MATHEMATICAL MODEL OF THE CLOUD FOR RAY TRACING

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***Abstract**: The three-dimensional computer graphics claimed today in many fields of the person activity: producing of computer games, TV, animation, advertise production, visualization systems of out-of-cockpit environment for transport simulators, CAD systems, scientific visualization, computer tomography etc. Especially high are requirements for realism of generated images. Realism rising leads to image detail increasing, necessity of shadows and light sources processing, the account of an environment transparency, generation of various special effects. Therefore in the field of a computer graphics researches are intensively conducted for the purpose of development of as much as possible effective models for three-dimensional scenes and fast methods of realistic image synthesis on their basis. One of the most promising methods is a ray tracing. The method provides possibility of synthesis of high realistic images; however it demands the large computational cost for the realization. The cloud synthesis model for a ray tracing is described. The model is directed to a real time graphics and allows raising realism of the synthesized image. Advantages of proposed model are the ability of working with cloud on different levels of detail, availability of bounding surfaces inside of cloud structure that allows to increase efficiency of an image synthesis algorithm, ease of cloud animation. Due to the great flexibility of a cloud model and high performance of its visualization algorithm these results can be used in real time visualization systems.*

***Keywords**: cloud, procedural modeling, ray tracing, sphere, visualization algorithm.*

***ACM Classification Keywords**: I.3.5 Computational Geometry and Object Modeling.*

***Conference topic**: Information Retrieval.*

Introduction

One of the problems of computer graphics is generation of images in real time. Thus one of the major parameters of the graphic system providing synthesis of a three-dimensional scene is realism of the resulting image.

In recent years active works are conducted on development of ray tracing, which provides possibility of synthesis for high realistic images of three-dimensional scenes. The idea of a method consists in carrying out of mathematical modeling of propagation of a ray in a direction from the observer to scene objects and further to light sources. Number of traced rays is proportional to resolution of display system [Yan, 1985]. Despite the big computing complexity demanded for processing a scene, this method possesses a number of advantages in comparison with everywhere widespread rasterization, namely: realization simplicity of inter-object rereflection effects, shadow generation, possibility of processing for analytically described surfaces (rasterization requires a pre-triangulation of all scene objects), the account of anisotropic properties of objects and environment. However the main advantage of this method is possibility of wide parallelization of calculations that allows using multicore processors and systems on their basis for carrying out of calculations.

Emergence of hardware and software (ATI Stream, NVIDIA CUDA, Intel OpenMP etc.) for the organization of multithreaded calculations gives the opportunity to solve right now a number of the problems related to generation of highly realistic images of three-dimensional objects in real time. Thus, development of mathematical models of objects and fast algorithms for a ray tracing is an actual problem.

One of possible applications of a ray tracing is the solution of a synthesis problem of the realistic cloud images in real time that is especially important for visualization systems of various vehicle simulators, tasks of meteorological data processing and image recognition.

Problem

Existing methods of clouds creation models can be divided on two groups. The first group includes methods based on modeling of physical processes occurring during the formation of clouds [Bouthors, 2008; Stam, 1995]. These methods require the assignment of a large number of input data, as well as a considerable amount of computing cost. The second group includes methods of procedural modeling of cloud shapes [Schpok, 2003; Harris, 2001; Voss, 1983]. Such methods are used when necessary to obtain an image of an arbitrary clouds or similar to the original, given in any way. They usually have more simple algorithms, but also let you create realistic three-dimensional image of the cloud.

The possibility of ray tracing to process analytically described objects can greatly simplify the cloud model and reduce the amount of data for presentation. One of the most simple and at the same time realistic cloud models are models based on the use of spheres and ellipsoids. However, in [Dobashi, 1999] due to lack of bounding surfaces need to cross the ray with all spheres of clouds, which leads to large computational cost. Model [Ostroushko, 2000] requires finding a smaller number of crossings through the use of the bounding surfaces. However, the use of ellipsoids as the basic building blocks leads to a more complicated calculation of the intersection points, which increases the computational costs.

Thus, it is necessary to develop a mathematical model based on the methods of procedural modeling of cloud shapes, which combines advantages of the models described in the sources [Bouthors, 2008: Stam, 1995], as well as the basic building blocks to use spheres and bounding surfaces.

Solution of the Task

Mathematical model of the cloud. The model is based on the model described in [Ostroushko, 2000]. The inputs in this model are the desired level of detail K and sizes of the cloud a, b, c. Based on this data sphere of the base level is formed with a radius r^0 and coordinates of the center x^0, y^0, z^0:

$$r^0 = \begin{cases} \min(a,b,c)/2, & K = 0, \\ \max(a,b,c)/2, & K > 0, \end{cases}$$

$$x^0 = 0, \quad y^0 = 0, \quad z^0 = 0.$$

In case $K = 0$ the cloud consists of a single sphere of radius r^0. If $K > 0$, then (a) deformation coefficients d_x, d_y, d_z for each axis are determined that allow to fit the cloud into the required dimensions, (b) the iterative process starts. The deformation coefficients for the first iteration step are calculated according to the following expressions:

$$d_x^0 = a/(2r^0), \quad d_y^0 = b/(2r^0), \quad d_z^0 = c/(2r^0).$$

For all following iteration steps $d_x^i = 1, \quad d_y^i = 1, \quad d_z^i = 1$.

At each iteration step the sphere obtained at the previous step is divided into five similar figures, forming the data to a new level of detail. The radii of the spheres in the new level are determined according to the expression:

$$r_j^{k+1} = l_j r^k ,$$

where $k \in \{0,\ldots,K-1\}$ – iteration number;

$j \in \{1,2,3,4,5\}$ – figure number;

l_j – random variable ranging from 0 to 1.

Coordinates of the centers of obtained spheres are defined as follows:

$$x_1^{k+1} = x^k + (r^k - r_1^{k+1})s_1 d_x{}^k, \quad y_1^{k+1} = y^k, \quad z_1^{k+1} = z^k + \xi_1 f_\Delta\left((r^k - r_1^{k+1})s_1, r^k - r_1^{k+1}\right),$$
$$x_2^{k+1} = x^k - (r^k - r_2^{k+1})s_2 d_x{}^k, \quad y_2^{k+1} = y^k, \quad z_2^{k+1} = z^k + \xi_2 f_\Delta\left((r^k - r_2^{k+1})s_2, r^k - r_2^{k+1}\right),$$
$$x_3^{k+1} = x^k + \xi_3 f_\Delta\left((r^k - r_3^{k+1})s_3, r^k - r_3^{k+1}\right), \quad y_3^{k+1} = y^k, \quad z_3^{k+1} = z^k + (r^k - r_3^{k+1})s_3 d_z{}^k,$$
$$x_4^{k+1} = x^k + \xi_4 f_\Delta\left((r^k - r_4^{k+1})s_4, r^k - r_4^{k+1}\right), \quad y_4^{k+1} = y^k, \quad z_4^{k+1} = z^k - (r^k - r_4^{k+1})s_4 d_z{}^k,$$

$$x_5^{k+1} = \begin{cases} x^k + \xi_5 f_\Delta\left(s_5, r^k - r_5^{k+1}\right), \xi_5 = -1, \\ x^k, \xi_5 = 1, \end{cases}$$
$$y_5^{k+1} = y^k - (r^k - r_5^{k+1})s_5 d_y{}^k,$$
$$z_5^{k+1} = \begin{cases} z^k + \xi_5 f_\Delta\left(s_5, r^k - r_5^{k+1}\right), \xi_5 = 1, \\ z^k, \xi_5 = -1. \end{cases}$$

here s_j is a value which is chosen randomly in the range of 0.5 to 1;

ξ_j is a value randomly chosen from {+1, -1};

$f_\Delta(C,R) = R^2 - C^2$ – function calculating one of the coordinates from the known values of radius R and other coordinate C. It allows to fit a new sphere into the sphere of previous level.

The use of randomly chosen values on each iteration allows eliminating periodicity of the structure of clouds. The iterative process continues until specified level of detail is reached. An example of generation of the next level of cloud description is shown in Figure 1.

The choice of the distribution of random variables used to construct the cloud model largely influences the results obtained and allows receiving various types of cloud formations. Thus, it was experimentally found that the best results when building a model of cumulus clouds can be obtained if l_i is in the range from 0.26 to 0.76, and s_i ranged from 0.9 to 1. Great influence on the obtained result has a number of figures into which the sphere is subdivided at each iteration step.

Transparency of the medium inside the cloud is determined by the meteorological optical range (MOR) S_m which is also an input parameter of the model. MOR determines the range of visibility of a black object and uniquely characterizes the weakening of the radiation by the environment.

For practical calculations of visibility the medium transmittance T is used, which for an optically homogeneous layer of medium with thickness equal to the unit length is called the specific transparency t. Knowing the specific transparency and thickness of the layer of the medium, we can determine the transmittance [McCartney, 1976]:

$$T = t^l . \tag{1}$$

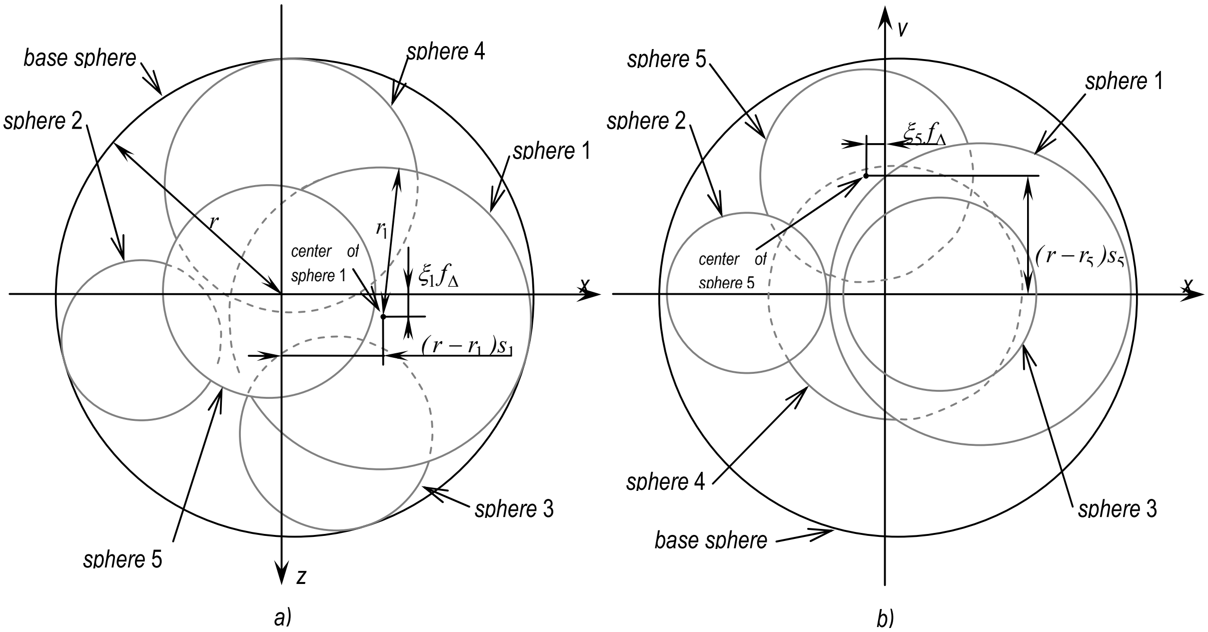

Figure 1. An example of subdivision of sphere when creating the next level of cloud description:
a) projection on the XZ plane, b) projection on the XY plane.

Specific transparency and MOR are related as follows:

$$S_м = \ln 0.02 / \ln t .$$

Thus, knowing the MOR and calculating the length of the path of the projection ray inside the sphere, we easily obtain the transmittance.

To reduce the sphericity of cloud the specific transparency should grow from the center to the periphery, which requires an additional function $f\left(d_i, r_i\right)$ that takes into account such variation. We propose to use the following function:

$$f(d,r) = \begin{cases} 1 - \dfrac{d}{r}, & d \le r, \\ 0, & d > r. \end{cases} \tag{2}$$

Then the transmittance of the i-th sphere, taking into account (1) and (2) is given by

$$T = T_i f\left(d_i, r_i\right) + 1 - f\left(d_i, r_i\right). \tag{3}$$

In addition, we propose to use the bump mapping technology, which will create a sense of surface irregularities [Blinn, 1978]. The apparent change in surface shape is achieved by changing the direction of normal in the point of intersection of the projection ray with the sphere and allows hiding the spherical structure of the cloud even more (Figure 2):

$$\vec{\mathbf{n}}' = f(u, v, \vec{\mathbf{n}}), \tag{4}$$

where $\vec{\mathbf{n}}$ – original normal to the sphere surface,

$f(u, v, \vec{\mathbf{n}})$ – parametric function of the normal variation,

u, v – parameters defining the position of the intersection point on the sphere surface.

Since the variations relate only to the normal direction (the coordinates of the intersection point do not change), then the amount of computation increases insignificantly. Function f can be represented analytically or, alternatively, it can use sampling from the texture map.

The use of bump mapping technology and variations in the specific transparency within the sphere allows obtaining a significant increase in realism of the generated images of clouds.

One of important features of this model is the easiness of cloud animation. It is carried out by changing parameters of spheres in the cloud model, specifically the radii of spheres and the coordinates of their centers. To animate the cloud the sequence is formed consisting of several implementations of cloud models, obtained by the method described above using the same number of iterations for all implementations. Since the sphere numbers in one implementation correspond to numbers in other implementations, it is easy to obtain correspondence between the two implementations. Through linear interpolation of parameters between the two consecutive implementations of models it is easy to achieve the modification of cloud shape in time. Using affine transformations - rotation, shift, scaling - in addition will allow to even more change the shape of cloud.

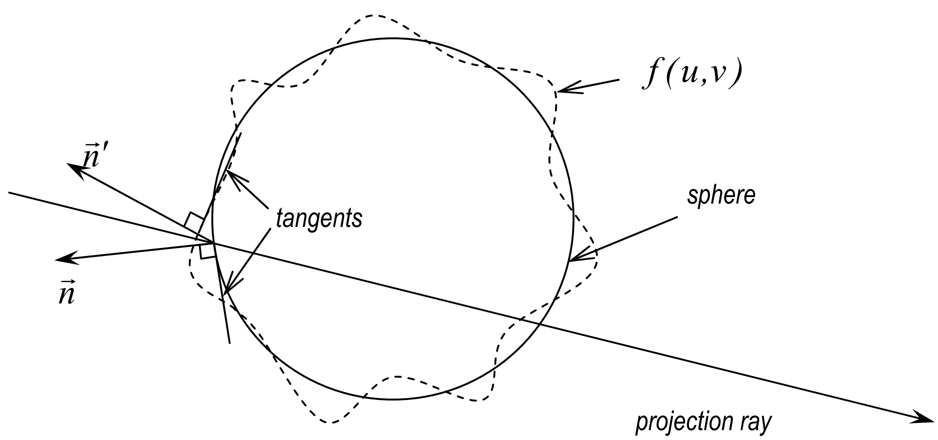

Figure 2 – Changing the direction of normal in the point of intersection of the projection ray with the sphere

The classical algorithm for the visualization of clouds. Currently, the main approach in the implementation of ray tracing is the solution of equations of the projection ray given in parametric form and the equations of the surface in an implicit form [Hill, 2001]. Let us consider it briefly.

Assume that the ray emanates from the point $\mathbf{S}$ in the direction $\vec{\mathbf{c}}$. Then the ray equation has the form:

$$r(t) = \mathbf{S} + \vec{\mathbf{c}}t . \tag{5}$$

The condition of coincidence of the ray with a point on the surface of the base sphere, given by the equation $x^2 + y^2 + z^2 - 1 = 0$, has the form

$$|\vec{\mathbf{c}}|^2 t^2 + 2(\mathbf{S} \cdot \vec{\mathbf{c}})t + (|\mathbf{S}|^2 - 1) = 0 .$$

This is a quadratic equation in t of the form $At^2 + 2Bt + C = 0$, where

$$A = |\vec{\mathbf{c}}|^2,\ B = \mathbf{S} \cdot \vec{\mathbf{c}},\ C = |\mathbf{S}|^2 - 1 .$$

The roots of the equation:

$$t_{1,2} = -\frac{B}{A} \mp \frac{\sqrt{B^2 - AC}}{A}. \qquad (6)$$

If the discriminant $B^2 - AC$ is negative, a solution is absent, and the ray passes the sphere. If the discriminant is equal to zero, then the ray touches the sphere in a single point. If the discriminant is positive then two intersection points t_1 and t_2 exist that correspond to plus and minus signs in equation (6).

Consider now the case when sphere center does not coincide with the beginning of coordinate system or radius of sphere is not equal to 1, which corresponds to applying affine transformation $\mathbf{M}$ to the sphere. Then before computation of (6) it is necessary to convert vector (5) into sphere coordinate system by multiplying it to the inverse matrix of sphere:

$$r'(t) = \mathbf{M}^{-1} r(t).$$

Then, using equation (6), the intersection points t_1 and t_2 are determined. The values without any conversion are directly used in equation (5) to determine the coordinates x, y, and z of the intersection points of projection ray with the sphere in the observer coordinate system.

To reduce the amount of computation in time of visualization of scene objects often the bounding primitives are used to easily allow a preliminary check on the possibility of a ray intersections with the object [Hill, 2001]. In the proposed clouds model as such bounding primitives can be used by the spheres of previous levels of detail, because each sphere of the previous level covers 5 spheres of the next level. Thus, if there is no intersection of the projection ray with a base sphere of clouds, it clearly points to the fact that any sphere of the next level of detail does not intersect with the ray. This property of the model allows to exclude from further work the rays which do not have intersections with the cloud and thereby reduce the amount of computing for visualization.

Results

The proposed model allowed obtaining a realistic cloud image, which requires for its description only a small amount of data. Thus, storage of cloud containing six levels of detail requires less than 50 KB. The images are presented in Figure 3. Also using this model, the cloud animation visualization has been conducted, results of which can be seen on the following link: http://rtsquare.com/videos/clmorf.avi. There you can also find other examples of the proposed model usage.

Table 1 shows the visualization time of model. Calculation of cloud image with resolution 800x600 pixels was performed on a workstation with a processor Intel CoreDuo E6600, 2 GB of RAM using one processor core.

Table 1 – Model visualization time

The number of spheres in the last level	Visualization time, ms
15625	4750
390625	9203
9765625	22116

a)

b)

Figure 3 - Images of clouds on the basis of the proposed model:
a) cirrus; b) cumulus clouds.

Conclusion

The developed model based on the methods of procedural modeling of cloud shape can generate realistic images of various cloud types (cumulus, cirrus, etc.) by controlling the probability distribution of random variables at the time of the model creation. A feature of this model is the fact that each sphere of any particular level is a bounding volume for the spheres of the next level. Firstly, this makes it easy to classify the projection rays by the presence of intersection with the cloud, and thus significantly reduce the amount of computation. Secondly, the use of identical elements at each level makes it possible to use adaptive algorithms for working with the model, choosing the desired level of detail, taking into account the angular resolution of graphics system. Thus, the farther away the cloud is from the observer, the lower the level number which provides the desired angular resolution, and, consequently, the less the amount of computation. Thirdly, the proposed model makes it easy to make animation of cloud. It should also be noted that the analytical descriptions can substantially reduce the amount of computation when geometric transformations are performed, since the rotation and translation require only to recalculate the coordinates of spheres center, and scaling will require an additional conversion of radii. The proposed model of the cloud is focused on the ray tracing and the ability to perform processing in real time.

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