Realistic Fire Simulation: A Survey

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Abstract

Abstract-**As fire is one of the basic elements of nature, realistic fire simulation plays a significant role in fire control, film special effects, military emulation, and virtual reality. Fire simulation has been being an eternal theme in the field of computer graphics, because of the anisotropic shape and complex physical mechanism of the fire. This paper presents a survey on the development of flame simulation, with a detailed introduction to the different kinds of methods applied in the field. The methods can be classified into several different kind, mainly include texture mapping method, particle system method, mathematical physics-based method, cellular automation method, image based tomographic reconstruction, and other methods. This paper analyzes the performance of different methods from real-time, reality, spatio-temporal complexity, editability, and interactivity. Finally, in connection with issues in the present research and possible future direction of development, the paper puts forth a number of theoretical and technical problems, hoping they can be resolved in the future.**

Keywords-fire/flame simulation; texture mapping; particle systems; model of mathematical physics; cellular automaton; tomographic reconstruction

I. INTRODUCTION

Fire simulation has significant research and economic value in the field of fire control, military emulation, movie special effects, and virtual reality. Fire has complex physics properties, rich expressional patterns and random motion properties. All this constitutes a challenge to its simulation. Most of the early fire simulation studies adopted simple texture mapping methods, including texture elements, body texture, procedural texture, dynamic texture, and video texture. Reeves et al. [1] in 1983 first systematically proposed a method of particle systems to expand the fire simulation. Particle system is a more successful technique which is used to model fuzzy objects, and is also the basis of many fire simulation algorithms. The mathematic and physics-based method is another research direction in the field of flame simulation. One of the main ideas is taking fire as a special kind of fluid; so that we can model and animate fire by solving the continuous Navier-Stokes (NS) equations. In 2003, Hasinoff [2, 3] proposed a reconstruction method based on flame image data obtained by two cameras to achieve the tomographic reconstruction of fire, which provide a new study thought for realistic simulation of the flame. Recently, researchers continuously explore new simulation methods, and develop the current simulation methods and theories, such as cellular automata model, mass-spring model, thermal diffusion model, temperature model, and so on.

At present, some articles summarized the flame simulation methods. Nhuyen et al. [4] at Stanford University introduced the methods of simulation and animation of fire and other natural phenomena in 2003. Fedkiw [5] also summarized the physics-based fire simulation methods in the survey of natural phenomena simulation. Ihrke [6] presented the capture and simulation techniques of fire and smoke, and reviewed the methods of image-based fire tomographic reconstruction. We reviews fire simulation methods in this paper. Firstly, we briefly introduce the evolution of the basic methods and techniques of fire simulation in Sect. 1. Then, based on the differences between the core concepts of algorithms, we classify the methods of fire simulation into following: texture based method, particle systems based method, mathematical physics based method, cellular automaton based method, image based tomographic reconstruction method, and other methods. We respectively introduce these approaches in detail in Sect. 2 ~7. Furthermore, Sect. 8 discusses the advantages and limitations of various approaches, and Sect. 9 presents the possible future trends of fire simulation. Finally, we summarize the whole text in Sect. 10.

II. THE TEXTURE BASED METHOD

Texture technique is using the texture mapping approach to model the whole or local effect from the view of computer visualization. In early studies, simple laminar flame was taken as texture to be attached to the flame-shaped implicit primitives, then body tracking

978-0-7695-4497-7/11 $26.00 © 2011 IEEE
DOI 10.1109/CAD/Graphics.2011.26

would be carried out on it. Subsequently some methods, such as, billboard, cross billboard, Texel, volume texture, procedural texture, and video texture, expanded the traditional texture technique. The texture based method is seldom used independently in file simulation; and usually applied with other methods to express the details of the simulation results.

In 1990, Inakage [7] used the texture mapping method to achieve the 2D flame simulation, by changing 3D points into 2D texture points, the low temperature part's color depended on the shadow model. King et al. [8] presented a technique to animate amorphous material such as fire and smoke in real-time with dedicated texture memory. The method used a coarse voxel grid to model object dynamics, and texture cycling to create local and global dynamics. In 2000 King [9] further proposed a method that using texture splat as basic element to simulate fire and other irregular objects. Perlin [10] proposed an empirical model of turbulence simulation, which consists of a superposition of 3D noise function; the turbulent function can not be directly used to simulate natural texture, but its random and self-similarity can better describe the texture irregularities, and it has been successfully used to create flame procedural texture. Wei et al. [11] proposed the use of textured splats as the basic display primitives for an open surface fire model. The highly detailed textures help to achieve a smooth boundary of the fire and gain the small-scale turbulence appearance. Schöl [12] put forward a video texture synthesis approach that generated the unlimited dynamic fire from a small amount of fire sequences. Rose et al. [13] introduced a method for real-time fire rendering. This approach used video-recorded or pre-rendered high-quality images of fire as textures to attain photorealistic stereo. DongGyu et al. [14] at Pusan National University proposed the use of billboard to generate the 3D simulation effect of fire and smoke in the phone games, and also implemented external forces on billboard for interactive fire simulation with game characters.

Texture mapping method has advantages in computing speed and model details. It can model the static fire with less time-consuming. However, it is difficult to obtain a realistic moving fire model because the textures have no the parameters of object motion. In addition, the simulated results of texture mapping leave noticeable artifacts, and it is hard to describe the role of external forces. Therefore, the texture based method is appropriate for the occasion when the demand of reality is not strict, and often combined with other methods.

III. THE PARTICLE SYSTEM BASED METHOD

Particle system modeling is a popular physics-based technique used to model fuzzy objects such as fire, smoke and explosions. A particle system is comprised of a number of particles; each particle has a set of attributes such as location, size, transparency, life, shape, speed, acceleration etc. Particles' constant motion through time will continuously change its properties. With the demise of the old particles and the production of new particles, particle goes through the process of birth, development and declination. Particle system can simulate the complex variability of the flame due to that the properties of particles can be controlled with some random functions.

Reeves [1] first constituted the notion of a particle system in 1983 to represent fuzzy objects such as clouds, fire and water. Yoshida et al. [15] used the idea of metaballs to display the 3D density distribution of smoke, including the consideration of its passage round obstacles. Somasekaran [16] presented a detailed review of particle systems, and implemented a real-time fire simulator using particle system. Lim [17] further proposed a new algorithm by combining particle system, level of detail(LOD) with GPU acceleration. This method have a good performance gains without significantly degrading the visual appearance of the fire when it is far away from the camera.

Particle system often combined with other simulation methods as a auxiliary mean of enhancing the overall performance or local details. Perry et al. [18] at MIT presented a new technique for fire synthesis which combines a particle system for flames with a model for flame spreading. This method provides parameters for explicitly controlling wind or gravity, while simultaneously incorporating properties such as geometry and flammability of the object being burned. Through the use of the method ,the resulting fire can interact more naturally with the material which is burning, as well as with the surrounding environment. Rødal et al. [19] put forward a physics-based framework for real-time fire simulation using the GPU. The simulation results are rendered using a particle system combined with a black-body radiation model where the physically based simulation governs both the motion and appearance of the particles. This approach achieved a better performance in visualizing bonfire and torch-like fire effect in real-time. Horvath and Geiger [20] proposed a combination of coarse particle grid simulation with view-oriented refinement simulations performed on GPU. The resulting images of fire produced by the method are extremely detailed and can be integrated seamlessly into film-resolution images.

Particle system is a successful simulation technique used for modeling fuzzy objects in the computer graphics, and also is the foundation of many fire simulation algorithms. Particle system has great advantages in flame simulation because it is computationally simple and feasible. However, it will consume a large amount of computing resources as the number of particles increases, which influences real-time. Furthermore, most of the flame particles properties are controlled by random function; it will cause more randomness to the simulated result.

IV. THE MATHEMATICAL PHYSICS-BASED METHOD

The mathematic and physics-based method uses the models of computational fluid dynamics (CFD) to simulate flame. One of the most important ideas is considering the flame as one special kind of fluid; we can model and animate fire by solving the continuous Navier-Stokes (NS) equations. The equations describe that velocity field's exact changes after an infinitesimal time in the condition of knowing velocity field and force. The incompressible Navier-Stokes equations are derived as Eq. (1) and Eq. (2).

$$\nabla u = 0 \qquad (1)$$

$$\frac{\partial u}{\partial t} = -(u\nabla)u - \frac{1}{\rho}\nabla p + v\nabla^2 u + f \qquad (2)$$

where u is the velocity, v is the viscosity, ρ is the density, p is the pressure and f is the body force. The left hand side of the momentum equation can be interpreted as the acceleration of a particle while the right hand side is the net force exerted. The mathematical physics-based simulation method establishes the model by the accurate dynamic behavior of the flame. There are mainly three types [21] at present, namely Eulerian method, Lagrangian method and Lattice-Boltzmann method (LBM).

A. Eulerian method

Eulerian method is to analyze the changes of such parameters as fluid velocity, pressure, and density when they vary over time at each fixed point in a moving fluid space and researches the changes when they move from one space point to another. It is a grid-based approach. Nguyen et al. [22] used the incompressible Navier-Stoke equations to independently model both vaporized fuel and hot gaseous products. Meanwhile, the hot gaseous products, smoke and soot rise under the influence of buoyancy and are rendered using a blackbody radiation model. Their method showed plausible interaction of the fire and smoke with objects, including ignition of objects by the flames. Melek et al. [23] used a interactive fluid dynamics solver to describe the motion of a 3-gas (oxidizing air, fuel gases, and exhaust gases) .The burning process is simulated by consuming fuel and air based on the amounts of fuel and air inside each grid cell. In 2003, Melek [24] further considered the decomposition of burning solids in the simulation and control of the combustion process. Some models succeeded in simulating a single fire in real time, while few tried to handle a large number of flames. Bridault et al. [25] proposed a set of technique which aims at handling numerous flames. They managed different levels of accuracy in the simulation, which is based on a fast fluid dynamics solver, and the approach is able to animate and render dozens of realistic flames in real-time. David in his master thesis [26] , made a series of experiments to the simulation and animation of fire, and achieved a controlled flame imaging and animation tools based on the Eularian method. Hong et al. [27] modeled flames and fire using the Navier-Stoke equations combined with the level set method and jump conditions to model the reaction. In particular, this method makes use of the detonation shock dynamics (DSD) framework in fire simulation to obtain flame wrinkling and cellular patterns features and bring new visual phenomena for computer graphics generated fire. Eulerian method to solve the property of the model in the fixed point set, using the finite difference formula for solving differential equations, calculating the changes of material properties with time in a series of static point set of changes, however, this method lacks an explicit definition of the object boundary.

B. Lagrangian method

Lagrangian method is to analyze the variation of pressure, speed, density and other fluid movement parameters of a given micro-group in a fluid with time or, in other words, to analyze the parameter changes of a fluid micro group when it transfers to another, aiming at revealling the movement of the whole fluid. Lagrangian method is a particle-based approach including finite element, boundary element, smooth particle dynamics(SPH), etc. Stam [28] first addressed SPH into the field of computer graphics in order to model fire and other gaseous phenomena. Muller [29] proposed an interactive method based on SPH to simulate fluids with free surface, and use special purpose kernels to increase stability and speed. Moreover, there has been a few kind of combination of Eulerian method and Lagrangian method. Selle [30] introduced a hybrid method that make synergistic use of Lagrangian vortex particle methods and Eulerian grid based methods to overcome the weaknesses of both, this method can generate highly turbulent fire and smoke effect which is unachievable by standard grid based methods. Losasso et al. [31] proposed a technique for melting and burning solid materials including the simulation of the resulting liquid and gas.

In his method that the solid is simulated with mesh-based technique and the subsequently created liquid or gas is simulated with grid-based technique. The main advantage of this method is that state of the art techniques are used for both the solid and the fluid without compromising simulation quality when coupling them together or converting one into the other. Kang et al. [32] presented a hybrid simulation method that is suitable for modeling chemically reactive fluids based on the theory of chemical kinetics. It was built to take advantage of both Eulerian and Lagrangian frameworks. The method effectively animated a wide range of chemical phenomena, including catalysis, explosions, fire and flame. Eulerian method and Lagrangian method have respective merits in dealing with different types of flame; the two methods combined can better control the fluid, thereby enhancing interaction control and verisimilitude.

C. *Lattice-Boltzmann method*

Unlike traditional CFD methods, which solve the governing equations of macroscopic properties, Lattice-Boltzmann method (LBM) is based on microscopic models and mesoscopic kinetic equations. The fundamental idea is to construct simplified kinetic models that incorporate the microscopic and mesoscopic physical processes so that the macroscopic averaged properties obey the desired macroscopic equations. Wei et al. [11] utilized the LBM to simulate physically-based equations describing the fire evolution and its interaction with the environment. The linear and local characteristics of the LBM enable to accelerate the computation with graphics hardware to reach real-time simulation speed. Zhao et al. [33] introduced a method for the animation of fire propagation and the burning consumption of objects. The LBM provides a physics-based simulation of the air flow around the burning object. Wei et al. [34] in 2004 presented a fast and simple physically-based method to simulate gaseous phenomena. The LBM is defined on a 2D or 3D discrete lattice, which is used to solve fluid animation based on different boundary conditions. The LBM simulation generates an accurate velocity field and can incorporate an optional temperature field to account for the buoyancy force of hot gas. LBM has advantages in the dynamic simulation of irregular objects, basically meet the requirements of real-time flame simulation, nevertheless its calculation is still complex, and it used. in conjunction with other methods

The mathematical physics-based method can be quite accurate description of the flame motion, but solving the NS equations is a process with hugely complicated and high calculation amount. So that is difficult to meet the real-time simulation requirements. Because the simulation result can accurately reflects the real phenomenon and physical process, computer graphics researchers always try to find a way to a rapid solution of NS equations, and then to meet the growing demand for real-time simulation..

V. THE CELLULAR AUTOMATION BASED METHOD

Cellular automaton (CA) models, first introduced by Von Neumann in 1950, have been successfully used in modeling physical systems and processes. Cellular models for fire growth use fixed distances between regularly spaced grid cells to solve the fire arrival time from one cell to the next. This approach involves a discrete process of ignitions within the regular structure of a grid-based landscape. CA consists of cells, cell state space, cell neighbors and local evolution rules. As Eq. (3) shown.

$$A = (L_d, S, N, f) \qquad (3)$$

where, A is a CA, L_d is cell space， d is the dimension of cell space， S is the finite state machine cells, N is a combination of cells in all areas, f is a state transition function.

Pakeshi et al. [35] proposed a flame model based on CA, in which the flame is constituted by a simple cell group. The cell is simple, but their combination configuration and system behavior are very complex. Karafyllidis et al. [36] used CA to predict the spreading of fire, for the first time, in both homogeneous and inhomogeneous forests and can easily incorporate weather conditions and land topography. Li and Magill [37] described a model for simulating bushfire spread using the cellular automaton approach that takes into account a number of environmental factors such as blush density, land height, flammability, and wind condition. Berjak [38] improved Karafyllidis's method and used data for three human-induced fires in the Mkuze Game Reserve, South Africa. Its approach was found to satisfactorily predict spatial fire behavior. Sullivan [39] developed a hybrid 2D CA with a preliminary convection/wind interaction component and the fire perimeter shape obtained closely resembles that found in free burning experimental fires in uniform fuels in flat open terrain.

CA is comprised by a large number of the same and interconnected cells. Its core is a finite state automaton, with simple rules, finite state, rather than describing the complex process can produce complex phenomenon. The feature of the CA basfed simulation method is that the cells are simple, but the combined results are complex. This method is suitable for low-dimensional case in a simple simulation.

VI. THE IMAGE BASED TOMOGRAPHIC RECONSTRUCTION METHOD

The image based tomographic reconstruction method is a process which firstly get the flame images simultaneously from several different perspectives in the real world, and make use of tomographic reconstruction technique according to different images to achieve realistic 3D flame simulation. Reconstruction methods including back projection, filtered back projection and convolution back projection.

Bheemul et al. [40] used three monochromatic CCD cameras which placed equidistantly and equiangularly from each other around the flame being monitored for the 3D visualization and quantitative characterization of gaseous flames. Hasinoff [2, 3] put forward a concept of flame-sheet decomposition of continuous 3D flame, by regarding the flame as a semitransparent 3D density field and the reconstruction of the flame as an issue equivalent to that of computerized flame-sheet imaging under strong constraints. In 2007, Hasinoff [41] further proposed a concept of density sheet instead of the flame sheet. Ihrke [42] improved Hasinoff's method and presented a method that is capable of reconstructing dynamic, volumetric models of fire for animation purposes. This method is similar to sparse-view computerized tomography and is applicable to static camera setups observing dynamic flames. They used an algebraic reconstruction method to restrict the solution space such that a high quality model is obtained from only a small number of camera images. Ishino et al. [43] advanced computerized tomography (CT) reconstruction technique for measuring an instantaneous 3D distribution of chemiluminescenece of flame. In the method, the 2D images of an objective flame are simultaneously taken from forty horizontal directions with a forty-lens camera. Gilabert et al. [44] employed combination of image processing techniques and filtered-back projection algorithms to reconstruct grey-scale sections of the flame from three 2D images taken by three identical CCD monochromatic cameras placed around the flame. The information obtained can directly be used for determining the geometrical, luminous and temperature characteristics of a flame on a 3D basis. In 2007, Gilabert [45] further replaced monochromatic cameras by RGB cameras.

Ihrke [46] in 2006 presented an optical tomography method that used an adaptive grid for the reconstruction of a three-dimensional density function from its projections. The proposed method is applied to reconstruct thin smoke and flames volumetrically from synchronized multi-video recordings. Atcheson and Ihrke [47] addressed a technique for 2D imaging and 3D tomographic reconstruction of time-varying, inhomogeneous refractive index fields. In 2008, they [48] further put forward the first time-resolved Schlieren tomography system for capturing full 3D, non-stationary gas flows on a dense volumetric grid. Schlieren tomography uses 2D ray deflection measurements to reconstruct a time-varying grid of 3D refractive index values, which directly correspond to physical properties of the flow. Berger and Ihrke et al. [49] further considered occlusion on the basis of 3D BOS, and proposed a new algorithm for reconstructing flame gas flow, i.e. time-varying gas flows around moving objects. Recently, Upton et al. [50] presented high-resolution and fully 3D measurements of the flame surface of a turbulent reacting flow. The significance of the powerful experimental tool is to provide new insight into turbulent combustion.

Image-based tomographic reconstruction of flame has been making considerable progress in recent years; this method has an unparalleled advantage in the details and credibility, because it used real data for reconstruction. However, it also has disadvantages that the data acquisition process is also complex, less controllable and of poor interactivity. Image-based tomographic reconstruction technique can transport faithfully the flames in the real world into virtual environments and achieve realistic fire simulation while maintaining their physical properties.

VII. OTHER SIMULATION METHODS

Flame simulation research is a process of continuous development and innovation, researchers utilize various perspectives and different directions to explore the method of realistic fire simulation, including: stereo vision, geometric constraints, PIV, mass-spring model, etc.

Rossi [51] put forward a instrumentation system, based on stereovision, for the visualization of fire fronts in outdoor conditions. In the method, images are captured simultaneously and processed using specialized algorithms. This system successfully measured 3D geometric parameters of fire fronts over a range of combustible and environmental conditions. Ioannides et al. [52] presented a model that can handle complex flames in real-time and manage interactivity. The fire is considered as a set of linear flames whose shapes are defined by the geometry of the combustible and the fuel distribution. The use of virtual wicks allows the user to put and merge flames onto any object easily. Hong et al. [53] proposed a unified framework for modeling and animating fire under general geometric constraints and evolving rules. It is an easy way to make a variety of fire effects on requests from artists. Balci and Foroosh [54] addressed the real-time 3D fire simulation problem using a spring-mass model. This method models the kinematics of flames by a mass-spring system, and it allows for incorporating external forces such as the gravity, and wind force for added realism. A specific characteristic of the method is that any object inserted in a flame can be modeled simply as an external force in the mass-spring system. Otsuka et al. [55] used particle image velocimetry (PIV) and the schlieren visualization equipment to measure the laminar and turbulent flame structure. This method is very promising and will help us understand details of the flame structure. Ishikawa et al. [56] introduced a technique for simulating fire spread taking into account the various properties of materials, and for an effective visualization of combustion phenomenon. In the method, the flame dynamics is obtained by combining the NS equations and the heat conduction equation.

Fire simulation in recent years has obtained more and more attention from researchers in different areas with their own perspective. Due to the limited paper space, they can not be totally enumerated; however we believe that every beneficial attempt will bring the new thinking about enhancing to the flame simulation research capacity.

VIII. Comparison of Various Methods

In recent years, people have put forward many fire simulation methods, in which some of the models tend to be more and more robust, but satisfactory methods is still quite limited. We analyzed the performance of different methods from the aspects of real-time, reality, spatio-temporal complexity, editability, and interactivity, as shown in TABLE I.

The texture based method has advantages in real-time and spatio-temporal complexity, but lacks interactivity. 2D dynamic texture with machine learning has certain editability. Texture mapping method is suitable for the simulation of fixed View, which usually used in combination with other methods. and the camera calibration and the data processing are both complex, so that the method can not meet the demand of real-time applications..Imaged based tomographic reconstruction is suitable on the occasion of strict demand on reality. It will have stronger realistic effect when combined with methods based on mathematical physics equations.

For the flame simulation, there is no perfect method that meets all the requirements of the simulation; every approach has its own suitable situations. Meanwhile, with a reasonable allocation, every method can achieve certain desired objectives and results.

IX. Research Trends and Potential Research Areas

In the process of fire situation related investigations review, we found that there are still some problems

Particle system is capable of showing certain details of the burning and the scene, especially the random changes in the flame, but its control process is too random to achieve the accurate description of the flame. Particles count is proportional to spatio-temporal complexity, but inversely proportional to real-time. More particles cause higher spatio-temporal complexity and worse real-time. Considering the collision detection of internal and external particles, we can achieve certain interactivity. Particle system is suitable on the occasion that there is less demand on physical consistence.

The mathematical physics-based methods have great advantages in the aspect of reality, editability, and interactivity, but it’s difficult to meet the demand of real-time and spatio-temporal complexity. With the improvement of compute hardware and software, GPU acceleration and CPU in parallel improve the simulation speed, but it is still difficult to meet the demand of actual real-time users. The mathematical physics-based methods are suitable on the occasion of high physical flame simulation.

The cellular automation method essentially is a model based on mathematical and physical; its constituent element is simple, but the combined results are complex. Thus real-time and spatio-temporal complexity is limited by the requirement of cell combination. This method is suitable for the simulation of the effect on flame spread.

Imaged based tomographic reconstruction methods are not concerned with measuring or simulating physical properties of fire, but the simulated results with generating visually accurate animations that can be rendered from arbitrary positions. These methods take great advantages on the part of visual reality, but they can not achieve editability and interactivity. In addition, the data acquisition equipment is expensive, need to be explored and studied in the research field of fire simulation.

A. Data acquisition and simulation of fire

Data acquisition and simulation of natural phenomena [57] refers to the controlled formation process of the virtual natural phenomena eventually generated in virtual environment by artificial means, i.e., data capture, data analysis and modeling, which are consistent with real ones in geometric, physical and behavioral attributes. Data acquisition and simulation techniques can transport faithfully the flames in the real world into virtual environments and achieve data-driven fire simulation while maintaining their physical properties. It is a realm full of vitality and opportunities.

B. Editable simulation results

Editability has great significance for film special effect producers and animators. The artists can easily achieve vividly flame models which maintain their physical properties by the simply editing. On the one hand, the simulation results can fully satisfy people's needs of realism and artistic; on the other hand, editable simulation results reduce the labor intensity of the artist and application developers. They no longer need to control models with the script, and do not need to manage every small event, because everything runs perfectly according to its own physical law.

C. Modular interaction

For various materials in special situations such as ignition, combustion, blowing off, and interaction with all kinds of objects can be distinguished with different modules. Each module focuses on a special behavior property, and in a common framework to realize the simulation of flames complex interactions.

D. Multiple methods combination

Different simulation methods have their own scope of application, and multiple methods combination will be the future trend. Multiple methods combination meets the specific demand of users, while variety of methods at different levels from respective views concern about certain details or overall performance.

Each method has its own advantages and suitable situations. In order to promote the development of various methods, there are still problems above that deserve further study. Resolution of these issues will certainly promote the level of flame realistic simulation.

X. CONCLUSIONS

Fire simulation has significant research and economic value in the field of fire control, military emulation, film special effects, and virtual reality. The related researches have been carried from various perspectives and different directions to explore the method of fire simulation. Many creative results have been achieved, and many successful applications have been found. At the same time there are still some problems need to be solved in this realm. In this paper, we presented current state-of-the-art methods of simulating fire for the computer graphics community. Each method has its own advantages and suitable situation, no methods are sufficient to meet the all of the simulation needs. It is an eternal topic that designing and developing a real-time, efficient, high realism, editable, interactive, and general fire simulation methods or practical software.

ACKNOWLEDGEMENTS

This work is supported by the National 973 Program of China (Grant No. 2009CB320805) and Fundamental Research Funds for the Central Universities of China.

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TABLE I. DIFFERENT METHODS OF FIRE SIMULATION PERFORMANCE COMPARISON

	Real-time	**Realistic**	**Spatio-temporal complexity**	**Editability**	**Interactivity**
Texture mapping	High	Low	Low	Low	No
Particle system	Inversely with particles count	Medium	Proportional to particles count	Random large and difficult to control	Medium
Mathematical physics-based	Low	High(physical consistency)	High	Parameter control	High
Cellular automation	Inversely proportional to the complexity of combined requirements	Have certain realistic	Cell simple but the combined complex	Modium	Limited
Tomographic reconstruction	No	High(visual consistency)	Data acquisition and processing complex	No	No