Physically based animation of sandstorm

By Shiguang Liu, Zhangye Wang*, Zheng Gong, Lei Huang and Qunsheng Peng

This paper describes a physically based method for modeling and animating sandstorm, a type of disastrous natural phenomenon. The method adopts a relatively stable incompressible multiple fluid model to simulate the motion of air, sand, and dust particles. The wind field of sandstorm is established based on Reynold-average Navier-Stokes equations. The sand and dust particle flow is therefore computed taking interaction among the wind, sand, and dust particles into account. To accelerate the modeling process of a dynamic sandstorm scene, a special Multi-Fluid Solver is designed and implemented on GPU. Various illumination effects of sandstorm scenes can be simulated by spectral sampling scattering calculation. Animations of realistic sandstorms occurring in desert and urban areas based on our model are demonstrated. Compared with the real sandstorm photos, our simulated results are satisfactory. Copyright © 2007 John Wiley & Sons, Ltd.

Received: 15 May 2007; Accepted: 15 May 2007

KEY WORDS: sandstorm; natural phenomena simulation; physically based animation; Multi-Fluid Solver; GPU

Introduction

Although many works were proposed for simulating natural scenes in the past two decades, relative little attention was paid to modeling and rendering of disastrous natural phenomena such as hurricane, tornado, sandstorm, debris flow, etc. One reason may be the complex physical mechanisms behind these natural disastrous phenomena. Recently, sandstorm, a type of disastrous phenomena related to desert, attracts much attention of the people around the world. Realistic simulation of dynamic sandstorm scene can be found applications in many domains. For example, movie and TV plots often include the desert scene. Desert areas are also the favorite sites for many PC game as battlegrounds. Ecologists can evaluate the ecological disaster of sandstorm by dynamic simulation. Mayors may focus on the traffic jams due to the low visibility caused by heavy sandstorm. Sand and dust particles may cause serious respiratory illness for people who inhale them. We propose a fast, physically based, and easily implemented method for modeling and animating realistic sandstorm scenes.

*Correspondence to: Z. Wang, State Key Lab of CADCG, Zhejiang University, Hangzhou 310027, P.R. China. E-mail: zyw@cad.zju.edu.cn

Sandstorm is a very strong windstorm which frequently happens in the desert and its neighboring area. It can carry huge amount of sand and dust in the atmosphere. This wind is usually caused by convection currents which are created by intense heating of the ground. Air is unstable when heated and this instability will cause the mixture of higher winds in the troposphere with winds in the lower atmosphere, incurring strong surface winds.

There are many research works about simulation of sandstorm in the field of physics and meteorology, however, these works mainly focus on precise numerical analysis, and are too complex to be used for animation. Until now, little work has been reported about realistic modeling and rendering of sandstorm in Computer Graphics.

In this paper, we propose a physically based method for modeling and animating sandstorm. First, we establish the unstable wind field of sandstorm based on Reynold-average Navier-Stokes equations. The motion of sand and dust particle is regarded as the continuous flows and they can be expressed by the non-viscosity fluid model taking the interaction among them into account. Then, we propose a GPU-based Multi-Fluid Solver for dynamic sandstorm scene. The variety of illumination effect of sandstorm scenes is simulated by spectral sampling of the scattering light. Finally,
according to the statistical distribution of the size of sand and dust particles, fantastic illumination effects of sandstorm in different areas and at different stages are rendered.

The rest of this paper is organized as follows. The Section Related Work gives a brief survey of related works. In Section Modeling of the Sandstorm we propose a physically based model of sandstorm. Section Rendering of Sandstorm Scene discusses the rendering methods of sandstorm. This is followed by Results and Discussion Section. Conclusions and Future Works are given at last.

Related Work

As a severe global natural disaster, sandstorms cause incredible damage of facilities every year in the world. It has been the hotspot in many fields especially for physics and meteorology, etc. Joseph et al. studied the relationship between the weather conditions and velocity of sandstorm. Later, more and more researchers began to simulate the wind-sand movement using the method of numerical analysis.

All the above works focus on studying the motion of sandstorm by experimental data or numerical analysis method. As they aim at calculating the movement of sandstorm as precise as possible, these models are too complicated to be visualized in practical application. To simulate the sandstorm scenes realistically and efficiently, an approximate physically based sandstorm model should be put forward. For simulation of fluid-like natural phenomena such as smoke, cloud, volcanic cloud, etc., most works adopt fluid models.

Multi-fluid models were also proposed accounting for gas–liquid fluid, gas–gas fluid, etc. Hong solved the multiphase flow through the bubble motion in liquid. And the volume of fluid (VOF) method was hired to track the free surface, the minimum stress surface tension method was used to calculate the surface tension directly from the material field. Premoze simulated the multi-fluid flow based on moving particle semi-implicit (MPS) without reactions. In fact, except for the simple mixing of different materials, the chemical reaction may exist. Combustion is an example. Nguyen et al. considered the gas was premixed and the reaction only happened at the interface of the blue core to generate hot gaseous products. Ihm simulated more general gas chemical reactions. According to the chemical kinetics, they used the reaction process to directly update the temperatures of substances and the divergence control function. By extending the particle level set method, Losasso et al. simulated interactions among multiple liquids. Liu et al. simulated tornado scene with a Two-Fluid model. Zhu et al. proposed a Two-Fluid Lattice Boltzmann model. With this model, they can simulate miscible binary mixtures like pouring honey into water, etc. Fan et al. simulated multiphase flow on curved surfaces using a method of adapted unstructured LBM. Zhao et al. simulated the phenomena of melting and flowing in multiphase environment.

For the gas-solid flow, volcanic clouds were modeled by Mizuno et al. They assumed that the flow was composed of two types of fluids: magma and entrained gas, and both were conveyed by the velocity field. Explosion can be regarded as gas-solid or gas-liquid flow. Feldman et al. suggested that explosion was composed of suspended particles and entrained gas. To account for the interactions between the particles and the gas during explosion, they enforced the drag force on each particle from the velocity difference and the opposite force was exerted on the fluid cells. They also employed particle system which included hundreds of thousands particles for modeling the movement of explosion particles.

However, in the case of sandstorm, air flow (wind field), and sand particle are not only conveyed by the velocity field. The interaction between sand particles and the air flow is also an important impetus. Furthermore, to model the dynamic sandstorm scene, a great number of sand and dust particles should be taken into account. So it would be quite difficult to simulate the scene at fast rendering rate by particle systems. Apparently an approximate physically based sandstorm model as well as an efficient calculating solver is in demand.

As the multi-phase fluids are more complex than the single fluid flow due to the different properties of components and the interactions among them, realistic multi-fluid simulation is a challenge task for computer graphics researchers.

Realistic simulation of sandstorm also includes modeling of sand particle, rendering of desert scene, etc. Bell et al. proposed a method of modeling granular materials such as sand and grains. They represented granular material by a large collection of non-spherical particles which might be in persistent contact. This method can be integrated to simulate highly dynamic phenomena such as splashing and avalanches efficiently. But as the number of particles is not large enough, the rendering effect of the scene need to be improved. Onoue and Nishita proposed a method for modeling and rendering realistic desert scenes include sand dunes and wind ripples. They rendered the dunes with the wind-ripples by bump-mapping using Level of Detail (LOD).
Benes described a procedural algorithm that improved the previous work of Onoue and Nishita by simulation of sand interacting with objects. Nevertheless, these works mainly deal with the static desert and fail to simulate dynamic sandstorm. In this paper, we present a new method to simulate the dynamic sandstorm scene. Below we will describe it in detail.

Modeling of the Sandstorm

We consider sandstorm as a multi-fluid composed of wind, sand, and small dust particle flows. Below we will discuss the model of wind fields, sand, and dust particle flow, respectively.

Wind Field

For the stable near-surface air flow, we can establish its wind field based on classical Navier-Stokes equations. But sandstorm is usually caused by unstable air flow, it is not suitable to be modeled with classical Navier-Stokes equations. Considering the effects of the atmospheric turbulence, we establish the wind field by Reynold-averaged Navier-Stokes equation which is expressed as:

\[
\frac{\partial \bar{\mathbf{u}}}{\partial t} = -\rho (\bar{\mathbf{u}} \cdot \nabla) \bar{\mathbf{u}} - \nabla p + \nu \nabla^2 \bar{\mathbf{u}} + \nabla \cdot \mathbf{\tau} + \mathbf{f} \tag{1}
\]

where \( \bar{\mathbf{u}} \) is the wind velocity, \( \rho \) is density, \( p \) is pressure, \( \nu \) denotes viscosity of the air, \( \mathbf{\tau} \) denotes Reynold shear stress which reflects the unstability by atmospheric turbulence, \( \mathbf{f} \) denotes any external forces acting on the air flow. The external force consists of vorticity confinement, interactions with sand particles. The first term is defined in Reference [23]. We will describe the second term in Subsection Interaction Among Wind, Sand, and Dust Particle Flow. The Reynold shear stress can be expressed as the following:

\[
\mathbf{\tau} = \rho \left( \frac{\partial \bar{\mathbf{u}}}{\partial y} \right)^2 c_k \tag{2}
\]

where \( y \) is the distance from the surface, \( c_k \) is the Von Karman constant and its value is 0.4. By Reynold shear stress, we can model the vorticity around each sand particle (Figure 1), to generate a more realistic simulation of air flow for sandstorm scene.

Suppose, sand and dust particles are not broken or merged in sandstorm, the air flow can be considered as incompressible fluid, that is,

\[
\nabla \cdot \bar{\mathbf{u}} = 0 \tag{3}
\]

Sand and Dust Particle Flow Model

For different types of sandstorm, the ratios of sand particle (of large size) and dust particle (of small size) are different. Sand and dust particles are discretely distributed in sandstorm. If the number of particles is not very large, we can trace every particle's track accurately by particle system. In fact, a sandstorm consists of a huge number of sands and dust particles, so tracing each particle is not feasible in this case. However, the particles' movements obey statistical distribution, and they have the similar properties as fluid, we can approximate the motion of sand and dust particle as non-viscosity, incompressible fluid, which can be described as the following:

\[
\frac{d\bar{\mathbf{u}}_d}{dt} = -(\bar{\mathbf{u}}_d \cdot \nabla)\bar{\mathbf{u}}_d - \nabla p_d + \bar{\mathbf{f}}_d \tag{4}
\]

\[
\nabla \cdot \bar{\mathbf{u}}_d = 0 \tag{5}
\]

where \( \bar{\mathbf{u}}_d \) is the velocity of sand particle flow, \( p_d \) is pressure, \( \bar{\mathbf{f}}_d \) denotes any external forces acting on the
Sand particle. \( \vec{F}_d \) consists of the valid gravity \( W_d \) of sand particle in air flow, and the entrainment force \( \vec{F}_e \) by air flow. Next, we will analyze the force of a single particle in air flow.

Suppose that the sand and dust particles are spherical, with mass \( m_d \), diameter \( D_d \), and density \( \rho_d \). For simplicity, we suppose that the particles move in XOY plane. The force consists of the valid gravity of sand particles and the entrainment force by air flow. The entrainment force is produced by the velocity difference between the air flow and the sand particle flow, and it is the most important driving force of sand particles. Figure 2 is the sketch of forces of a sand particle in the air flow. The valid gravity of a sand or dust particle in the air flow is expressed as:

\[
W_d = \frac{1}{6} \pi D_d^3 (\rho_d - \rho)g
\]  

(6)

where the subtraction part is buoyancy of the sand particle in the air flow, \( \rho \) and \( g \) are the density and acceleration of gravity, respectively. The entrainment force is expressed as:

\[
\vec{F}_e = C_D \pi \nu D_d (\vec{u}_d - \vec{u})
\]  

(7)

where \( \vec{u}_d \) is the velocity of the sand particle, \( \nu \) the viscosity of the atmosphere, \( C_D \) the coefficient of resistance and we calculate it by the following empirical formula:

\[
C_D = \frac{24}{Re} + \frac{6}{(1 + Re)^{1/2}} + 0.4
\]  

(8)

where \( Re \) is the Reynold number corresponding to different air flow motion.

The above analysis is for a single particle. As we consider the motion of particles as an incompressible fluid, the Euler method can be used to solve it. In this case, each sand or dust particle actually belongs to a group of particles in a voxel. In this way, we can simulate the motion and interaction among the wind, sand, and dust particles based on voxel, which is more efficient compared with particle system.

**Interaction Among Wind, Sand, and Dust Particle Flow**

Following the theory of fluid dynamics, sandstorm is different from other natural phenomena such as smoke, fire, etc. due to the obvious interaction among the sand, dust particle flow and the wind field. When the sand and dust particles are blown into the air, it will be entrained by the wind. On the contrary, the velocity of the wind will be affected by the counterforce of the sand and dust particle flow. In fact, for sandstorm, its external force is mainly the interaction force between sand particle flow and air flow, which is caused by the velocity difference between them. Here we will discuss the modeling of interaction force for sandstorm.

The wind field, sand, and dust particle flows can be regarded as continuous fluid. So the interaction among them can be modeled as that between wind field and a group of these particles. We account the sand and dust particles in a unit volume as a whole, and the counterforce to the wind field by the sand and dust particle flow is equivalent to adding a body force to the wind field model.

According to Subsection Sand and Dust Particle Flow Model, the force exerted by a single particle moving through the gas is \( C_D \pi \mu D_d (\vec{u}_d - \vec{u}) \). We describe the diameter distribution of sand and dust particles in sandstorms by Equation (9):

\[
n(D_p) = N_0 \frac{1}{\sqrt{2 \pi \eta D_p}} \exp \left( -\frac{(\ln D_p - \delta)^2}{2\eta^2} \right)
\]  

(9)

where \( \eta \), \( \delta \) is mean value and standard variance of \( \ln D_p \). \( N_0 \) is the total number of sand particles in the unit volume. Figure 3 shows the distribution of sand particle in sandstorms of different visibility. Here, L, M, S are the different types of sandstorm under low, moderate and high visibilities, respectively.

Due to the diameter of sand and dust particle is tens to hundreds microns, the interaction force between them can be ignored. So the interaction force between sand particles in a unit volume and the air flow can be expressed as:

\[
\vec{F}_{DF} = \int n(D_p) \cdot C_D \pi \mu D_d (\vec{u}_d - \vec{u}) dD_p
\]  

(10)
**Multi-Fluid Solver on GPU**

Our sandstorm model distinguishes from previous fluid model in that our model describes a multiple fluid system, one is air flow and the others are sand and dust particle flows. If we use the previous methods such as to solve multiple Navier-Stokes equations separately for multiple velocity texture in one rendering pass, the calculating time cost will be increased several times.

To avoid this, we solve the multiple Navier-Stokes equations in parallel in one rendering pass by combining multiple field data texture into one texture. The technique of flat 3D texture is also used to store the 3D texture data. Different from the previous methods, we store the air flow (wind) velocity texture and the sand and dust particle flow velocity texture in one flat 3D texture rather than in several flat 3D textures, as shown in Figure 4. In this figure, the green part is for the sand particle flow, and the blue part is for the air flow. It is convenient to read and store velocity data by the Y coordinate. If the Y coordinate is above 0.5, it represents the data of the sand and dust particle flow. If not, it represents the data of the air flow. It is similar for other field data such as pressures and so on.

The calculation flow can be described as follows. First, we initialize the air flow and sand particle flow, set the initial condition and boundary condition. Then, we solve the Navier-Stokes equations on GPU by the Semi-Lagrange methods. There are several velocity texture data in one flat 3D texture. They can be both updated or only one is updated during one step. We show this flow in Figure 5. In this figure, the yellow part includes texture operation, and the white part involves no texture operation. By this method, we can solve multiple Navier-Stokes equations in parallel in one rendering pass. No wonder, the size of our flat 3D texture is several times as large as that of the previous method, but it does not affect the calculation efficiency very much for the linear calculation function of GPU.
Rendering of Sandstorm Scene

To generate realistic images of sandstorms, we must consider the interaction of various types of components of sandstorm with natural light. Sandstorm appears with different color at different areas and stages. This is mainly due to scattering and absorption effect of particles in sandstorm. Our rendering model of sandstorm scene is based on multiple Mie scattering theory. And we adopt pre-computation technique to accelerate the rendering rate. Below we will simply describe Mie scattering model and discuss our rendering method.

Mie Scattering Model for Natural Light

Mie scattering model is a classical theory for explaining scattering of spherical particles. Suppose a particle is of diameter $D_d$, refractive index $m$. Mie’s model of scattering can be expressed as:

$$I(\lambda) = I_0(\lambda) \left( \frac{i_1 + i_2}{2k^2D_d^2} \right)$$  \hspace{1cm} (11)

where $\lambda$ is the wavelength of incident light, the meaning of other parameters in Equation (11) can be found in Reference [27].

Calculation of Scattering in Sandstorm

According to the data of experiment and measurement, we find that the shape of the majority of sand and dust particles is spherical. According to the Isometric-Sphere theory, sand, and dust particles in sandstorm can thus be regarded as spherical for simplicity.28

![Figure 6. The incident radiance of a voxel.](image)

![Figure 7. Rendering sandstorm in hardware.](image)

![Figure 8. Comparison between our rendering result and the real photo in desert, (a) our rendering result, (b) the real photo.](image)
The ratio is
\[ \frac{I_{sc}}{I_0} = \exp(Q_{sc}(\lambda) \cdot l) \]  
(12)

where \( Q_{sc}(\lambda) \) is the scattering section of a particle. Considering the distribution of sand particles in sandstorm (See Section Modeling of the Sandstorm), we define the scattering coefficient of sand particles in a unit volume as
\[ \sigma(\lambda) = \int_0^\infty \frac{\pi D_p^2}{4} Q_{sc}(D_p) dD_p \]  
(13)

As the computation of the Mie scattering is very complicated, which include calculation of scattering section and scattering coefficient, here we use a new method to pre-compute these terms of sand particles with different diameter and store the results as a look-up table. While rendering, we can interpolate data from this table. The spectral sampling interval of incident light is 5 nm from 380 to 780 nm, and sampling interval of scattering angle is 1 degree from 0° to 180°.
Figure 11. Series of sandstorm scenes in desert, (a)–(d) show that sandstorm is drawing near the viewpoint.

Rendering of Sandstorm Scene

To produce the realistic appearance of sandstorm scene, multiple scattering effect of sands must be considered. Here we discrete the space filled with sandstorm into voxels. For each voxel $P_{i,j}$, its incident radiance from direction $\omega$ includes the direct light from the light source in direction $\omega$ and multiple scattered light from other voxels (See Figure 6). The multiple scattering model is expressed as:

$$I_{P_{i,j}} = I_0 \cdot \prod_{j=1}^{N} \sigma_j(\lambda) + \sum_{j=1}^{N} I_m \prod_{k=j+1}^{N} \sigma_k(\lambda)$$  \hspace{1cm} (14)

where $I_m$ is the multiple scattering into direction $\omega$ at arbitrary voxel $X$. In-scattering from the six neighboring voxels are sampled, so $I_m$ can be expressed as:

$$I_m = \sum_{s=1}^{6} I_{P_s} \cdot p(\theta) \cdot \sigma_s(\lambda)$$  \hspace{1cm} (15)

where $p(\theta)$ is phase function. For scattering of sand particles is almost isotropic, we consider the phase function as constant.

Our rendering method is a two-pass algorithm. As shown in Figure 7, we pre-compute the shading of sandstorm scene according to the position of each voxel and the incident direction of light source in the first pass. Then, we use the shading result to render the scene under fixed viewpoint in the second pass.

Results and Discussion

With the proposed methods, we successfully generated various types of realistic sandstorm scenes on a PC with
As far as we know, it is the first time to simulate sandstorm scenes realistically based on physical principles.

We have proposed a novel physically based method for modeling and animating sandstorm scenes. Our method adopts multi-phase fluid models to simulate the motion of air, sand, and dust particles in the sandstorm. The wind field is established by Reynolds-Average Navier-Stokes equations and the sand and dust particle flow is built with the non-viscosity fluid model taking the statistical distribution of particles of varied size into account. To efficiently compute the dynamic sandstorm scene, we design a Multi-Fluid Solver and implement it on GPU to achieve high rendering rates. By spectral sampling of the light scattering, the peculiar illumination effect of dynamic sandstorm scenes is revealed. Compared with real sandstorm displays, our simulated results are quite satisfactory. The contributions of this paper can be summarized as follows.

1. We have proposed a novel physically based method for modeling and animating sandstorm scenes.
2. Rather than using single fluid model, we adopt multiple fluid model to deal with the motion and the complex interaction of various components in the sandstorm. A special Multi-Fluid Solver is designed and implemented on GPU, which greatly accelerates the rendering speed of the scene.
3. Our system is easy to implement. With different initial parameters, the wind, sand, and dust particle flows will blow automatically and users can generate various realistic sandstorm scenes with different visibility at different stages.

Furthermore, this model can be extended to simulate other phenomena of multiple gas-solid mixtures. However, it is not suitable for simulating phenomena with obvious interface, such as oil-water, etc. Simulating these phenomena involves reconstructing the dynamic free surface, which is our next goal. On the other hand, our dynamic sandstorm model is still far from perfect. For example, though we can simulate realistic dynamic sandstorm scenes which is far from the viewpoint, we still suffer from fog-like appearance of sand particles when it is close to the viewpoint. Euler-based method combining with particle system suggests a potential way for overcoming this limitation. Our future works also include simulation of other natural disastrous phenomena such as debris flow, avalanche, etc.

Conclusion and Future Works

This research was supported by 973 Program of China under Grant No. 2002CB312101, the National High Technology Research and Development Program of China(863 Program) under Grant No. 2006AA01Z314 and Natural Science Foundation of China under Grant No. 60475013 and No. 60603076. We are deeply grateful to the reviewers for their precise comments, which have improved the quality of this paper and will benefit our future work.

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Authors' biographies:

Shiguang Liu is assistant professor at School of Computer Science and Technology, Tianjin University P.R. China. He graduated from Zhejiang University and in 2007 he received a PhD from State Key Lab of CAD&CG. His research interests include natural phenomena simulation, fluid simulation and computer animation.

Zhangye Wang is associate professor at the State Key Laboratory of CAD&CG, Zhejiang University, P. R. China. He received his BS degree in Physics in 1987 and MSc degree in Optics in 1990, respectively, both from East China Normal University. In 2002, he received his PhD in computer graphics from Zhejiang University. His research interests include realistic image synthesis, computer animation and virtual reality.
Jiaotong University, P.R. China. His research interests include realistic image synthesis and simulation of multiple scattering.

Lei Huang is a MS candidate at the State Key Lab of CAD&CG, Zhejiang University, P.R. China. He received his BS degree in Department of Computer Science, Hunan University, P.R. China. His research interests include realistic image synthesis and natural phenomena simulation.

Qunsheng Peng is professor at the State Key Lab of CAD&CG, Zhejiang University. His research interests include realistic image synthesis, virtual reality, infrared image synthesis, point-based rendering, scientific visualization, and biological calculation, etc. He graduated from Beijing Mechanical College in 1970 and received a PhD from the Department of Computing Studies, University of East Anglia, in 1983. He is currently the Vice Chairman of the Academic Committee, State Key Lab of CAD&CG, Zhejiang University and is serving as a member of the editorial boards of several Chinese journals.