouds. These include system, hardware, data representation, user, and method.

In this thesis, the system refers to a general application environment that makes the users' workable space. The real-time virtual environment (online-based system) is becoming the current trend and highly demanding feature in computer graphics applications. However, rendering this real-time feature is excessively expensive without extensive optimizations (Kivi et al., 2022; Toft et al., 2016). An example of a case study by Hasegawa et al. (2017) stated that it was challenging to understand and realize the virtual world in a real-time environment for the game "FINAL FANTASY XV" due to its highly-advanced requirements. Moreover, the real-time feature that accounts for 3D volumetric- or physics-based representation is difficult to be incorporated in several graphical applications due to its performance requirement (Kivi et al., 2022; Wu et al., 2022; Nair, 2020; Xie et al., 2020; Goswami, 2019; Vyatkin and Dolgovesov, 2019; Babić, 2018; Goswami and Neyret, 2017).

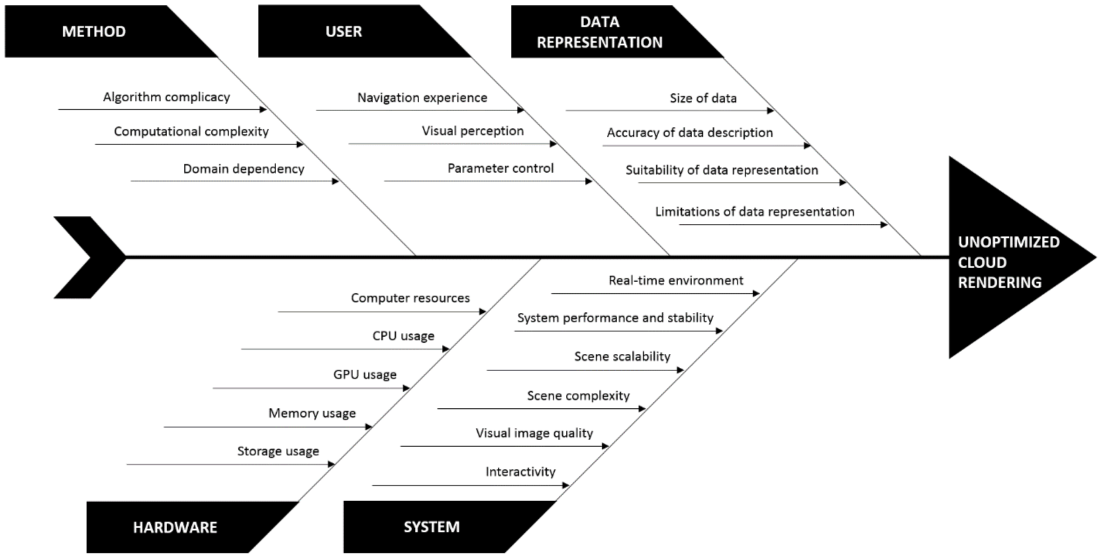

Figure 1.5 Summary of existing issues for an unoptimized atmospheric cloud rendering.

In order to achieve high performance and maintain the system's stability, high frame rates are the key metric for performance measurement and evaluation. However, it still appears to be a problem in the computer graphics community to improve and maintain system stability in real-time atmospheric cloud rendering systems (Chen et al., 2022; Kivi et al., 2022; Wright et al., 2019; Xie et al., 2019). In some cases, even though the system has successfully created incredible cloud formations, it, unfortunately, cannot stabilize the real-time frame rates during run-time (Türe et al., 2021; Junede and Asp, 2020).

The scalability of the scene also plays an essential role in the performance of the atmospheric cloud rendering system. The scene's size depends on the scope of the 3D domain that is targeted (Herrera et al., 2021; Webanck et al., 2018). Creating large cloud environments with large spatial extents would be a burden to the system to manage the scene smoothly in a real-time environment (Hädrich et al., 2020; Wright et al., 2019). Furthermore, the scene's complexity has added to the difficulty of developing efficient and effective 3D cloud scenes due to its complex structure, uncertain characteristics, and unique properties of lighting effects (Xie et al., 2019).

In terms of visual image quality, it is a vital factor to produce realistic outputs for final rendered images. However, there is a trade-off between quality and performance. For graphical applications that consider high fidelity features as a primary element, such as meteorology visualization, it is challenging to render high-quality clouds, especially involving large-scale volumetric data (Zhang et al., 2022; Ronen et al., 2021; Sde-Chen et al., 2021; Zhang et al., 2019). High resolutions of outputs are needed for applications that emphasize the physics-based accuracy and naturalness of the visual clouds. However, previous work showed very coarse visual resolutions (Goswami and Neyret, 2017) or lacked cloud images' natural appearance (Junede and Asp, 2020). Simple texture-based cloud representation could be applied, but the visual image quality looks flat appearance and unrealistic (Babić, 2018; Vyatkin and Dolgovesov, 2019). Flat textures could display visual artifacts (Hillaire, 2020). The artifacts could also happen at the adjacent bricks' boundaries when exploiting the hierarchical-based cloud representation (Zhang et al., 2019).

Interactivity is defined by the significant interaction between the user and the system. Previously, Goswami (2019) argued that physics-based cloud representation is inappropriate to be developed for interactive applications. Moreover, adding an interactive dynamic rendering feature into the cloud visualization system would worst the performance in terms of efficiency. Certain cloud rendering systems are suitable for specific types of applications only. For example, Nowak et al. (2018) pointed out that the texture-based cloud representation is only suitable for ground-level games such as first-person or third-person game genres. In comparison, Vyatkin and Dolgovesov (2019) stated that texture-based clouds could only work well in 3D scenes where the camera is far from the clouds. However, as mentioned earlier, they claimed that this representation is problematic against the open-world game types where it is intolerable to render scenes near or inside the clouds interactively.

The data representation defines the description of the cloud model and its properties used. The first issue is related to the size of the data. Häggström (2018) highlighted the cloud coverage issue when dealing with image-based cloud representation. An extensive collection of high-resolution images is needed to represent the different types of cloud coverage (Satilmis et al., 2022; Mirbauer et al., 2022; Sde-Chen et al., 2021). In addition, frequent data retrieval and updates involved affect the rendering performance.

The accuracy of data description also plays a significant role in modeling and rendering atmospheric clouds. However, it is challenging to describe cloud data with an accurate model and method for weather research and forecasting (Dandini et al., 2022; Xie et al., 2019). They also claimed it is difficult to propose and design a suitable model to link virtual clouds with actual physical data (Xie et al., 2020).

Atmospheric clouds are natural objects in the sky with fuzzy shapes and appearances. There is a need for suitable data representation to be the base of the cloud model. Polygonal-based representation might be well-suited for solid objects, but it is less suitable for participating media such as clouds (Kobak and Alda, 2017). Vast collections of polygonal geometries are needed to visualize complicated atmospheric clouds, and therefore this high polygon count could burden the system (Nilsson, 2022; Nair, 2020).

The other issue is related to the limitations of existing cloud representations. According to previous work (Mirbauer et al., 2022; Türe et al., 2022; Sde-Chen et al., 2021; Häggström, 2018; Iwasaki et al., 2017), it is challenging to synthesize and render realistic atmospheric clouds by acquiring and analyzing from a single or multiple photographic images (image-based representations). Applying the physics-based representation (e.g., Goswami and Neyret, 2017) or volumetric-based representation (e.g., Pettersson, 2020; Webanck, 2019) has constraints on the detailed appearance of clouds due to repeated use of small volumes in order to save memory usage during run-time processing.

The hardware represents the machine to run the system. In general, applying complicated cloud rendering methods for large-scale data requires more computer resources to run smoothly (Kivi et al., 2022; Goswami, 2020; Hu et al., 2018). Based on previous experience on implementing the real-time atmospheric cloud rendering system, there are some issues regarding the computer hardware, including the CPU overhead (Jiménez de Parga and Gómez Palomo, 2019), high memory consumption

(Bittner, 2020), under-utilized GPU (Bittner, 2020), and a large amount of storage space needed for keeping the high-resolution images representing different cloud types and variations (Häggström, 2018).

The user refers to the human that interacts and perceives with the system. Most 3D interactive graphical applications involve user navigation into the scene to explore and familiarize themselves with the virtual environment. However, by applying the texture-based representation, the user would lose the sense of scene navigation due to the tricky flat appearance of images to represent the clouds (Türe et al., 2021; Wu et al., 2021; Babić, 2018). Meanwhile, by implementing the volumetric-based cloud representation, the visual quality of the system could be improved. However, it prevents smooth interaction by the user with the scene due to lagging problems (Hädrich et al., 2020). In terms of visual perception, rendering unrealistic clouds would cause a static appearance and lose depth of perception due to the limited dimension of texture-based representation (Hillaire, 2020; Babić, 2018).

In video production rendering and game engine development, 3D artists and designers are the primary users capable of producing photorealistic results of rendered images. The key feature of their capability is the freedom to control parameters related to the cloud properties. However, providing artistic parameter control to these users is not an easy task (Wu and Fu, 2022; Hu et al., 2018). Determining specific parameters requires an understanding of users towards the characteristics of the clouds. Trial-and-error efforts are needed to familiarize with the parameters to yield better results. Previously, lacking parameter controls has caused unsatisfied results of cloud appearance (Webanck et al., 2018).

The method refers to the issues that involve particular procedures to render the atmospheric clouds. Algorithm complicacy is one factor that hinders the development of real-time atmospheric cloud rendering and visualization systems. In general, rendering engines of modern interactive applications have become highly complex heaps of special-purpose methods (Nilsson, 2022; Wu, 2021; Brechpunkt, 2020, Goswami, 2020). Specifically, it is a complicated task to implement the atmospheric cloud rendering that considers physically-accurate models (Hädrich et al., 2020;

Webanck et al., 2018; Duarte and Gomes, 2017; Favorskaya and Jain, 2017). It is because it involves complex numerical calculations and physics formulations. The complicacy of method and algorithm would increase if the volumetric-based representation or hybridization method is implemented (Max, 2021; Hu et al., 2018; Goswami and Neyret, 2017).

The computational complexity usually involves the high time complexity to run the cloud rendering method. Most of the respective researchers agreed that it is a high computational cost to render the atmospheric clouds either using volumetric-based (Max, 2021; Hädrich et al., 2020; Vyatkin and Dolgovesov, 2019; Babić, 2018; Häggström, 2018), physics-based (Nilsson, 2022; Xie et al., 2020; Goswami, 2019; Duarte and Gomes, 2017), texture-based (Mirbauer et al., 2022; Hillaire, 2020), or hierarchical-based representation (Hofmann et al., 2021; Sharma et al., 2021; Zhang et al., 2019). Consequently, per-frame cloud rendering becomes slower due to huge computation (volumetric- and physics-based), expensive updates of look-up tables (LUT) when there is a change of cloud properties (texture-based), or increase in complexity when implementing the slicing and rendering batches on graph structure (hierarchical-based).

The last issue is the domain dependency in which special care needs to be taken to render personalized cloud data concerning the target domain. Previously, it was reported that only a few methods were proposed for meteorological-related purposes accounting for weather forecast data (Rudenko et al., 2022; Röber et al., 2021; Xie et al., 2019). Therefore, there is a great demand and opportunities for developing this domain-dependent method.

In the following subsections, this thesis divides the primary explanations of problem background into three main focus rendering optimization methods as mentioned in Section 1.1: (i) ray tracing, (ii) lighting, and (iii) visibility. Figure 1.6 illustrates the summary of the related problems.

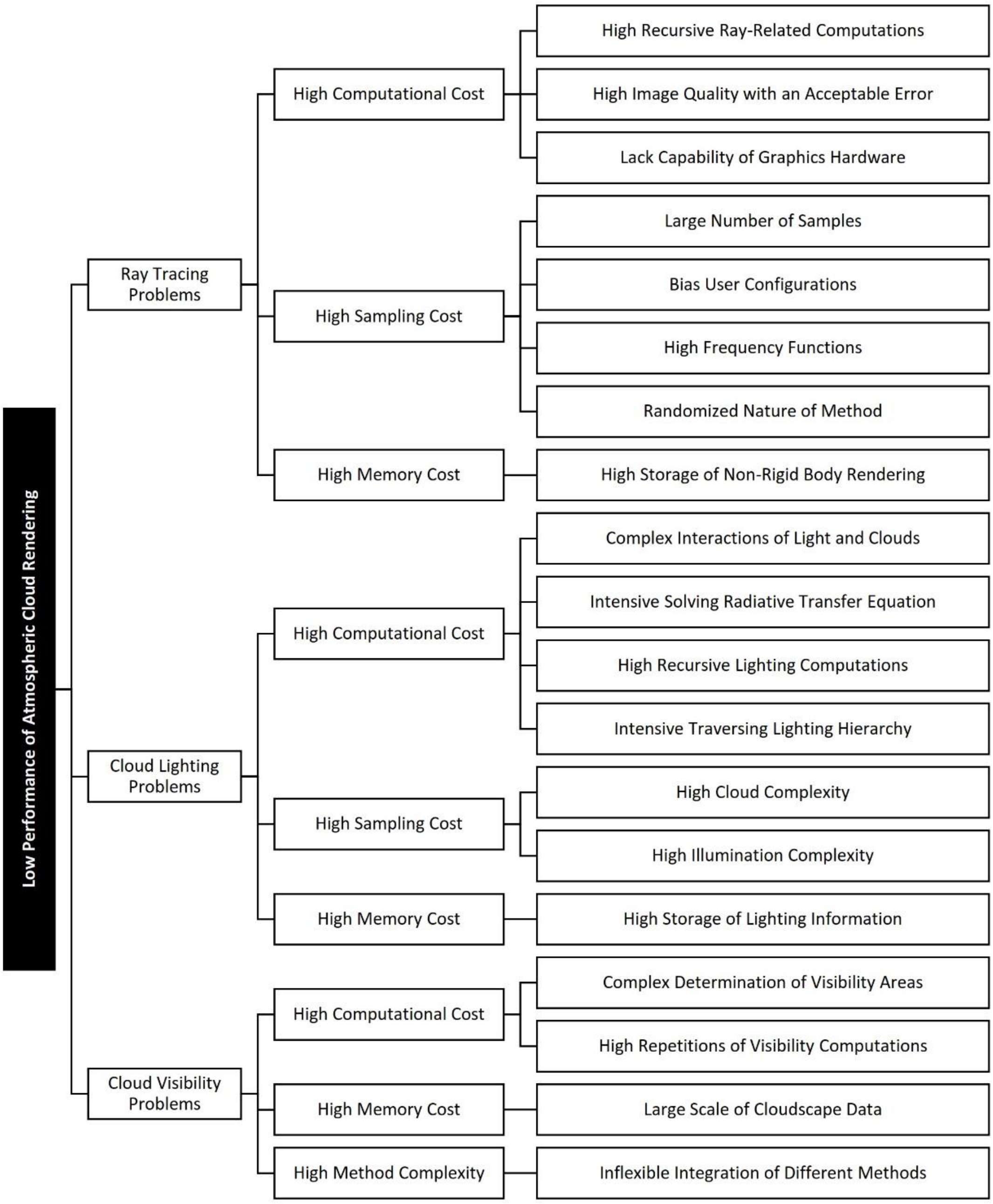

Figure 1.6 Summary of existing cloud ray tracing, lighting, and visibility problems towards the low-performance issue of atmospheric cloud rendering.

1.2.1 Problems of Cloud Ray Tracing Methods

The cloud ray tracing problems can be divided into three major components: computational, sampling, and memory costs. Regarding the high computational cost, most of the previous ray tracing-based methods (classical ray tracing, ray marching, and path tracing) require intensive computations to complete the whole rendering process (Kivi et al., 2022; Hofmann et al., 2021; Ang et al., 2018). The reasons for this problem are because of high recursive computations of ray-related operations (Steger et al., 2022; Jiang and Kainz, 2021; Barré-Brisebois et al., 2019; Jiménez de Parga, 2019), productions of high image quality with an acceptable error (Mirbauer et al., 2022; Brechpunkt, 2020; Kallweit et al., 2017), and lack capability of graphics hardware (Hofmann et al., 2020). Consequently, it has affected the system's performance, is a drawback for real-time processes, and is mainly applied to offline applications (Hofmann et al., 2021). For example, the previous methods such as path tracing that were impractical to be used for real-time previously would be the potential candidate for the modern solution of atmospheric cloud rendering in computer graphics to produce high performance and image quality under one roof of the framework without facing the complex architecture of 3D rendering. Based on the recent related work done by Hofmann et al. (2021), they were capable of performing rendering of the Disney Cloud consisting of 188.4 million voxels, which consumed 60.7 milliseconds of total computational time during runtime. Note that the minimum requirement for developing the real-time system is to achieve less than 16.67 milliseconds per frame. Therefore, there is still a gap in improving the performance based on the computational time in a real-time environment.

The sampling process is the backbone of the ray tracing-based methods causing the high sampling cost issue. To realize the high quality of rendered images involves many samples to shoot and determine the affected surfaces of atmospheric clouds due to reflections of rays in the 3D scene (Hofmann et al., 2021; Huo and Yoon, 2021; Hofmann et al., 2020; Barré-Brisebois et al., 2019; Toft et al., 2016). However, although recent advancements in consumer graphics hardware, the achievable sample counts for real-time path tracing remain low (Wu et al., 2022; Huo and Yoon, 2021; Keller et al., 2019). In ray marching methods, the user needs to set up the step length parameter for sampling purposes. Thus, biased user configurations occurred (Villemin et al., 2018). If the step length is too big (low number of samples), it affects the quality of the final rendered results. Otherwise, it produces excellent results, but the trade-off with performance is due to the high number of samples. The unbiased integration methods can be an alternative approach, but due to the high-frequency functions, it would not be easy to implement in the real-time environment (Villemin et al., 2018).

While classical ray tracing and path tracing methods could provide elegantly realistic results, the randomized nature of these methods could produce noise artifact results for each rendered frame (Brechpunkt, 2020). Therefore, additional post-filter work is required to denoise or smoothen the related images (Zhang et al., 2022; Hofmann et al., 2021; Barré-Brisebois et al., 2019).

The high memory cost requires memory-intensive processes to load and render a large number of atmospheric clouds in a real-time environment. Due to high storage involvement, it must be loaded into the main memory to keep the non-rigid cloud bodies during the run-time processing phase (Wu et al., 2022; Hofmann et al., 2021; Max, 2021; Goswami, 2020; Barré-Brisebois et al., 2019; Kobak and Alda, 2017).

1.2.2 Problems of Cloud Lighting Methods

The cloud lighting problems are also divided into computational, sampling, and memory costs. In terms of high computational cost, the key factor contributing to this problem is the complex interactions of light and clouds that involve a lot of processing time, especially considering the scattering of lights (Satilmis et al., 2022; Wu et al., 2022; Levis et al., 2021; Ronen et al., 2021; Türe et al., 2021; Dobashi et al., 2017). Implementing physically-correct cloud lighting involves intensively solving radiative transfer equation (RTE) to estimate the light transport behavior involving multiple scattering of lights (Dandini et al., 2022; Ronen et al., 2021; Wu et al., 2021; Zhu, 2020; Kubota, 2018; Kallweit et al., 2017; Kutz et al., 2017). As a result, it is not easy to compute while maintaining interactive or real-time rates. Zhu (2020) pointed out that this computational challenge would slow down the production speed of developers and artists as users of the system. Moreover, producing realistic cloud lighting involves high recursive computations due to the repetitive rendering equation (Nimier-David et al., 2022; Czerninski and Schechner, 2021; Talčík and Kovács, 2019). Goswami (2020) stated that the computational cost could be reduced by simplifying and limiting the light scattering into a single form (single scattering method), but accordingly, unrealistic results would be obtained. The hierarchical light clustering method makes it difficult to control the computational cost due to intensive traversing lighting hierarchy structure to determine the correct lighting effects towards the corresponding clouds (Brechpunkt, 2020).

In general, the high sampling cost involves many processes to determine the lighting effects on the atmospheric clouds. Most of the time, it requires a high sampling of lighting steps (Kivi et al., 2022; Hofmann et al., 2021; Huo and Yoon, 2021; Zheng et al., 2021; Toft et al., 2016). Kutz et al. (2017) reported many expensive sampling of spatially varying volume parameters involved when applying the delta tracking techniques. Besides, many samples are also required to reduce estimation variance for Monte Carlo-based volumetric cloud rendering (Satilmis et al., 2022; Wu et al., 2022; Sde-Chen et al., 2021; Zhu, 2020; Kallweit et al., 2017).

The sampling cost can be further refined into cloud and illumination components. Regarding the high cloud complexity, there is a challenge to render complex cloud characteristics such as high albedo materials efficiently and accurately (Nilsson, 2022; Huo and Yoon, 2021; Wu et al., 2021; Goswami, 2020; Kallweit et al., 2017). Regarding the high illumination complexity, it is a cumbersome task to process in real-time due to the nature of light scattering and absorption in the clouds, especially the in-scattering, multiple scattering, and inter-reflection components (Fernandes, 2021; Ronen et al., 2021; Brechpunkt, 2020; Shihan et al., 2020; Barré-Brisebois et al., 2019; Guo et al., 2019; Panin and Nikolenko, 2019; Xie et al., 2019; Nowak et al., 2018). However, there is a demand for efficient rendering methods and approximations to capture multiple scattering (Hofmann et al., 2021; Goswami, 2020). The use of RTE in producing high realistic cloud lighting effects involves complex radiometric functions that prevent real-time rendering in modern graphics hardware (Jiménez de Parga and Gómez Palomo, 2018). For example, according to Hofmann et al. (2021), they exploited 5.3 million path sampling for rendering the Disney Cloud, resulting in 16 frames per second of the rendering speed in real-time. This obtaining result was slower than the minimum standard of real-time rate, which is 60 frames per second. Hence, there is an opportunity to enhance the sampling cost and to fill in the gap to increase the performance in terms of the rendering speed for a real-time environment considering the acceptable visual realism concurrently.

The high memory cost also becomes a cause of cloud lighting problems. Based on the previous work, most of this problem is due to the pre-processing step in capturing the cloud lighting information (also called pre-computed lighting). Although this pre-computed lighting method is faster than the conventional scattering computation method, it incurs a higher storage cost (Guo et al., 2022; Kivi et al., 2022; Wu et al., 2022; Ge et al., 2019). In addition, this high storage cost of lighting information would exceed any memory bounds (Brechpunkt, 2020).

1.2.3 Problems of Cloud Visibility Methods

In general, the visibility in computer graphics can be divided into two types. The first type is focusing on visual appearance to produce high quality images in 3D environment. The related works include the use of image-based methods (e.g., Mirbauer et al., 2022; Satilmis et al., 2020; Iwasaki et al., 2017), ray-tracing based methods (e.g., Miller et al., 2019; Webanck et al., 2018), neural-based methods (e.g., Zhang et al., 2021; Zhang et al., 2020), physics-based methods (e.g., Hädrich et al., 2020; Guo et al., 2019), and meteorological-applied methods (e.g., Yu, 2020; Rimensberger et al., 2019). The second type is focusing on performance in order to reduce the system overhead and level up the system efficiency and stability simultaneously (e.g., Hofmann and Evans, 2021; Bittner, 2020; Dai et al., 2020). Both visibility types are essential in developing realistic real-time 3D visualization systems in order to obtain satisfactory results based on user perception and experience in virtual environment (Chen et al., 2022; Jiménez de Parga and Gómez Palomo, 2018).

Visibility computation is still a long-standing problem in computer graphics (Koch and Wimmer, 2021). The cloud visibility problems are divided into computational, memory, and method integration costs. Regarding the high computational cost, the main problem is how much visible data is to be displayed at each frame concerning the viewpoint and field of view during the run-time. It is complex to determine the visible set areas in a real-time environment. Most real-time visibility-related methods have only limited the view and display to a position near the ground (Koch and Wimmer, 2021; Pettersson, 2020). However, there is a need to develop real-time applications that account for non-ground views as a base of the system, such as flight simulation. In addition, only a few methods enable rendering and visualization of the entire planet from the outer space view, including fully volumetric cloud layers (Pettersson, 2020). Besides, there is a challenge in visibility updates if a new viewpoint or orientation occurs due to high repetitions of visibility computations (Max, 2021). As a result, this caused slow convergence to obtain the final rendered images optimally.

A large scale of atmospheric cloudscape data would be involved in the high memory cost. It would affect the performance of the main memory used to load and display the entire clouds on the screen. In general, the causes of the high memory usage are due to the large size of data (Nilsson, 2022; Czerninski and Schechner, 2021; Hu et al., 2018; Wang et al., 2012). It would be more problematic if the type of object representation used to model the atmospheric clouds is too complex such as using volumetric representation (Fernandes and Walter, 2020; Jiménez de Parga, 2019; Babić, 2018). On the one hand, there is a demand for efficient rendering of large-scale clouds covering hundreds of kilometers or areas (Dobashi et al., 2017). On the other hand, there is a demand for real-time rendering improvements for larger cloud volumes with high density and albedo (Hofmann et al., 2021). For example, based on the recent work done by Hofmann and Evans (2021), their system consumed about 585.2 MB of memory for applying and executing the baseline approach (Museth, 2021). Thus, there is a chance to improve memory usage while running the cloudscape visualization system in a real-time interactive environment.

There are several recent works on 3D visibility optimizations in computer graphics to accelerate the system's performance (Ronen et al., 2021; Zhou et al., 2021; Hu et al., 2020; O'Rourke, 2017; Barringer et al., 2016). However, incorporating different methods to enhance efficiency further is not an easy task. In recent solutions towards rendering atmospheric clouds, implementing the ray tracing-based method would be preferable as a base approach for rendering instead of the rasterization method. Adding other optimization methods into ray tracing to accelerate the rendering process is becoming the trend. Nonetheless, high method complexity would challenge the computer graphics community. It is due to the inflexible integration of different methods. Based on Keller et al. (2019), there is a lack of adaptation of ray tracing and level-of-details method. This unsolved problem would be an opportunity for the researchers to explore and solve it.

1.3 Problem Statement

The central problem to be researched in this proposed study is the lack of rendering optimization towards the volumetric cloudscape in the real-time 3D virtual environment. As a basis for the study, this research identified the problem threefold.

First, the issue is the high computational cost of implementing the real-time interactive volumetric path tracing method on consumer-level computer hardware due to a lot of processing power needed to compute direct and indirect ray shooting paths towards atmospheric cloudscapes recursively for the intersection test. Consequently, it requires a longer time to complete the process, thus slowing down the production of the developers or designers to produce high-quality results due to frequent hiccup visual occurrences and navigation systems. There is a great demand for an efficient ray tracing-based rendering method for atmospheric cloudscapes to be realized in real-time using a volumetric element as a base of object representation. Based on the recent work, they could only rendered the atmospheric clouds consuming 60.7 milliseconds of total computational time during runtime. Therefore, there is still a gap in improving the performance based on the computational time in a real-time environment.

Second, the issue is the high sampling cost of capturing the natural lighting effects of atmospheric clouds in a real-time environment. Even though this high sample count would produce a realistic quality of rendered images, it is far too slow to be used in real-time interactive applications due to slow rendering speed (low frame rates). Consequently, a limited number of samples could be applied in a real-time environment in order to maintain performance and realism. The recent work exploited 5.3 million path sampling for rendering the atmospheric clouds, resulting in 16 frames per second of the rendering speed in real-time. This obtaining result was slower than the minimum standard of real-time rate (60 frames per second). Hence, there is an opportunity to enhance the sampling cost and to fill in the gap to increase the rendering speed performance for a real-time environment considering the acceptable visual realism concurrently.

Third, the issue is the high memory cost of 3D volumetric representation of cloudscape rendering in real-time. It is due to many uniform volume elements (voxels) covered in the field of view, especially when dealing with the fly-through-based navigation system that involves exploring and penetrating the 3D volumetric clouds interactively. This large voxel count to be rendered and updated would intensify memory consumption. In the worst-case scenario, the system would be terminated due to the insufficient memory available during run-time. Hence, there is a high demand for a method to manage memory usage in a real-time environment by considering the visibility aspect of a 3D scene via the level-of-detail of volumetric clouds concerning the viewpoint and field of view. Note that the recent work consumed about 585.2 MB of memory storage for applying and executing the baseline approach. Thus, there is a chance to improve memory usage while running the cloudscape visualization system in a real-time interactive environment.

1.4 Research Goal

The main goal of this research is to propose the real-time volumetric rendering optimization approach for cloudscapes in a 3D virtual environment that accounts for the ray tracing, lighting, and visibility aspects of atmospheric clouds with better performance in terms of the computational, sampling, and memory costs and acceptable visual realism of the final rendered images.

1.5 Research Objectives

The objectives of this research are:

(a) To enhance the path tracing method that could reduce the computation time of rendering the atmospheric cloudscape.

(b) To improve the cloud lighting method accounting for the multiple scattering of lights that could reduce the number of samples to capture light information of the atmospheric cloudscape and accelerate the speed performance of the system.

(c) To propose a new hybrid cloud visibility acceleration method considering the view-dependent, multi-resolution level-of-detail and invisible culling that could reduce memory usage to minimize the scene complexity of the real-time volumetric atmospheric cloudscape rendering.

1.6 Research Scopes

The research focuses on optimizing the rendering performance of atmospheric clouds in a real-time virtual environment. The scopes of this research are bound by several limitations, which are as follows:

(a) This research focuses on the rendering components of atmospheric clouds. Cloud detection, modeling, and animation are out of the scope. Specifically, this research only looks into the performance optimization aspect of the rendering component. Time and space complexity are the critical criteria for implementing the performance optimization aspect. Note that the performance aspect is the primary aim of this research. Meanwhile, the visual realism aspect would be a secondary aim to balance high performance and high image quality. To evaluate the realisticness of the visual rendered images, the reviews of the domain experts are required to present the subjective assessment results.

(b) This research focuses on rendering static cloudscapes. Animated cloudscapes are not covered. Managing static clouds is considered a big enough research scope in the computer graphics community (Kivi et al., 2022; Wu et al., 2022; Goswami, 2020; Cerezo et al., 2005).

(c) This research uses volumetric representation for atmospheric clouds. Volume-based representation is the most natural way of representing the 3D object in the real-world (Goswami, 2020; Hufnagel and Held, 2012; Cerezo et al., 2005). Specifically, this research uses the sparse-based volumetric cloud data sets as the inputs for the system to operate. These data sets are well-developed, robust, high availability, trendy, and primarily used in computer-generated imagery (CGI) movies (Max, 2021; Hofmann et al., 2021; Pettersson, 2020; Jabłoński and Martyn, 2016; Hoetzlein, 2016; Palmer et al., 2014; Museth, 2013).

(d) This research focuses on the ray tracing-based rendering method instead of the raster-based rendering method (rasterization), which is now becoming the conventional method and too complex to implement (Turquin, 2020; McGuire, 2019; Christensen et al., 2018). In contrast, ray tracing is a current trend for graphical interaction applications due to its high flexibility and versatility of visualizing the natural aspects of the real-world scene (Durand, 1999).

(e) This research is not involving cloud computing and point clouds. These two terms frequently appear while searching on cloud rendering. Cloud computing refers to the technology or infrastructure provided for establishing parallel computing on multiple machines. In this thesis, the research was conducted on a single machine only. The point clouds refer to the representations of 3D objects in point form in which most of the objects used in the research work are not related to the atmospheric clouds. Thus, both terms were not considered in this research.

1.7 Research Significance

Research on atmospheric cloud rendering and visualization is crucial in a wide range of applications and domains. This thesis explains and highlights the significance of this research based on five impacts: the global world, industries, government sectors, communities, and body of knowledge.

1.7.1 Impact on Global World

The Sustainable Development Goals (SDGs) are designed for United Nations (UN) Agenda 2030, consisting of 17 interlinked global goals, as illustrated in Figure 1.7. This research contribution is close to SDG 13 (Climate Action). There is a need to improve the climate projections, including lifting the existing monitoring and forecasting systems to understand better the natural phenomena of land-atmosphere-ocean feedback, primarily via the incorporation of the computer-based model (Kulmala et al., 2021; ITUNews, 2017). Thus, the role of visualizing and rendering the atmospheric clouds plays as one of the crucial elements in climate activities. It could be used to develop and further support Earth system simulators that would be a crucial tool to meet the needs for the SDG. It could also help in decision-making contexts where weather and climate impacts could deliver various levels of complexity for decision-makers in related domains and applications (Griggs et al., 2021; World Meteorological Organization, 2021).

According to the research report on the global market study (Next Move Strategy Consulting, 2021), global visualization and 3D rendering software have witnessed rapid growth in the market due to the high demand for virtual environment systems especially accounts for real-time display, cost-effectiveness, and time efficiency. At an estimated value of over USD 1.63 billion in 2019, the Global Visualization and 3D Rendering Software Market is predicted to thrive at a Compound Annual Growth Rate (CAGR) of 17.5% and valued at over USD 9.61 billion over the forecast year 2020-2030 (Figure 1.8). Therefore, by implementing the methods proposed in this thesis, it could contribute to the development of the global visualization and 3D rendering software either via plugin or stand-alone system for several applications such as gaming, media and entertainment, research and training, architecture, life sciences, and geographic information systems, to name a few.

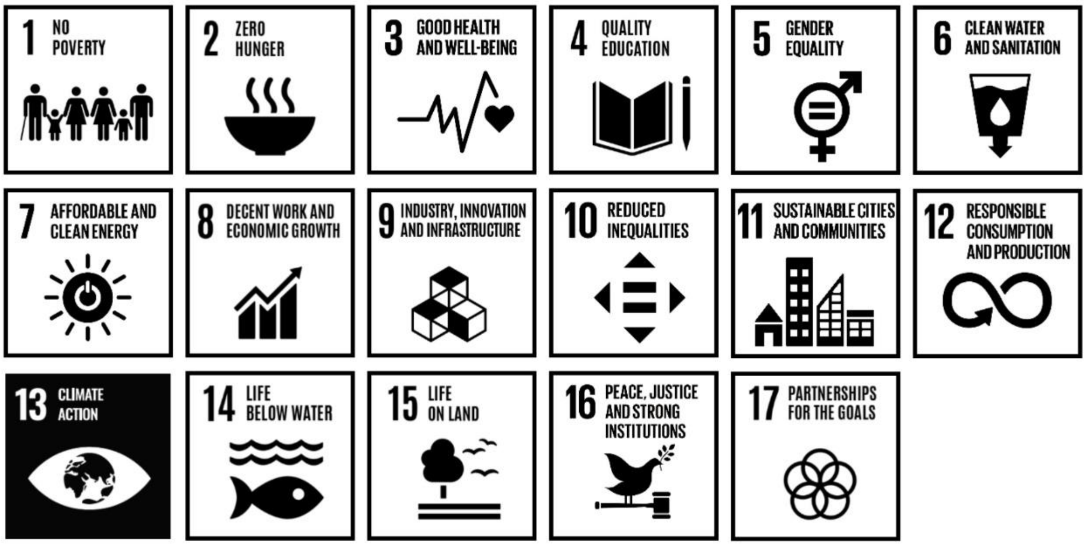

Figure 1.7 The Sustainable Development Goals (SDGs) (black-filled rectangles represent the focused areas of this research).

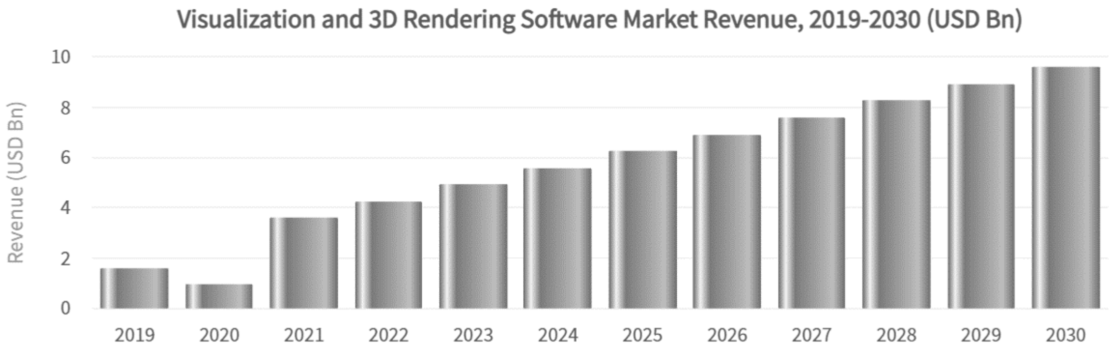

Figure 1.8 Global analysis and industrial forecast on visualization and 3D rendering software (Next Move Strategy Consulting, 2021).

1.7.2 Impact on Industries

The proposed methods in this thesis are targeted to be applied in several essential industries, including gaming, movie making, and aviation.

The gaming industry is highly dependent on advancements in rendering and graphic processing. There are some demands for implementing atmospheric cloud rendering in the game productions, especially for the outdoor environment. For example, it can be applied in first-person shooting games, third-person adventures, role-playing games, racing games, and open-world games. The demands include fast 3D visualization, realistic visual appearance, and responsive interaction in a virtual game environment without lagging the system (Brechpunkt, 2020; Bauer, 2019; Nowak et al., 2018; Hasegawa et al., 2017; Schneider and Vos, 2017). In order to realize these demands, speed performance is becoming a significant factor in producing a robust and convincing game. Here the optimization methods play an essential role in increasing the performance. On the development side, the optimization methods could help the game developers (either programmers or design artists) to complete their assigned tasks in a shorter time, thus accelerating the whole game production. Furthermore, major game engines such as the Unity Engine and the Unreal Engine do not ship with a default implementation for volumetric cloudscapes. Therefore a custom implementation or a third-party plugin is required (Bittner, 2020).

In movie productions, to make a 90-minute film incorporating large amounts of computer-generated imagery (CGI), as much as 100 hours of footage may be rendered and discarded, just as a conventional movie director shoots and reshoots the same scene many times (Azultec, 2019). In addition, a single movie release can spend as much as USD 50 million on rendering scenes. One of the essential elements in creating a CGI is the atmospheric effects of the sky, clouds, and precipitations. These effects could give the scenes an impressive and distinct mood with their presence. To realize visually convincing effects, the 3D artists have to put extensive efforts because it is a complicated task and requires long hours of rendering processes in order to obtain the desired outcomes (Hanrahan and Catmull, 2021; Georgiev et al., 2018). By proposing the solution and simplifying specific rendering processes via optimization methods in the existing rendering engine, the artists could make the realistic requirement needed and leave the computational tasks run by the computer at the back to accelerate the rendering to gain the final results. Pixar's RenderMan and Autodesk's Arnold are two examples of active rendering engines for movie productions available on the market (Christensen et al., 2018; Kulla et al., 2018).

In the aviation industry, atmospheric cloud rendering and visualization could be implemented as a part of the weather model in the flight simulation system. It could be used for training purposes. It is beneficial for beginner-level pilots to master their maneuvering skills and feel immersively the virtual outdoor environment during the flight session before experiencing the actual physical plane. In contrast, it is hazardous to fly near any cumulonimbus cloud formations because activities within and around it could drag the plane into it, leading to a crash (Azultec, 2019). Real-time display and visual scene updates are necessary for this flight system in order to simulate and emulate the real-world environment. The proposed optimization methods in this thesis could become a handy solution to realize the requirements mentioned earlier. Microsoft Flight Simulator, Prepar3D, and X-Plane are examples of the existing flight simulation systems that could be used to train and sharpen the pilot's navigation skills, knowledge, and experience (Benedikz et al., 2020; EuroFighter, 2017).

1.7.3 Impact on Government Sectors

The atmospheric cloud rendering and visualization system could also be applied for government sectors, especially the education and meteorological agencies.

For the education agency, it could be exploited to teach subjects related to the atmospheric sciences to the students to expose them to understand the natural atmospheric phenomena, the cloud behaviors, and its related surrounding elements in real-time visual form. It can be implemented in school (e.g., Malleus et al., 2017) or university level (e.g., Petters, 2021; Jiménez de Parga and Gómez Palomo, 2019). It could also be taught in a virtual reality environment to immerse the related concepts (e.g., Li et al., 2020). In Malaysia, the related agencies are the Ministry of Education (MOE) and the Ministry of Higher Education (MOHE).

The atmospheric clouds could be valuable aids in weather-related systems for the meteorological agency. Visualizing the atmospheric clouds in a real-time environment would help understand the characteristics of clouds to anticipate future weather conditions and climate activities (Pałubicki et al., 2022; Bony et al., 2017; Cohn, 2017). The Malaysian Meteorological Department, located under the Ministry of Environment and Water (MEWA), could play a crucial role in applying it in Malaysia.

1.7.4 Impact on Communities

The research work proposed in this thesis would majorly impact research and development communities from different domains. This research could collaborate between the computer graphics community and subject matter experts from other communities such as meteorological, geo-information, remote sensing, and education. A great deal of research work could be conducted and expanded to solve the global issues related to atmospheric clouds (e.g., Hofmann et al., 2021; Hädrich et al., 2020; Li et al., 2020; Yu, 2020; Satilmis et al., 2020; Xie et al., 2019; Kaur and Sohi, 2017; Malleus et al., 2017).

1.7.5 Impact on Body of Knowledge

The research in this thesis follows the 2012 ACM Computing Classification System developed by the Association for Computing Machinery (2012) as the main body of knowledge. Figure 1.9 denotes the related taxonomic classification and the focus areas targeted for this research. By proposing three optimization methods for rendering atmospheric clouds, these methods contribute to three different categories. First, the enhanced real-time path tracing optimization method has expanded the computing capability of ray tracing. Second, the simplified scattering-related lighting method has contributed to reflectance modeling by speeding up the system's performance. Third, the unification of the ray tracing-based method with LOD and the culling of unnecessary data to be loaded in real-time via visibility consideration has minimized the memory consumption of running the real-time atmospheric cloud rendering.

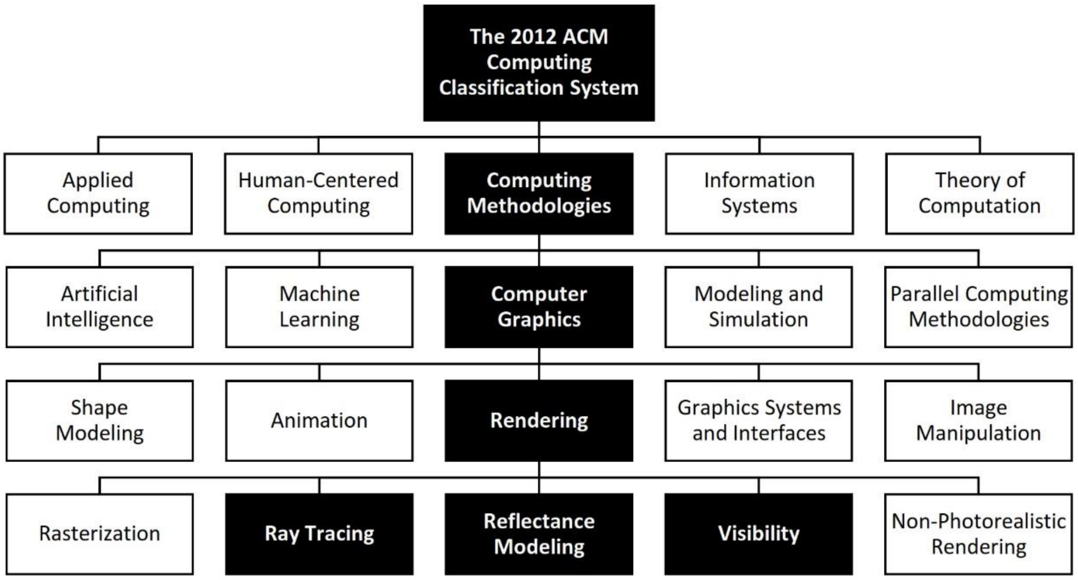

Figure 1.9 The 2012 ACM Computing Classification System (black-filled rectangles represent the focused areas of this research).

1.8 Thesis Organization

This thesis is organized into six chapters, and a general summarization of each chapter is provided as follows:

(a) **Chapter 1** gives an overview of the research background and determines the research problems, problem statement, goal, objectives, scopes, and significance.

(b) **Chapter 2** presents the basic concepts of atmospheric cloud visualization and rendering. It also reviews the existing methods of atmospheric cloud ray tracing, lighting, and visibility to develop the specific research direction for this study.

(c) **Chapter 3** describes the situational analysis and research framework supporting this study's objectives. The other matters include data sources, instrumentations, and procedures for analyzing the experimental results.

(d) **Chapter 4** explains the proposed solutions in detail for each designated path tracing, light scattering, and visibility acceleration method step-by-step procedures.

(e) **Chapter 5** presents and discusses the experimental results.

(f) **Chapter 6** outlines the results' overall conclusions and presents the contributions to the research. This chapter also recommends several potential improvements for future research works.

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