Gaseous Volume Visualization Using Particle Maps

Neeharika Adabala[1] and Swami Manohar[1,2]

[1]Supercomputer Education and Research Center,
[2]Computer Science and Automation,
Indian Institute of Science, Bangalore, India

Abstract
This paper presents a new method of rendering gaseous volumes using particle maps which store the particles that model the gaseous volume. The particle maps enable quick estimation of densities within a gaseous volume during rendering, analogous to how photon maps enable estimation of radiance during ray tracing.
Particle based approaches to model gases are inherently simple and facilitate easy inclusion of physical correctness, but do not generally give realistic images. The alternate of texture based approaches give realistic images but have limited scope for inclusion of physical correctness. We combine these two approaches to give a method that (i) has flexibility to model any gaseous geometry, (ii) offers high scope for incorporation of physical correctness, (iii) does not possess arcane control parameters and (iv) results in realistic images.

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1. Introduction

Real world scenes often contain gaseous phenomena, like steam rising from a tea cup, exhausts of vehicles, smoke, clouds, etc. Any effort to model such scenes in graphics require the rendering of gaseous volumes.

The existing methods to model gaseous phenomena fall mainly into the categories of particle or texture based approaches. Particle based approaches have the advantage that physical correctness of the dynamics of the gas can be incorporated with ease into them. But they have limited application when generating realistic images and are usually used for modeling phenomena that treat individual particles as light sources, for example, explosions [12] and fireworks [8]. Texture based approaches on the other hand give more realistic images. Solid textures have been used to visualize gases [3] and turbulent gaseous phenomena [13]. But these approaches are computationally expensive and often involve tuning of arcane parameters. Since the particle based approaches and texture based approaches have complementary advantages, in this paper a method to combine these approaches is proposed, in order to obtain the advantages of both. This is realized by modeling the gas as particles. Rendering is performed by grouping the particles and estimating the density to decide the brightness, making the proposed method similar to texture based approaches. The particle systems are stored in particle maps to speed up the estimation of densities during the rendering phase.

Other methods that combine particle and texture based approaches are: Stam and Fiume [14] model gas as a density distribution of particles where each particle represents a density, "blob" of gas, rather than a simple particle. Our method differs from their approach because we use a set of simple particles rather than "blobs" to model the gas. Foster and Metaxas [4] use simple particles to model the motion of hot turbulent gas. A density map is computed from the particle distribution and volume rendered. In this approach a cell resolution is required to compute the density map. Grid artifacts result if the gas exhibits finer motion than the cell resolution. Our approach does not use a grid, and also there is no explicit creation of a density map, the densities are computed from the particle map while rendering.

The work by Ebert [3] and Nishita et. al. [9] which result in realistic images of clouds use metaballs to model the shape of clouds, which is different from the simple particles which form the basis of modeling the gas in this work. Also we limit ourselves to the low albedo case in this paper.

2. Implementation

Rendering of gaseous volumes requires methods used to render participating media. The references to work in this area

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can be obtained from [5] and the survey [10]. The common feature in these approaches is that it is necessary to find an integral along the line of sight during the process of rendering [11]. It is also often necessary to know the density at locations within the participating medium to determine how much light is scattered and transmitted by that particular region. Therefore, when a participating medium is modeled by a particle system it is necessary to store it in a data structure that enables easy determination of :

- the number of particles that lie along the line of sight, and
- the density of the particles at any location of interest within the particle system.

As these operations occur repeatedly during rendering it is necessary that the searches on the data structure are quick. These requirements are similar to the requirements for estimation of radiance in localized regions after tracking photons from light sources to diffusion surfaces and participating media that has been solved using photon maps by Jensen and Christensen[5]. Therefore, the particles system is stored as a particle map in a multidimensional search tree, the kd-tree [1], which allows efficient look up for range searches.

We consider the low albedo case for ray tracing of volume densities given by Kajiya and Von Herzen[7] for rendering particle maps. In their approach the brightness of a ray passing through a gaseous volume is given by

$$\begin{aligned} B \;=\; & \int_{t_{near}}^{t_{far}} e^{-\tau \int_{t_{near}}^{t} \rho(x(u),y(u),z(u))du} \\ & \text{x} \;\left[\sum_i I_i(x(t),y(t),z(t))\, p(cos(\theta))\right] \\ & \text{x} \;\; \rho(x(t),y(t),z(t))dt \;\;, \end{aligned} \tag{1}$$

where

$$I_i(x,y,z) = e^{-\tau \int_{t_{near}}^{t_{far}} \rho(x(s),y(s),z(s))ds}. \tag{2}$$

In equation (1) the first term accounts for the attenuation of light as it passes through the volume of gas from the location of interest to reach the eye. The integral in the term estimates the densities of gas that a ray encounters along its path from t_{near} to t. This term is evaluated from the particle map by performing a cylindrical range search on it. The result of the search is the number of particles that lie within the cylinder along the ray, usually a small fraction of the total number of particles used to model the gas. This number is transformed into a value usable in the equation (1) by using the fact that when there are no particles along the ray then the light does not experience any attenuation. Further, the attenuation should strictly increase in a smooth manner with increase in number of particles. Also, it should have a finite range in order to avoid causing the expressions in the equation to be driven to saturation. The sigmoid function which is one of the most common activation function used in the field of artificial neural networks [6] exhibits the behavior described above.

The logistic function which is an example of a sigmoid function has been used for achieving the required transformation. This function is made to have a finite range of $[0,1]$, as given below:

$$f(x) = \frac{2}{1+e^{-k_1 x}} - 1 \tag{3}$$

where k_1 is a positive real constant. The value of k_1 controls the slope of the function. Small values of k_1 should be chosen when a large number of particles are used in the modeling of the gaseous volume and relatively large values when few particles are used.

$I_i(x(t),y(t),z(t))$ in the second term in the equation (1) accounts for the attenuation experienced by the light from the i light sources in the scene. It is evaluated using the equation (2). This term is similar to the first term in equation (1), and is evaluated in a similar fashion. The phase function which is any one of the functions described by Blinn[2] is represented by $p(cos(\theta))$ in this term.

The third term in equation (1), which is the density at location (x,y,z), is responsible for making the brightness observed proportional to the density of the gas at the location. This value is estimated by performing a nearest neighbour search on the particle map. The radii values obtained from the N nearest neighbours search have to be transformed into a density value in order to use in equation (1). An obvious approach would be to compute $\frac{N}{\frac{4}{3}\pi r^3}$ where $r = d_{farthest}$ is the distance of the farthest particle obtained from the N nearest neighbours search. However, very often $d^3_{farthest}$ lies in the range of 10^{-4} to 10^{-6} so this approach results in very large values and cannot be used.

The alternative is to use a function which transforms the results from our search to a finite small range (the range $[0,1]$ is chosen here) in a meaningful way. It is known that small radii imply that there are many particles close to the location and so the density is high. Also as the radii become larger the density should strictly decrease smoothly. Therefore, a monotonically decreasing function is chosen to transform the radii values into density values. It was found that use of only the distance of farthest particle for the estimation of density results in images that are noisy. Therefore, the density is estimated by taking a weighted sum of the negative exponential of the distances of the nearest and the farthest (Nth) particles obtained from the N nearest neighbours search. Which is as follows:

$$\rho(x,y,z) = w_1 e^{-k_2 d_{nearest}} + w_2 e^{-k_2 d_{farthest}} \tag{4}$$

where k_2 is a constant which is > 1, w_1 and w_2 are such that $w_1 + w_2 = 1$ and both lie in $[0,1]$. The distances of the nearest and the farthest (Nth) particle form the point, (x,y,z), where the density is being estimated are represented by $d_{nearest}$ and $d_{farthest}$ respectively.

The following is the algorithm for the rendering of the gaseous volume represented by particle maps:

1. *For each time step repeat steps 2 to 4*
2. *Generate particles of the gaseous volume or update existing particle locations.*
3. *Create the particle map by building the kd-tree with the particles.*
4. *Ray trace the scene using the equation (1) for rendering the gaseous volume as follows:*
    a. *Find the particles that lie along the ray from the eye to the location of interest, point $p(x,y,z)$, in the gaseous volume by performing a cylindrical range search and transform the result using equation (3). Use the obtained value in place of the integral in the first term of the brightness equation.*
    b. *Find the number of particles along the path of light source to location of interest, $p(x,y,z)$, compute attenuation as before and multiply by phase function.*
    c. *Estimate the density at $p(x,y,z)$ by performing a nearest neighbour search. Use equation (4) to obtain the density value.*

    Multiply the values obtained in the steps 4a, 4b and 4c and repeat step 4 by moving the point of interest along the ray in the volume and compute the sum to obtain the brightness of the ray.

The above algorithm has been implemented using an optimized kd-tree. Figure 1 and Figure 2 show sample images generated by our method. Figure 3 is the image of "EG 99" created using particle maps.

3. Conclusions and Future Work

A new method of visualizing gaseous volumes represented by particle systems has been given. The particle system has been stored as a particle map in a kd-tree for rendering. A method of rendering the gaseous volume using the particle map for the low albedo case by performing range searches and nearest neighbour searches on the particle map has been presented. This approach combines the texture and particle based methods and offers

- flexibility to model any gaseous geometry, as particle systems which form the basis for the model are inherently flexible.
- high scope for incorporation of physical correctness, because many scientific equations of dynamics can be applied to displace particles in space to give a physically correct particle system without changing any other aspect of the algorithm.
- does not possess arcane control parameters; this is with reference to some of the texture based methods which have the dynamics of the gaseous volume incorporated into the texture resulting in a number of parameters which simultaneously dictate the appearance and dynamics of the gaseous volume. In our case we have two parameters that control only the appearance of the gaseous volume.
- results in realistic images; by grouping the particles and using them to define densities we get more realistic images than by rendering individual motion blurred particles.

Ongoing work in using particle maps for high albedo case and radiance based rendering is expected to give promising results as particle maps enable quick estimation of localized properties of particle systems. Methods of merging particle maps with photon maps to have a single map for participating media are also being investigated.

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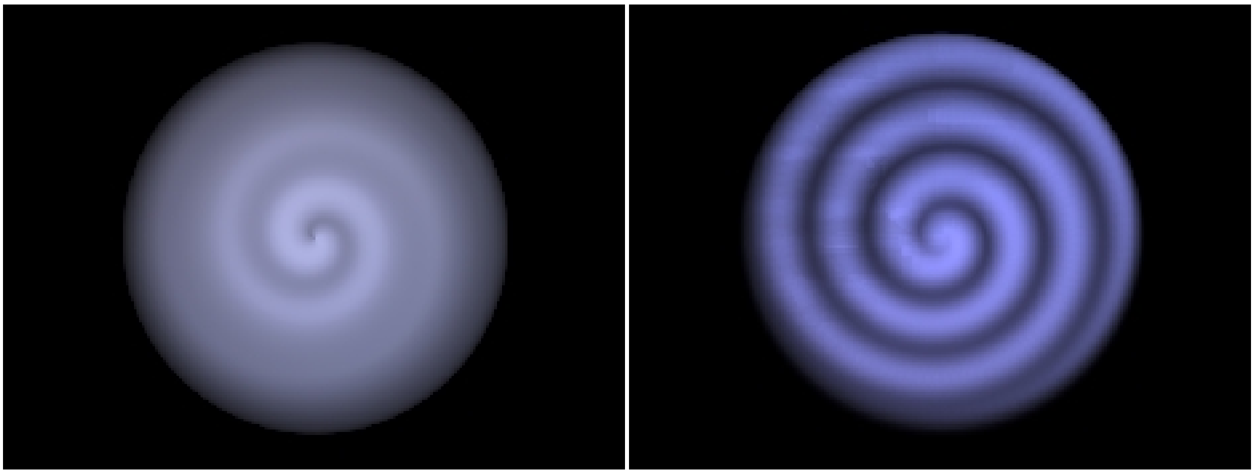

Figure 1: *Spiral shaped gaseous volume (left) generated by texture based approach (right) generated with particle maps. These images show that the particle map approach captures details of the gaseous density distribution more clearly than the texture based approach.*

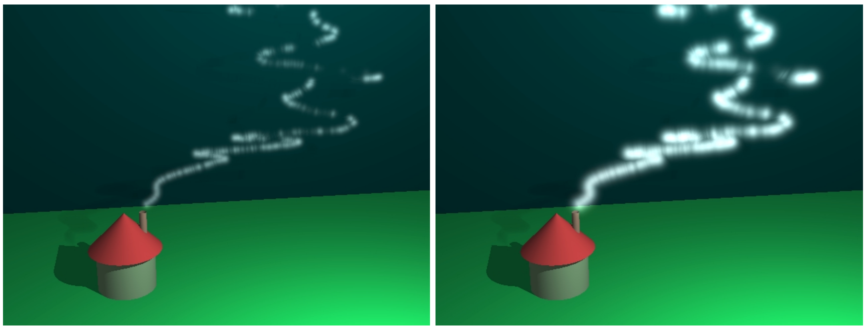

Figure 2: *Images showing trails of smoke, generated with* $k_2 = 100$ *(left) and* $k_2 = 30$ *(right).*

Figure 3: *Gaseous volume in the form of "EG 99" was created using 8200 particles. This demonstrates the ability to model arbitrary gaseous volumes by the particle maps approach.*