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Atmospheric Cloud Representation Methods in Computer Graphics: A Review

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ABSTRACT

Cloud representation is one of the important components in the atmospheric cloud visualization system. Lack of review papers on the cloud representation methods available in the area of computer graphics has directed towards the difficulty for researchers to understand the appropriate solutions. Therefore, this paper aims to provide a comprehensive review of the atmospheric cloud representation methods that have been proposed in the computer graphics domain, involving the classical and the current state-of-the-art approaches. The reviewing process was conducted by searching, selecting, and analyzing the prominent articles collected from online digital libraries and search engines. We highlighted the taxonomic classification of the existing cloud representation methods in solving the atmospheric cloud-related problems. Finally, research issues and directions in the area of cloud representations and visualization have been discussed. This review would be significantly beneficial for researchers to clearly understand the general picture of the existing methods and thus helping them in choosing the best-suited approach for their future research and development.

Key words : Atmospheric clouds, cloud representation, cloud modeling, cloud shape, computer graphics, visualization.

1. INTRODUCTION

The cloud plays a crucial appearance role in the atmospheric landscape. It represents one of the important elements that contributed to the richness of the natural phenomena in the sky. Understanding the atmospheric cloud existence is a necessity [1], thus the World Meteorological Organization (WMO) published a new edition of the International Cloud Atlas (ICA) in the form of an electronically accessible website for public reference (https://cloudatlas.wmo.int/) [2]. In computer graphics, the atmospheric clouds are frequently being used in many visual-related applications such as meteorological studies, video games production, film making, flight simulation, military training, mixed reality systems, art visualization, advertisement, and education.

There is a demand for the visualization of the virtual atmospheric clouds in the computer graphics area. The cloud visualization model normally consists of five vital components in order to produce a high- quality visual appearance of the clouds. They are (i) cloud representation, (ii) cloud modeling, (iii) cloud animation, (iv) cloud illumination, and (v) cloud rendering. The cloud representation acts as a base to significantly support the other four cloud visualization components. Without the proper use and design of atmospheric cloud representation, the clouds could not be displayed correctly in the virtual environment. Therefore, computer graphics approaches and methods are needed to realize this cloud visualization system.

In general, visualizing the atmospheric clouds is a challenging task. This is due to the fact that the clouds have a complex nature of gaseous representation in the real world. Furthermore, there are many types of clouds that existed with different characteristics and representations. Many atmospheric cloud representation methods (e.g. [3]-[7]) have been proposed for the last forty years by the computer graphics community to solve different issues regarding the visualization of atmospheric clouds. However, lack of review papers could be referred on the cloud representation methods available in the area of computer graphics caused some difficulties for researchers especially novice and inexperienced researchers to understand and choose the appropriate solutions for their research work. To the best of our knowledge, the latest survey paper that covered the atmospheric cloud representations was elaborated by Hufnagel and Held [8] in 2012 and there is no available comprehensive review since then.

The objective of this paper is to provide a comprehensive and up-to-date review of the atmospheric cloud representation methods that have been proposed in the computer graphics, covering the traditional and the contemporary proposed solutions. This review would be beneficial as a quick reference for the researchers to explore in the journey of understanding the diversity of atmospheric cloud representation methods exploited in the computer graphics area. The reviewing process was conducted based on three important strategies designated for searching, selection, and analysis of the published articles respectively. The contributions of this paper include (i) introducing the up-to-date taxonomy of the existing cloud representation methods and (ii) anticipating the potential research opportunities in the cloud visualization system considering the atmospheric cloud representation as a foundation for future research, development, and innovation. This paper will be an extension of the previous survey papers [8]-[16], a book [17], and theses [3], [18]-[26] in terms of the methods used for representing clouds in computer graphics as well as a complement of our previous works [134], [135].

The remaining of this paper is organized as follows: Section 2 describes the methodology used for the review process; Section 3 explains on the analysis based on the literature search findings; Section 4 gives an up-to-date reviews on the existing atmospheric cloud representation methods; Section 5 highlights the research issues for the future research directions regarding the atmospheric cloud visualization research work; and Section 6 concludes the paper.

2. REVIEW METHODOLOGY

The methodological approach for conducting the reviewing process of the cloud representation methods in computer graphics is needed. It consists of three main important strategies that need to be followed sequentially to come out with a high-quality review. These strategies are explained in the next subsections. Figure 1 illustrates the flowchart to graphically represent the overall courses of our review methodology.

2.1 Search Strategy

The online digital libraries and databases are our main potential sources for searching the high-impact publications and most-cited research articles. We broadly searched for articles in the following resources:

- ACM Digital Library (https://dl.acm.org)
- IEEE Xplore Digital Library (https://ieeexplore.ieee.org)
- ScienceDirect (https://www.sciencedirect.com)
- Scopus (https://www.scopus.com)
- Springer Link (https://link.springer.com)
- Taylor & Francis Online (https://www.tandfonline.com)
- Web of Science (https://apps.webofknowledge.com)
- Wiley Online Library (https://onlinelibrary.wiley.com)

We also searched for articles in the available search engines as the grey literature to support the above-mentioned main resources and avoid missing any important publications regarding the atmospheric cloud representation methods. These includes:

- CiteSeerX (https://citeseerx.ist.psu.edu)
- Google Scholar (https://scholar.google.com)
- ResearchGate (https://www.researchgate.net)
- Semantic Scholar (https://www.semanticscholar.org)

The keywords that were used in the searching queries are “clouds”, “atmospheric clouds”, “cloud representation”, “cloud modeling”, “modeling clouds”, “cloud shape”, “cloud generation”, “cloud construction”, “cloud creation” and “cloud formation”. The terminologies such as shape, modeling, generation, construction, creation, and formation were included in the search requests because their contributions towards the development of atmospheric cloud representations were highly used in the cloud research work.

2.2 Selection Strategy

The selection criteria are made to finalize the articles to be selected for further analysis. Table 1 indicates a summary of the criteria used for conducting the literature search. The articles must be in English and the proposed methods in the potential articles should be applied in solving the computer graphics problems. Furthermore, the articles that are focusing on cloud computing, and point clouds are excluded because those terminologies are out of our scope and our review intends to focus on the cloud modeling methods only. Duplication of articles due to searching different online databases and search engines were detected and removed manually.

Table 1: Selection criteria for searching the published articles

Inclusion Criteria	Exclusion Criteria
Articles published as journal papers, conference papers, books, book chapters, technical reports, theses, course notes.	Articles not written in the English language.
Contributions of the articles must be applied in the computer graphics field.	Articles focusing on cloud computing that are not referring to the atmospheric clouds.
No restriction on year of publication.	Articles focusing on point clouds that are not referring to the atmospheric clouds.

2.3 Analysis Strategy

There are two types of analyses were done in this paper. First, an analysis of the literature search results was done. All articles that have passed the requirement of inclusion and exclusion criteria were entered the final stage in which the data were analyzed based on the distribution of the selected articles by types and year of publication. Second, an analysis of the types of cloud representation methods was done. A thorough reading process was done for all the selected articles. These data were then categorized based on their specific representations. The taxonomy of cloud representation methods was constructed to illustrate the big picture of the methods involved. Both analyses are explained in Section 3 and Section 4 respectively.

3. ANALYSIS OF THE LITERATURE SEARCH

According to the searching and screening activities in the previous section, there are 112 articles have been selected and compiled for further analysis of the literature search results. Regarding the distribution of selected publications based on the types of articles, most of the selected articles are obtained from journals and conference papers. The conference papers contributed 57.14% out of all selected articles, followed by 36.61% of the journal papers and 6.25% of the remaining types of published articles, as illustrated in Figure 2. A few articles in the form of book chapters, technical reports, thesis, and course notes were collected during the literature search and we chose only the articles that gave a big impact on the

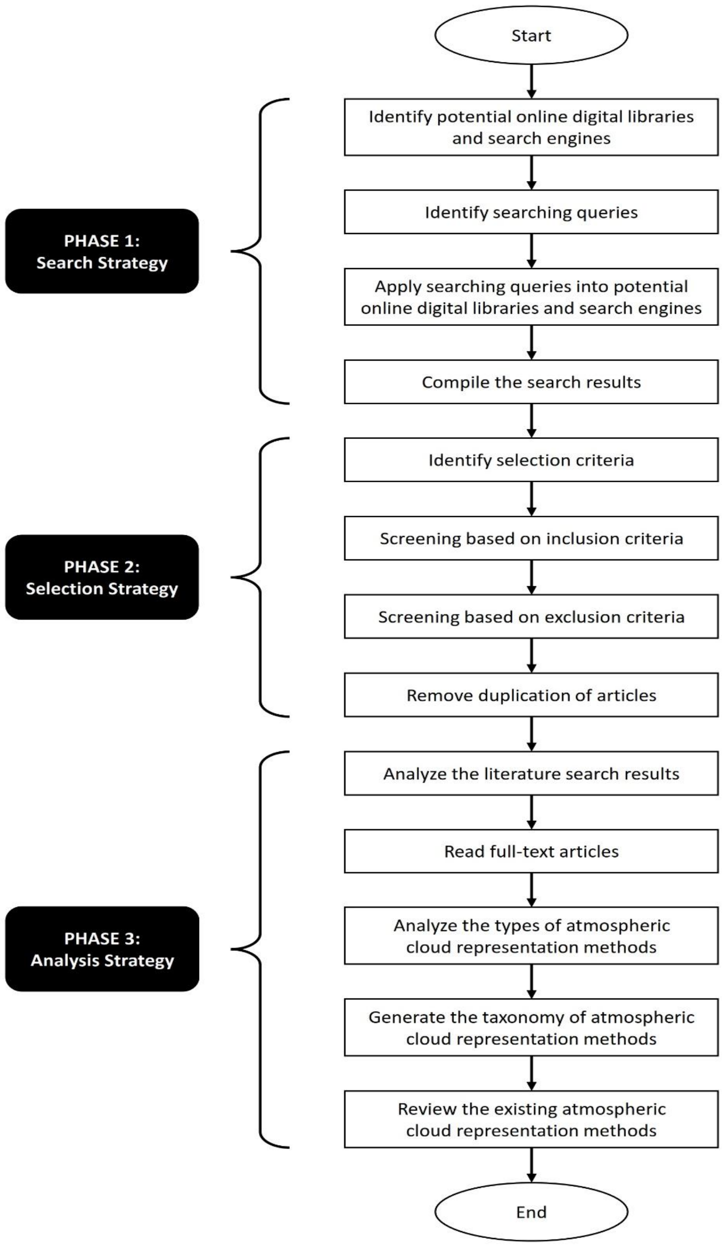

Figure 1: Flowchart of the review methodology

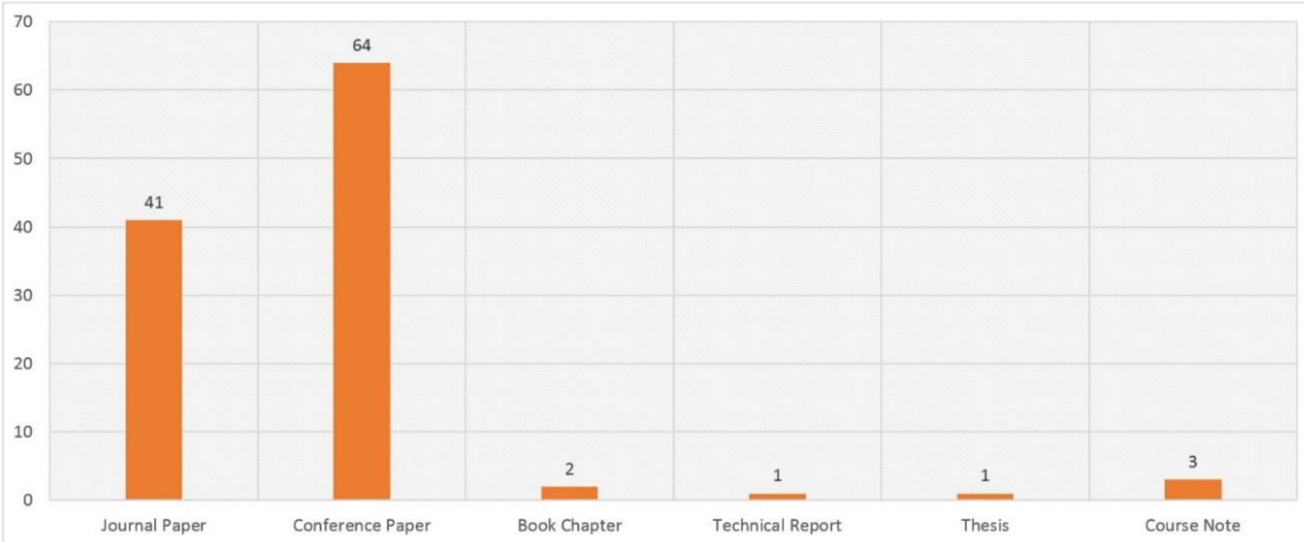

Figure 2: Distribution of selected publications by document types

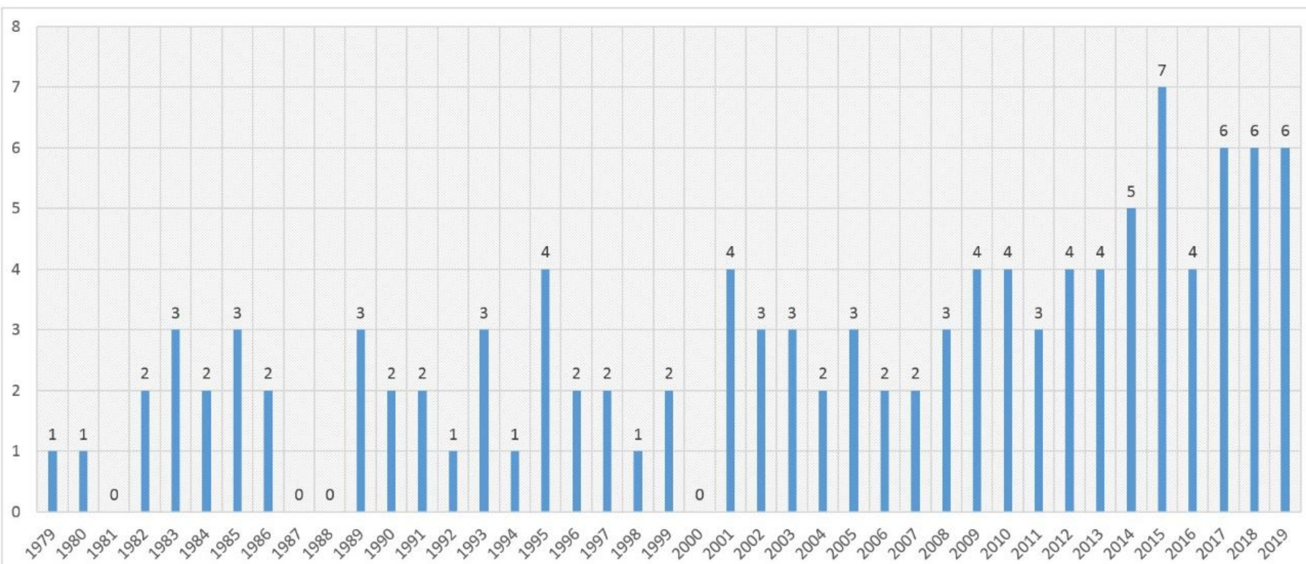

Figure 3: Distribution of selected publications by year

cloud representation research work in computer graphics. The course notes were selected from the talk sessions in the big events in the computer graphics domain provided by the game companies which implemented the atmospheric clouds as one of the important components in their specific game engine.

Regarding the distribution of selected articles based on the year of publication, the range of years obtained from this review process is from the range of 1979 to 2019. Hence, around forty years have been used to work in the computer graphics field and there are still many open problems that need to be solved. Figure 3 shows the year-wise distribution of the selected articles. There were many proposed methods by the researchers even though most of them are the enhancement of the previous research works and need some adaptation of methods for the particular application of interest. In the last five years (2014-2019), the number of published articles shows a significant increment which contributed to 25.89% out of all the selected articles (29 over 112 articles). The most significant and novel research works can be seen at the 1980s (16 published articles, 14.29% out of all the selected articles) by the most prominent researchers and high citation authors. During that time, the research on atmospheric clouds was on the rise. Their preliminary research works have been used as a base for developing more advanced methods and approaches.

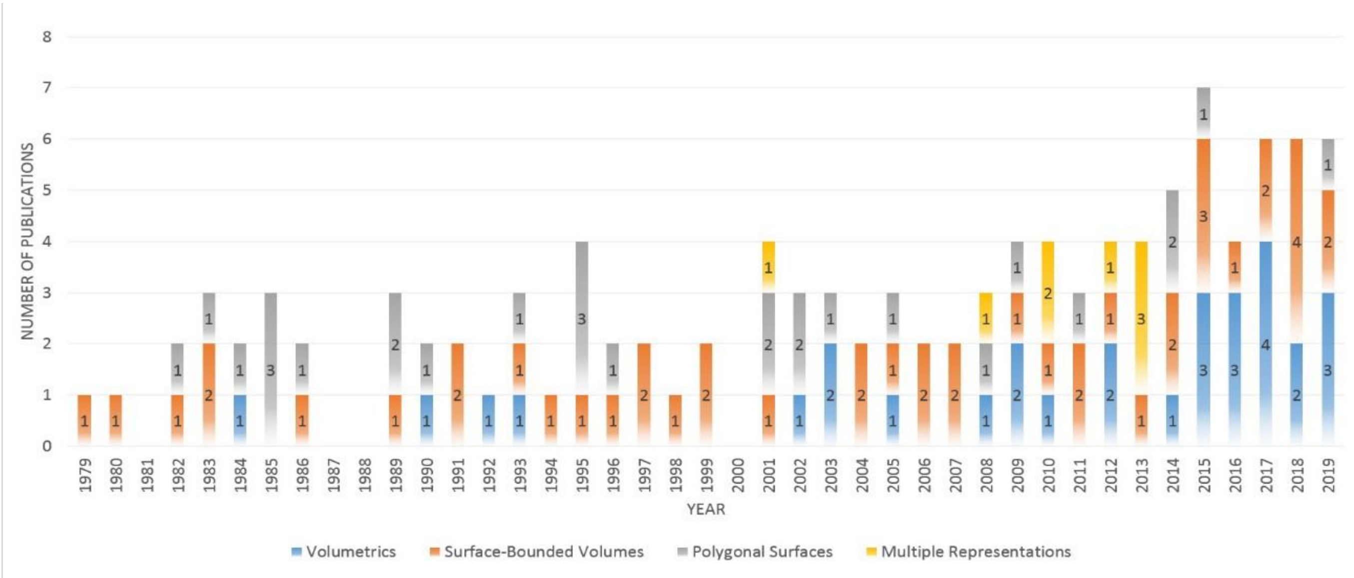

Figure 4: Distribution of atmospheric cloud representation methods by year

4. REVIEW OF EXISTING CLOUD REPRESENTATION METHODS

The analysis of the existing methods for representing atmospheric clouds is made on the 112 selected articles from the previous literature search results. The goals of this analysis are to classify the atmospheric cloud representation methods into specific categories and to construct the taxonomic classification in the form of a diagram and a table of summary. In this paper, we classify the atmospheric cloud representations into four main categories: (i) volumetric, (ii) surface-bounded volume, (iii) polygonal surface, and (iv) multiple representations. This classification was made in consideration with the previous survey paper [8] and added new classification(s) when needed.

Based on the analysis of the existing atmospheric cloud representation methods obtained from the selected articles, as shown in Figure 4, there is a trend that the researchers attempted to exploit the capability of volumetric representations for the last five years. The methods that might be difficult to be developed during the 1980s and 1990s would be feasible in recent years due to the advancement of hardware technologies. That is why the preliminary research works were mostly focused on the surface-bounded volume and polygonal surface representations.All types of cloud representation methods are illustrated in Figure 5 in the form of the taxonomic diagram to visually give a whole picture of the existing atmospheric cloud representation methods involved. The proposed methods in the selected articles are explained, reviewed, and discussed in the following sub-sections.

4.1 Volumetric Representations

Volumetric representations are based on a series of volumetric pixels (also known as voxels) to build up the solid object. These representations provide a full three-dimensional feature in three-dimensional (3D) space in which a voxel could be considered as the three-dimensional (3D) equivalent of a pixel and the tiniest distinguishable element of a 3D object. A volumetric-based method is typically represented by a specific grid value in 3D space or a combination of 2D images. In this paper, we introduce four methods within this category: (i) voxel grids, (ii) hierarchical space subdivisions, (iii) plane slicing, and (iv) hybrid method.

4.1.1 Voxel Grids

Voxel grids use the regularly spaced grid representation (also called 3D grid) distributed to the whole cloud object. The visibility of a voxel is dependent on the level of opacity or transparency. In the cloud modeling and visualization system, a series of voxels will be a density function to generate the shape of atmospheric clouds. For each voxel, it could be characterized by a cube, sphere or level sets.

4.1.1.1 Cubical-Based Voxels

This method uses the small cube-based shape to represent every 3D voxel in the 3D regular grid space. This is a general representation of the voxelized method and thus some of the selected articles that were not mentioned clearly about the voxel types in their papers were put in this category.

Kajiya and Von Herzen [27] were the first researchers that fully used 3D volumetrical representation and they proposed a volume densities for rendering clouds using ray tracing method. Ebert and Parent [28] proposed a new method that efficiently combines volume rendering and scanline A-buffer techniques for any ray-traceable objects using 3D solid volumetrical gaseous objects, especially for atmospheric

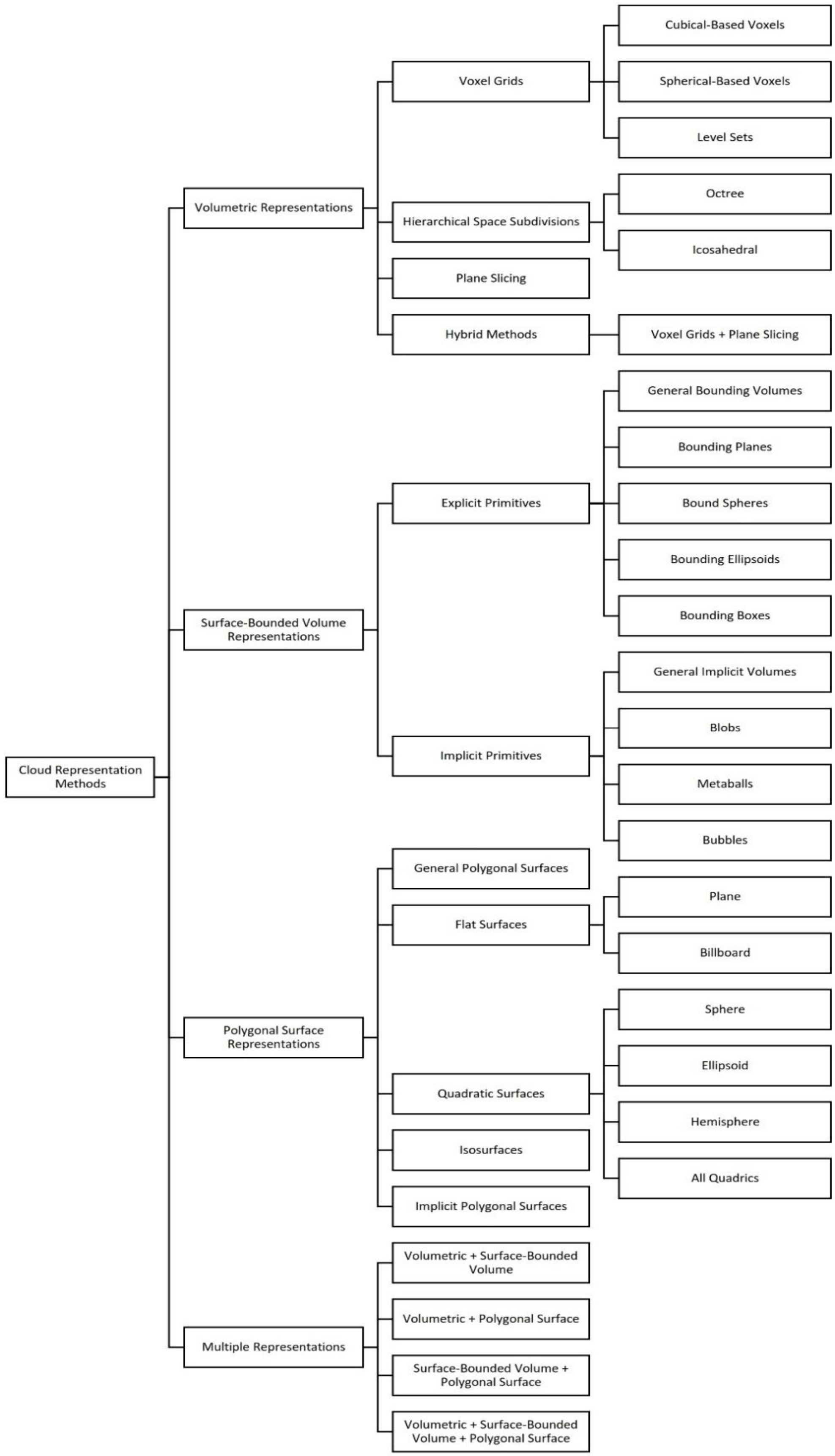

Figure 5: Taxonomic classification of the atmospheric cloud representation methods

clouds. Sakas and Gerth [29] introduced distance and pyramidal-volume sampling for applying to the 3D density voxel fields. Sakas [30] presented a new stochastic-based spectral synthesis method based on the spectral theory of turbulence in Fourier space in texture function. The generated voxel fields are allocated as a density 3D solid texture. A specific cubical-based voxel representation was proposed by Sun et al. [31] for generating 3D volumetric clouds using the Cube-Diamond-Square algorithm.

Several researchers were attempting to solve issues regarding the physically-based cloud simulation. Overby et al. [32] proposed a new approach to explicitly modeling many natural phenomena that led to the formation of atmospheric clouds using an interactive numerical fluid simulator. Dobashi et al. [33], and Kobak and Alda [34] proposed cumulus-type cloud formation controllers based on computational fluid dynamics. Bi et al. [35] used this representation to generate the grid structure of cellular automata.

There are a number of development of the volumetric clouds in movie productions. Batte and Fu [36] from Pixar Animation Studios used volumetrical cloud maps to model 3D imaginary character with cloud effects in the short film "Partly Cloudy". Penney [37] from Penrose Studios used a third-party procedural modeling package to create the cloud voxel grids for the production of VR movie "Allumette". These grids were exported with a custom file format and rendered using a ray marcher. Webb et al. [38] from Pixar Animation Studios created a library that contains many cloud pieces generated from procedural noise, fluid simulations, and satellite images. The modeled cloud pieces were stored in a specific 3D volumetric data format. This library was used in the making of the film "The Good Dinosaur".

Generating volumetric clouds via image-based methods is the alternative approach. Dobashi et al. [39] created a 3D grid representation to build up the synthetic atmospheric clouds and be one of the input parameters for implementing the optimization method from image resources. Dobashi [40] extended their previous research work in [39] by adding some user controls on the cloud formation. Dobashi et al. [41] improved their previous work in [39, 40] by incorporating fluid dynamics elements and user controllers to generate the cloud shape. Yuan and Guo [42] presented a method for meteorological studies to reconstruct cumulus clouds from high-resolution Landsat8 satellite images using the volumetrical representation of cloud top and base via segmentation and estimation methods. Iwasaki et al. [43] proposed a new image-based modeling method for atmospheric clouds using a single photograph and an example volumetric cloud dataset. Zhang et al. [44] presented a reconstruction framework fitting physically-based constraints to model large-scale cloud scenes from satellite images.

4.1.1.2 Spherical-Based Voxels

This method uses the sphere-based shape instead of using the cube-based representation to represent the voxel elements in a regular grid structure. Riley et al. [45] exploited the spherical-based voxels to develop a new method for visualizing the multi-field meteorological data that considers physics-based visual opaqueness and illumination computations for achieving the accurate display of the multi-scale and storm-type clouds. Krall and Harrington [46] from Digital Domain used a proprietary voxel data via spherical-based representation format during the pre-processing phase using Storm tool for the making of film "Stealth".

4.1.1.3 Level Sets

Level sets are the voxels used to store the distance values of a narrow-band area [26]. OpenVDB and SideFX's Houdini are examples of libraries and procedural tools that were used for 3D grid modeling, storage and manipulation. These representations were used in movie productions. Hasegawa et al. [47] from Rhythm and Hues Studios used the Cumulo tool to convert modeled base cloud shapes into level sets and applies displacement noise, and generates a new level set for geometrical displacement. It was used in the making of the film "The A-Team". Miller et al. [48] converted the polygonal clouds into narrow-band level sets, represented in a compact data structure. This data structure forms the basic volumetric representation for their clouds visualization system. Wright et al. [6] from Walt Disney Animation Studios produced an animated virtual reality short video named "A Kite's Tale" where SideFX's Houdini toolset was used to shape the clouds in virtual reality environment.

4.1.2 Hierarchical Space Subdivisions

Space subdivisions are the methods organized in a systematic tree structure. Different from the regular grid representation, these methods are capable to organize multi-size voxels in a hierarchical manner in which the depth and breadth of the tree can be controlled dynamically. Moreover, efficient computations can be achieved with a proper design of the tree structure. Based on the analysis of the selected articles, two types of hierarchical space subdivision methods were identified, that is, octree and icosahedral.

4.1.2.1 Octree

An octree is a tree data structure in which each internal node has exactly eight children. Octrees are most often used to partition a 3D space by recursively subdividing it into eight octants. Octrees are the 3D representation of quadtrees. Goswami [49] presented a physics-inspired procedural method for interactive animation of realistic, single-layered cumulus clouds for the landscape-scale size. This method makes use of the hierarchical octree structure via spherical thermal units called parcels.

4.1.2.2 Icosahedral

In geometry, a regular icosahedron is a convex polyhedron with 20 faces, 30 edges, and 12 vertices. In the icosahedral subdivision, an icosahedron can be used to define a high geodesic polyhedron by dividing triangulated faces into smaller triangles and projecting all the new vertices onto a sphere. Higher-order polygonal faces can be divided into triangles by adding new vertices centered on each face. Rimensberger et al. [4] are the only researchers that used icosahedral grids to compute the numerical simulations for visualizing the cloud water content.

4.1.3 Plane Slicing

Plane slicing methods are based on the combination of 2D flat surfaces that are organized close to each other in order to form a volumetric body (3D solid object). These methods can be represented as either axis-aligned or view-aligned plane mode. Schpok et al. [50] created an interactive modeling and animation of volumetric clouds providing intuitive user controllers by applying the plane slicing whereby the orientations of the planes are organized and directed in parallel or orthogonal to the light vector so that it reduces the difference between the normal of the plane and the camera view (the eye). Xu et al. [51] presented a method for physically plausible modeling and real-time rendering of large scale cloud scenes from weather forecast data which includes stratus clouds and cumulus clouds. They used the axis-aligned multi-resolution splatted slices to form the volumetric representation. Murphy et al. [52] from Pixar Animation Studios developed workflows for animated films, “Cars 3” and “Incredibles 2” that maintain the good use of volumetric cloud representation via a series of layered cards (quadrangle-shape plane) and squashed skydomes provided in SideFX’s Houdini toolset. Nowak et al. [53] presented the effective methods for obtaining realistic real-time clouds in Unreal Engine 4 by implementing the density pseudo volume textures in the simulation grid.

4.1.4 Hybrid Methods

Hybrid methods refer to the methods that are able to mix and adapt two or more existing methods to introduce the new approach to solve a particular problem in the related field. In our taxonomy for volumetric representation, there are three possibilities of combining the existing methods which are come from voxel grids, space subdivisions or plane slicing. Based on our analysis, Xu et al. [54] proposed probability fields that control the cellular automata for modeling the clouds by combining the representation of the voxel grid (using regular cubic subspaces) and plane slicing of volume textures.

4.2 Surface-Bounded Volume Representations

Surface-bounded volume representations have similar representations like volumetric representations. The difference between both of them is the density values of the inner cloud objects. In volumetric representation, the inner part is filled with the regular size of voxels. Meanwhile, in surface-bounded volume representation, the inner part is normally represented by a series of particles or bounding volumes that have different sizes scattered and constrained by the outer closed surface. In this paper, the surface-bounded volumes are divided into two categories that are based on explicit and implicit primitives.

4.2.1 Explicit Primitives

Explicit primitives in this section are referring to as the geometrical-based bounded volumes that can be used to represent and the atmospheric clouds. These include the general bounding volumes, bounding planes, bounding spheres, bounding ellipsoids, and bounding boxes.

4.2.1.1 General Bounding Volumes

General bounding volumes are defined as the methods that are not mentioned or explained regarding the bounding volume that was used in the research project. Reeves [55] introduced the particle systems which is a method for modeling natural phenomena of fuzzy objects such as clouds, fire, and water. The particle systems model an object as a cloud of primitive particles that define its volume. He claimed that it can be applied for modeling clouds with efficient rendering methods. Yu and Wang [56] proposed a sampling technique that enables users to accurately model various types of cloud shapes from a 2D image. Gong [57] proposed a simple, efficient approach based on computer vision and particle system to model various 3D clouds. This method uses computer vision technology to extract 3D structure information of clouds from images, then using particle technology to fill the 3D space and render the clouds. Schneider [58, 59] from Guerrilla Games developed an authoring real-time cloudscapes with the Decima Engine using an extended cloud map as a bounding volume and using remap function considering cloud coverage and cloud type for modeling the cloud density. They used this method for the production of the action role-playing game called “Horizon Zero Dawn”.

4.2.1.2 Bounding Planes

Bounding planes are defined as the methods that two flat surfaces organized in the top and bottom position so that the cloud volume is estimated based on the bounded area within both flat surfaces. Dungan [60] used a height field algorithm to estimate the cloud layer which acts as a region bounded by a top and bottom plane. Max [61], [62] used a cloud volume which is defined by the region between two height fields containing the clouds between two single-valued surfaces.

4.2.1.3 Bounding Spheres

Bounding spheres are the enclosing balls or spherical bounding regions which are defined by a center point and a radius. Blinn [63] used the spherical-based geometry of the cloud layer consisting of particles. Ostroushko et al. [64] used bounding spheres to formulate a mathematical model of the cloud. Goswami and Neyret [65] used bounding sphere representation as a base for presenting an efficient, physics-based procedural model for the real-time animation and visualization of cumulus clouds at landscape size.

4.2.1.4 Bounding Ellipsoids

Bounding ellipsoids are defined as the extended version of bounding spheres but have three different radii. Fishman and Schachter [66] demonstrated an example of opaque and solid ellipsoidal clouds, generated by a height field algorithm to represent the cloud layer of cumulus clouds. Stam and Fiume [67] presented general stochastic-based modeling primitive in which the general shape of the cloud model is constrained by an ellipsoidal correlation function that controls the interpolation of user-supplied data values at the macroscopic level.

4.2.1.5 Bounding Boxes

Bounding boxes are defined as the enclosing cubes or cuboids that are characterized by eight vertices and constrained by six flat surfaces. Inakage [68], [69] used the atmospheric cube (A-cube) which acts as a bounding volume for the environment to be modeled including the clouds. Rana et al. [70] proposed an efficient algorithm based on the randomized method to create detailed shapes of clouds using bounding boxes and particle systems. Hu et al. [71] presented an algorithm that can generate large scale clouds distribution in the simulation world based on several cloud templates. Suzuki et al. [72] proposed an interactive sketch-based retrieval system for cloud volumes by using a precomputed database. The database of cloud volumes is generated in advance by numerical analysis of atmospheric fluid dynamics.

4.2.2 Implicit Primitives

Implicit primitives in this section are referring to as the combination of the explicit primitives in the form of different sizes and overlapping positions in order to generate the irregular shape of surface-bounded volumes. The blending function is needed to model the clouds. These include the general implicit volumes, blobs, metaballs, and bubbles. In general, blobs, metaballs, and bubbles are referring to the same concept of representing the particles in implicit modeling of clouds. But in this paper, we separate these terminologies to ease the reader to find and see the division of specific categories or references.

4.2.2.1 General Implicit Volumes

General implicit volumes are defined as the methods that are not mentioned or explained regarding the implicit volume that was used in the research project. Lipus and Guid [73] introduced a new technique for blending implicit primitives, especially suitable for modeling the clouds.

Regarding the procedural methods of cloud modeling, Cui et al. [74] proposed a new method used to cloud modeling named, Fractal Particle Method, which is build up with the combination of particle systems and Fractal algorithm rendering with smoke effect to render vividly via implicit cloud groups. Montenegro et al. [75] proposed a new method of modeling clouds by combining volume implicit modeling with procedural noise techniques. Webanck et al. [76] proposed a compact procedural model for representing the different types of clouds based on the level of altitudes. They used implicit functions by mathematically combining global characteristics of density function and definition of cloud appearance. Kang and Kim [77], and Kang et al. [78] proposed a method for modeling clouds by exploiting the L-system algorithms and parameters.

Regarding the data-driven methods of modeling clouds, Yuan et al. [79] presented a method for estimating the shape of a cumulus cloud from a single image, which is suitable for flight simulations and video games via propagation scheme. Cen et al. [80] proposed a novel method to extract relevant cloud information from both satellite and natural images to construct a large-scale cloud scene with details. Implicit volume representation was used by integrating the coarse 3D cloud modeling extracted from satellite images and cloud image generation using optimization method via conditional Generative Adversarial Network (cGAN) which gets inputs from the cloud contour and cloud image dataset. Chen et al. [81] proposed a sketch-based retrieval system from pre-generated cumulus cloud models for cumulus cloud scene construction by generating 3D cloud models from natural images and then constructing a 3D cloud model database. Xie et al. [7] analyzed the weather forecast data and build a group of the spherical-shape representation that constructs the basic shape of clouds.

Regarding the modeling of clouds for art visualization, Alvarez et al. [82] presented several methods to generate clouds and smoke with a toon-shading-like style by allowing the abstraction of the visual and geometric complexity of the gaseous phenomena using a particle system. The abstraction process is made using implicit surfaces, which are used later to calculate the silhouette and obtain the resulting image. Wei et al. [83] proposed a new painting interface for volumetric cloud modeling using Chinese brush simulation. It is represented by implicit sphere-edge format.

4.2.2.2 Blobs

The blob representation was first introduced by Stam and Fiume [84] to model gaseous as density distributions of particles. The evolution of a density distribution within their wind field is defined by a diffusion formulation. They efficiently solved this equation by modeling the gaseous object as a “fuzzy blobby” with time-varying parameters. Later, Stam [85] used random blobs based on ellipsoid primitives to represent the random density field. Stam and Fiume [86] proposed the use of warped blobs for representing, animating, and illuminating of gaseous phenomena by reformulating the advection-diffusion equation for densities. Bouthors and Neyret [87] stored a hierarchy of quasi-spherical blobs living on top of each other. Abdessamed et al. [88] proposed a fast procedural method for modeling and rendering cumulus clouds using blobs representation with the use of hierarchical spheres of particles.

4.2.2.3 Metaballs

The metaball representation was first demonstrated by Nishita et al. [89] in which the clouds are defined by density fields, which are modeled by the metaballs. The refinement of cloud shapes was modeled by applying the Fractal method to metaballs. Further research works were done in [90], [91] by the same researchers to improve the results. Ebert [92] proposed a new, flexible, natural, intuitive, volume modeling and animation technique that combines implicit functions consisting of the spherical-based metaballs with turbulence-based procedural methods. Hufnagel et al. [93] presented an approach to visualizing clouds by employing a particle system that consists of softballs (metaballs). They used view-dependent, flattened and textured metaballs with spherical-shape representation. Recently, Quiros [3] developed cumulus-type clouds with optimized metaballs algorithms.

Regarding the data-driven methods of modeling clouds, Dobashi et al. [94, 95] proposed image-centric cloud modeling where the high visual quality of clouds was generated using metaballs based on satellite images to represent the density distribution of clouds. Roditakis [96] used the soft body modeling technique of metaballs based on the cloud bottom and top height measurements to build up the 3D volume from point clouds. Man [97] proposed a method that transforms the original cloud map to the inner representation using the Radial Basis Function (RBF) neural network. The cloud was represented by a set of spherical-based metaballs with specific parameters of a sphere including center coordinates, radius, and density value.

4.2.2.4 Bubbles

Bubble representation is very famous in the ultrasound field. In computer graphics, Neyret [98] proposed a method to qualitatively simulate the growth and animation of convective clouds by generating bubbles for displacements of 3D air parcels in the design model.

4.3 Polygonal Surface Representations

Polygonal surface representations are other solutions and the simplest one. These methods concern on the outer surface of the object without taking into consideration of its volume properties. In this paper, the polygonal surfaces are divided into five categories: general polygonal surfaces, flat surfaces, quadratic surfaces, isosurfaces, and implicit polygonal surfaces.

4.3.1 General Polygonal Surfaces

General polygonal surfaces are defined as the methods that are not mentioned or explained regarding the type of polygonal-based representation that was used in the research project. Perlin [99] introduced the concepts of solid texture used in the Pixel Stream Editor. Lee et al. [100] used satellite images to generate clouds in order to visualize weather information. They introduced the features of metacomputing, a method for handling a collection of assorted resources and described an application for cloud detection and visualization of satellite images. They also presented the methods for estimating the height of clouds from the satellite images.

4.3.2 Flat Surfaces

Flat surfaces are defined as the 2D planar representations that are used to display any objects in a simple geometrical form. These representations are normally being used due to its light computations compared to the volumetric and surface-bounded volume representations. There are two types of representations were implemented in the selected articles: plane and billboard.

4.3.2.1 Plane

A plane is defined as a single, simple 2D flat face of an object. This plane is used as a frame to attach the textured map onto its surface. The position and orientation of the plane are normally fixed and set in advance. Norton et al. [101] used a plane to map the sky with cloud appearances as a texturing function that is based on the convolution approximation in the frequency domain which is called the clamping function. Voss [102], [103] used the plane to map the results of computing the Fourier series of Gaussian fractals. Musgrave and Berger [104] proposed a method that consists of a single plane with a bump-textured map and a solid noise function. Gamito et al. [105] and Luciani et al. [106] used a 2D plane to model particle grid from fluid simulation with an appropriately-high resolution output. Raczkowski and Kaminski [107] presented a simple method that is used to model various types of clouds using fractals and sine functions to obtain realistic results via plane representation. Hu et al. [108] proposed a simple real-time method for modeling and rendering clouds in which the cloud density is formed by simulating the projected motion of cloud particles onto a 2D plane. Gong and Hu [109] introduced a new system to create various sky scenes and one of the key elements was mapping the cloud image onto a 2D plane which acts as a textured image for sky map hierarchy.

4.3.2.2 Billboard

Billboard also is defined as the 2D flat face of an object. However, the orientation of this method is reliant on the current viewing angle during the run-time process and it will be updated if there is a change of the camera view position and orientation. This representation is also known as impostor or sprite. Harris and Lastra [110] used dynamic impostors which are reliant to viewer position and orientation to accelerate cloud rendering by exploiting frame-to-frame coherence in interactive flight simulation to model and render clouds. Heinzlreiter et al. [111] presented a real-time cloud visualization methods by using transparency-blended billboard textures considering the camera view-dependent. Wang [112] from Microsoft Corporation enhanced the splatted texture on particles work in [110] to create a dozen visually different cloud types such as nimbostratus, cumulonimbus, and altocumulus by blending and matching 16 distinctive textures on the particles and mapping them onto impostors. Zhang et al. [113] used impostors to level up rendering performance.

4.3.3 Quadratic Surfaces

Quadratic surfaces are also called quadrics and they are the generalization of conic sections. In this paper, we identified three specific types of quadratic surfaces that were used in representing the atmospheric clouds: sphere, ellipsoid, and hemisphere as well as one representation that supports all quadratic surfaces.

4.3.3.1 Sphere

A sphere is defined as a perfectly round shape of a geometrical object in 3D space. This geometrical representation is frequently being used because it is a simple shape to be defined via a center point and a radius. Thus, the computation is very fast. Yaeger et al. [114] used a spherical-based polygonal surface as a medium to map the particles in physical simulation. Saupe [115] developed an application to model and visualize a fractal planet that used the unit sphere as a basic representation. Nishita et al. [116] proposed a method to display the earth as viewed from outer space using the imaginary sphere representation.

4.3.3.2 Ellipsoid

An ellipsoid is defined as a modified version of the spherical object. The ellipsoidal surfaces are rarely used to map the cloud images. Nonetheless, Gardner [117] proposed a new method to cloud simulation using curved surfaces in the form the hollow ellipsoids where the translucence components are controlled by a mathematical texture function.

4.3.3.3 Hemisphere

Hemisphere is defined as half of a sphere. In computer graphics, this representation is normally referred to as dome or skydome. It is a simple method to display the atmospheric components such as sky and clouds. Hasan et al. [118] presented a method to generate and render the procedural clouds in real-time on programmable 3D graphics hardware using skydome representation. Alldieck et al. [119] generated a realistic entire sky populated with clouds that are visually alike to those from the hemispherical photographic image using a cloud mesh approach whereby a model for representing a sky populated with clouds, consisting of a two-sided mesh shaped around a hemisphere. Mukhina and Bezgodov [120] proposed a method for modeling clouds by generating noise texture in which the clouds are approximately projected on the surface of the hemispherical disc instead of a plane. The cloud environment consists of multiple layers of clouds. Recently, Shen et al. [5] presented Aesthetically- Oriented Atmospheric Scattering (AOAS) which is a research on the feasibility study of using real-time rendering as a tool to explore sky styles including the clouds. They used skydome as their base of visualizing the sky elements.

4.3.3.4 All Quadrics

All quadrics are defined as any surfaces that can be derived from the slicing of a conic section. Gardner [121] proposed a new method which composes of any quadric surfaces bounded with planes and overlaid with textured images. The texture function was generated using the principle of Fourier expansion. It provides an efficient and effective means of representing a wide range of natural phenomena features. Lewis [122] used quadric-boundary-represented model in which the texture function is generated based on the solid noise synthesis via Wiener interpolation and convolution approximation.

4.3.4 Isosurfaces

Isosurfaces are the 3D version of the isolines or 3D equivalent of a contour line. Trembilski [123] presented methods for visualizing clouds from data produced by a meteorological weather simulation. They used isosurfaces representation because the original data has too rough grid resolution. They are then refined and deformed the isosurfaces to get more detailed outputs. Thus, cumulus clouds can be produced from any given isosurfaces. Later, Trembilski and Brobler [124] presented polygonal-based transparency computation methods using isosurface-based representation for achieving high- performance visualization of clouds from weather simulation data which was exclusively designed for the hardware- supported polygonal transparency computations.

4.3.5 Implicit Polygonal Surfaces

Implicit polygonal surfaces are the simplified version of implicit volume representation in which there are no inner parts of the object are considered, only outer polygonal surfaces are the main concern in these polygonal-boundary representations. Wither et al. [125] proposed methods to gather the spherical primitives by arranging the union of sphere-shaped objects based on the requirement of user-sketched 2D outlines, and to automatically generate 3D surface detail while retaining the 2D outline.

4.4 Multiple Representations

Based on the three representation methods that have been explained previously, we identified and introduced an extra category to denote the multiple representations that were adopted in the atmospheric cloud visualization system. The purpose of using this approach is to allow the use of different representations for specific types of atmospheric clouds because each cloud type has different characteristics and properties. The following subsections will explain the examples of previous work that have been done in the computer graphics field.

4.4.1 Volumetric and Surface-Bounded Volume

Miyazaki et al. [126] and Qiu et al. [127] proposed a method for modeling various types of clouds by simulating the cloud formation processes by using a Coupled Map Lattice (CML). The proposed method is based on the physics-based simulation of computational fluid dynamics which portrays the cloud shapes. They generated metaballs at the 3D voxel grid of lattice points in order to render the clouds.

4.4.2 Volumetric and Polygonal Surfaces

Bouthors et al. [128] proposed an algorithm for the real-time realistic simulation of multiple anisotropic scattering of light in their volumetric-based cloud model. They represented the clouds by incorporating the hypertexture (3D texture) for the inner part of the clouds and the polygonal surface meshes for the outer part of the clouds. Stiver et al. [129] proposed a freehand sketching system that was able to control the modeling of volumetric clouds. The inputs from the sketching process are used to generate a closed mesh, defining the initial cloud volume and later refine it.

4.4.3 Surface-Bounded Volume and Polygonal Surfaces

Do et al. [130] presented a new method for modeling various kinds of visually plausible clouds with less effort. The cloud representation used in their research work was made by applying the hierarchical seed particles with various spherical sizes and the alpha-blended billboards for fast rendering. Yang et al. [131] proposed a new framework that attempted to solve the specific cloud type problems by taking into account the weather forecast data and using two types of cloud representations. They developed the searching method to retrieve the 2D texture from the texture database and map onto a 2D plane for visualizing the cirrus clouds. They also developed an interpolation method to construct large-scale stratus by blending particles based on modified data points (metaball-like representation). Yuan et al. [132] proposed methods to construct the cloud shapes from the satellite images by modeling the large scale clouds using the cloud properties of the retrieval theory. They represented cirrus clouds with 2D plane representation while using the bounding planes for stratus clouds.

4.4.4 Surface-Bounded Volume and Polygonal Surfaces

Dobashi et al. [133] used a three-tier cloud representation for generating the clouds. Their method firstly calculates the values representing the intensity and the opacity of clouds per-pixel from an input photographic image and then stored them as a cloud image. For the cirrus cloud, the cloud image is the result of a 2D textured image mapped onto a 2D plane. For altocumulus the cloud, they used metaball representation. For the cumulus cloud, they used the volumetric representation.

4.5 Discussion

In this section, the atmospheric cloud representation methods are discussed. Table 2 indicates a summary of the related methods based on the analysis of the 112 selected publication articles and Figure 6 shows some examples of atmospheric cloud representations developed in the selected articles. The discussion will look into several aspects. These include the complexity of the methods, computational burden, memory consumption, quality of visual outputs, and suitability of target applications.

Regarding the complexity of the cloud representation methods, the volumetric, surface-bounded volume representations, and multiple representations have high complexity in terms of learning, understanding, and implementing the methods especially the development of voxelized and implicit-based volume methods. The proper design is required on how to arrange the voxels or particles effectively. Furthermore, the consideration also must be taken for correctly blending the texture function between the overlapping implicit primitives if using the surface-bounded volumes. Thus, a lot of time needed to fully realize these kinds of methods. Polygonal surfaces are the most preferable representations for developing a simple cloud visualization system.

Regarding the computational burden when executing the cloud representation methods, the polygonal surface representation will use less computational power and the speed of the system during run-time is faster than the volumetric, surface-bounded volume, and multiple representations. High computation time and high complexity of volume-related representations have decreasingly influenced the frame rates of the system. The use of high-end hardware technology is required to efficiently help accelerate the performance of the system.

Regarding the memory consumption involved when executing the cloud representation methods, it is the fact that it will be directly proportional to the computational usage. That means the higher processing time needed to execute the method, the higher also the memory will be used and therefore slowing down the speed of the system. This issue can be reduced by injecting the optimization or simplification methods into the system.

Regarding the quality of visual outputs, all the cloud representation methods are capable to provide a foundation for producing high-quality results. The mutual relationship between cloud representation and the other cloud components such as modeling, animation, illumination, and rendering must be appropriately designed and developed. Note that the cloud representation methods are the supporting components only for yielding a realistic cloud visualization system.

Regarding the suitability of target applications, there are two types of applications that need to be taken into account: online and offline applications. In this paper, online applications are referring to the visual systems that involve user interaction in a

Table 2: Summary of the atmospheric cloud representation methods by author, year and references

Method	**Sub-Method**	**Sub-Sub-Method**	**References**
Volumetric Representations	Voxel Grids	Cubical-Based Voxels	Kajiya and Von Herzen (1984) [27], Ebert and Parent (1990) [28], Sakas and Gerth (1992) [29], Sakas (1993) [30], Sun et al. (2015) [31], Overby et al. (2002) [32], Dobashi et al. (2008) [33], Kobak and Alda (2017) [34], Bi et al. (2016) [35], Batte and Fu (2009) [36], Penney (2016) [37], Webb et al. (2016) [38], Dobashi et al. (2012) [39], Dobashi (2014) [40], Dobashi et al. (2017) [41], Yuan and Guo (2015) [42], Iwasaki et al. (2017) [43], Zhang et al. (2017) [44]
		Spherical-Based Voxels	Riley et al. (2003) [45], Krall and Harrington (2005) [46]
		Level Sets	Wright et al. (2019) [6], Hasegawa et al. (2010) [47], Miller et al. (2012) [48]
	Hierarchical Space Subdivisions	Octree	Goswami (2019) [49]
		Icosahedral	Rimensberger et al. (2019) [4]
	Plane Slicing	-	Schpok et al. (2003) [50], Xu et al. (2015) [51], Murphy et al. (2018) [52], Nowak et al. (2018) [53]
	Hybrid Methods	Incorporation of Voxel Grids and Plane Slicing	Xu et al. (2009) [54]
Surface-Bounded Volume Representations	Explicit Primitives	General Bounding Volumes	Reeves (1983) [55], Yu and Wang (2011) [56], Gong (2012) [57], Schneider (2017) [58], Schneider (2018) [59]
		Bounding Planes	Dungan (1979) [60], Max (1983) [61], Max (1986) [62]
		Bounding Spheres	Blinn (1982) [63], Ostroushko et al. (2010) [64], Goswami and Neyret (2016) [65]
		Bounding Ellipsoids	Fishman and Schachter (1980) [66], Stam and Fiume (1991) [67]
		Bounding Boxes	Inakage (1989) [68], Inakage (1991) [69], Rana et al. (2006) [70], Hu et al. (2009) [71], Suzuki et al. (2015) [72]
	Implicit Primitives	General Implicit Volumes	Xie et al. (2019) [7], Lipus and Guid (2005) [73], Cui et al. (2011) [74], Montenegro et al. (2017) [75], Webanck et al. (2018) [76], Kang and Kim (2015) [77], Kang et al. (2015) [78], Yuan et al. (2014) [79], Cen et al. (2018) [80],

			Chen et al. (2018) [81], Alvarez et al. (2007) [82], Wei et al. (2014) [83]
		Blobs	Stam and Fiume (1993) [84], Stam (1994) [85], Stam and Fiume (1995) [86], Bouthors and Neyret (2004) [87], Abdessamed et al. (2013) [88]
		Metaballs	Quiros (2019) [3], Nishita et al. (1996) [89], Nishita and Dobashi (1999) [90], Nishita and Dobashi (2001) [91], Ebert (1997) [92], Hufnagel et al. (2007) [93], Dobashi et al. (1998) [94], Dobashi et al. (1999) [95], Roditakis (2004) [96], Man (2006) [97]
		Bubbles	Neyret (1997) [98]
Polygonal Surface Representations	General Polygonal Surfaces	-	Perlin (1985) [99], Lee et al. (1996) [100]
	Flat Surfaces	Plane	Norton et al. (1982) [101], Voss (1983) [102], Voss (1985) [103], Musgrave and Berger (1990) [104], Gamito et al. (1995) [105], Luciani et al. (1995) [106], Raczkowski and Kaminski (1995) [107], Hu et al (2009) [108], Gong and Hu (2011) [109]
		Billboard	Harris and Lastra (2001) [110], Heinzlreiter et al. (2002) [111], Wang (2003) [112], Zhang et al. (2014) [113]
	Quadratic Surfaces	Sphere	Yaeger et al. (1986) [114], Saupe (1989) [115], Nishita et al. (1993) [116]
		Ellipsoid	Gardner (1985) [117]
		Hemisphere	Shen et al. (2019) [5], Hasan et al. (2005) [118], Alldieck et al. (2014) [119], Mukhina and Bezgodov (2015) [120]
		All Quadrics	Gardner (1984) [121], Lewis (1989) [122]
	Isosurfaces	-	Trembilski (2001) [123], Trembilski and Brobler (2002) [124]
	Implicit Polygonal Surfaces	-	Wither et al. (2008) [125]
Multiple Representations	Volumetric and Surface-Bounded Volume	-	Miyazaki et al. (2001) [126], Qiu et al. (2013) [127]
	Volumetric and Polygonal Surfaces	-	Bouthors et al. (2008) [128], Stiver et al. (2010) [129]
	Surface-Bounded Volume and Polygonal Surfaces	-	Do et al. (2012) [130], Yang et al. (2013) [131], Yuan et al. (2013) [132]
	Volumetric, Surface-Bounded Volume and Polygonal Surfaces	-	Dobashi et al. (2010) [133]

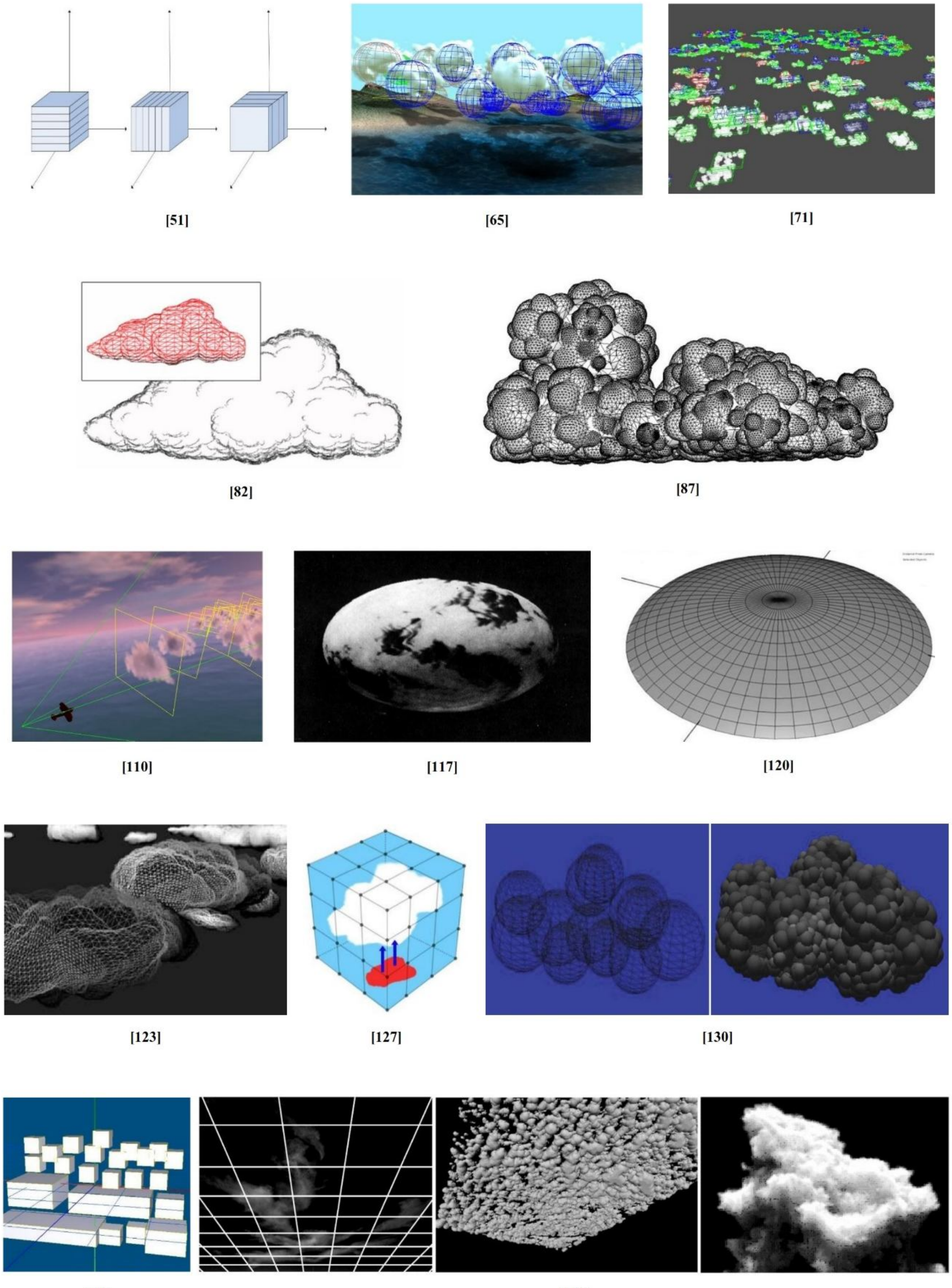

Figure 6: Examples of the atmospheric cloud representation methods

real-time environment and focus on system performances. Examples of online applications are video games, flight simulation, and virtual reality. While offline systems are referring to the systems that there are no user interactions involved and focus on delivering high-quality computer-generation images (CGI) as the final outputs, even though the processing time to complete the tasks is very high. Examples of offline applications are movies and advertisements. The polygonal surface representations are mostly beneficial for online or real-time applications, whereas the volume-related representations are suitable for offline applications. On the other perspective, the polygonal-based representations are recommended for applications that involve the viewing from the ground to the sky or the outer space to see the whole planet because they are no close communication between the user or camera view with the cloud objects. While the volume-related representations are very useful when there is the involvement of penetrating the clouds such as during real-time navigation in flight simulation. Hence, this will give a significant level of immersiveness for the user to explore the atmospheric landscape.

5. RESEARCH ISSUES AND DIRECTIONS

In this section, a number of research issues and directions are discussed. It will give some insights and ideas for the researchers to plan their future work.

5.1 Exploration of Hybrid-Able Cloud Representation Methods

Based on the analysis that has been done on the existing cloud representation methods, there are a few hybrid methods available exist [54], [127], [129], [131]. They do not wholly explore yet. Thus leaving some rooms for researchers to think about the state-of-the-art methods and approaches to solve the current-related problems and further improve the current findings as their new contributions. The researchers are able to mix more than one method from the same category of method or could attempt to cross combine the representation methods from different main categories.

5.2 Diversity of Virtual Cloudscapes

Visualizing the gaseous-based phenomena such as atmospheric clouds is a challenging task. There are many types of atmospheric clouds appeared in the sky at one time. Different types of clouds have different kinds of properties to represent them. For example, stratiform clouds with fog-like layers, cirriform clouds with wispy properties at high altitude appearance, and cumuliform clouds with cotton-like form. In order to visualize different cloud types, it would be difficult to represent them by using only one representation method. Based on the previous works [126]-[133], the exploration of multiple cloud representations only was not fully covered yet. Therefore, there are many opportunities to contribute to these kinds of representations by enhancing the existing methods. The other challenge of using the multiple representations is that the researchers need to encounter the high method complexity, high computation time, and high memory consumption. Hence, a strategic scheme is needed to handle and reduce those three ‘high’ features in order to maintain the performance of the system, especially for real-time graphics applications. Level-of-details management could be considered as one of the ways to efficiently handle diverse types of virtual cloudscapes.

5.3 Exploitation of Hardware-Driven Technologies

According to the previous work [3], [34], [75], [120], we observed that there is a trend in using the high-end hardware in the atmospheric cloud research work recently. The advancement of present hardware technologies could be a booster for accelerating the performance of the atmospheric cloud visualization system. The following technologies could be investigated, adopted and possibly integrated into cloud research work. These include the use of the:

- Parallel, multi-core central processing unit (CPU),
- Graphics processing unit (GPU),
- Hard drive to store data that cannot be fit into the computer’s main memory (RAM) via out-of-core algorithms,
- Distributed computing system, and
- Cloud and fog computing.

Note that by using these kinds of technologies into the atmospheric cloud visualization system, the researchers should take into consideration the supporting operating system, the architecture of the processor of CPU or GPU, and the bandwidth of transferring and visualizing the data.

6. CONCLUSION

In this paper, we have presented a comprehensive review of the atmospheric cloud representation methods in the field of computer graphics. We introduced an up-to-date taxonomic classification of the existing cloud representation methods that comprises of four noteworthy cloud representations: volumetrics, surface-bounded volumes, polygonal surfaces, and multiple representations. This classification was made based on the analysis of the selected publication articles that have gone through step-by-step strategies as planned in the review methodology. The strengths and weaknesses of each representation were discussed and elaborated in terms of the method complexity, computational burden, memory consumption, quality of visual outputs, and suitability of target applications. Finally, we have pointed out the research issues and directions that could be participated by researchers for their future research work. This review is expected to help the computer graphics community especially beginner-level researchers to understand the whole picture involving the methods adopted and to enlighten the researchers on the methods that can be exploited, explored, modified, and adapted to fit with respect to their particular domain and the problem of interest.

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