Visual Model of Fire

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Abstract
This paper presents a fire model based on dynamic particle chains. The chains are shaped and moved by a varying velocity field and constitute a density field, which is rendered using the ray tracing method. What we want to present are some new ideas we added to those inspired by our great predecessors' works, as well as some interesting results one can get with their use.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Animation

1. Introduction

Fire - as one of the most fascinating natural phenomena and, simultaneously, one of the most dangerous - has been of interest to computer graphics for years. Its underlying physical processes are sophisticated, and modelling even a small part of them, which is essential for obtaining convincing visual effects, is a great challenge. This has been undertaken many times and in various ways, but has not always resulted in images that at least in some degree intoxicate like those created by nature. The natural pattern seems peerless and, as such, wonderfully drives the imagination of those trying to imitate it.

2. Previous work

Fire models presented previously have been based on a varying combination of two techniques, in which either physically-driven simulations, or methods based on procedural and particle systems modeling are used. Particle systems evolved from their classical form in [Ree83] and [CMTM90] to ones using particle chains that in more and more sophisticated ways define the phenomenon: from [PP94], through [BPP01] to a gorgeous method presented in [LF02]. A very important element, that, in the context of modelling fire, made this path of evolution possible, was a technique of introducing turbulence to a velocity field that moves and shapes particle chains or single particles' routes.

Alternatively, physically based methods have appeared: one using diffusion processes [SF95] and later, one presented in [NFJ02], modelling a wide range of processes that constitute fire phenomena: fluid flow, blue core, gas expansion and blackbody radiation, and hence leading to glamorous visual effects.

Apart from modelling fire, the way it spreads was also a matter of concern, and here it is absolutely necessary to mention the idea that first appeared in [PP94].

3. Essential model

In our model fire is represented by a set of glimmers - dynamic particle chains. They represent the burning gas element which size places them between particles and independent flame structures. Glimmers are introduced to a changing velocity field which is responsible for buoyant force, wind, turbulence, and gas flow around the scene's objects. The field shapes the chains and moves them in a 3D space.

The source of fire is a surface of an object or its volumetric representation with the way fire spreads defined. The fire propagation model is not the subject of this work so the sources we present are designed for achieving particular effects.

Glimmers constitute a density field. A single glimmer's density function is defined in the way that gives desirable results for every configuration of the glimmer's particles. The resultant density field is visualised using a ray tracing algorithm. The density field influences the intensity of light sources responsible for scene illumination by the fire.

The phenomenon's simulation is realized by sequentially repeating steps:

- the velocity field is being prepared - its changing components are refreshed;
- the set of glimmers is modified: its elements are moved by the velocity field, old glimmers disappear and new ones are created by fire sources;
- the density field's values are computed in the points of a regular grid; simultaneous light source intensities are calculated;
- the density table is visualised by a raytracer.

3.1. Glimmers

A single glimmer is characterized by:

- the list of particles originating it;
- actual and maximum length of that list;
- age;
- type;
- its speed multiplier;
- mass determining its contribution to the density field;
- ancillary attributes determining the actual way the particle list is modified and the time when the next such change will occur.

The values of following attributes- the glimmer base's coordinates, the maximum length of its particles' list, its type, and speed multiplier are randomly assigned (within certain extents) at the moment of generation of glimmer.

The particle chain defining a glimmer is an approximation of a curve tangent at every point to the velocity field. The positions of consecutive particles in the chain are solutions of the equation of motion of the point placed in the velocity field, obtained by using a simple Euler integration scheme. The position of the base of the glimmer is constant for a glimmer attached to the burning object surface, or varying for a detached one.

The number of particles originating the glimmer is varying; at the moment of activation of the glimmer it equals one, then it is incremented to the maximum length of the particle list, after that it is decremented to zero and the glimmer disappears. The time interval between neighbouring changes of the glimmer particle list's length is an important parameter affecting the dynamics of the phenomenon.

The glimmer detaches from the burning object's surface when its length begins to shorten. But some (in practice about 40%) of the glimmers remain attached to that surface all their lifetime; we avoid unpleasant gaps near the surface that appear in the final effect, if all of glimmers drift away from the source of fire.

The velocity field vector computed in the glimmer particles' positions is multiplied by an individual value of the glimmer's speed multiplier. That prevents glimmers from combining in bigger groups of elements traveling together and shaped in the same way. Additionally flare bases' speeds are multiplied by globally set coefficient which value also determines the dynamics of fire.

3.2. Glimmer sources

A source of fire is an object's surface or its volumetric representation. In the first case the coordinates of the glimmer's base, generated by a source, are determined by uniform or time-dependent distribution on the surface of the object (sphere, ring, cylinder or plane). The number of glimmers generated in every simulation step is a value from animator-defined range or a function of time (Figure 1, Animation 1).
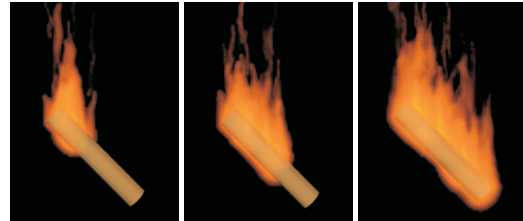

Figure 1: *A simple fire source with the number of glimmers generated in every simulation step and their coordinates defined by linear functions of time.*

For a plane it is possible to give a greyscale fire propagation map and a fuel map describing desirable properties of the object (Figure 2, Animation 2, 3).
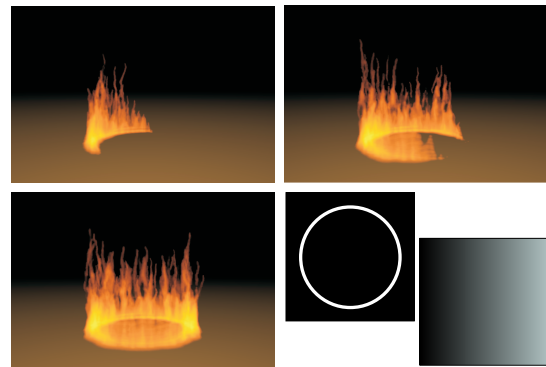

Figure 2: *A burning ring effect achieved by covering a plane with a fuel map (on the left) and a fire propagation map (on the right).*

In a similar way, using 3D maps, the animator defines the behaviour of volumetrically represented fire sources (Figure 3).

3.3. Velocity field

The velocity field is a sum of components responsible for buoyant force, wind, the burning object's movement, turbulence, and gas flow around the scene's objects. Most of these components change due to the animator's control, or vary in a way defined by a time function.

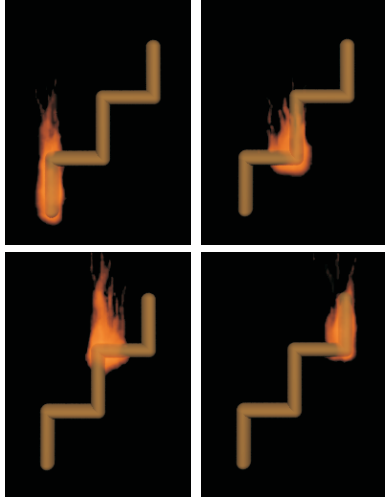The vector specifying the value of the velocity field in a

Figure 3: *A volumetrically defined source of fire covered with both a fuel map (constant value for every voxel of an object) and a fire propagation map (a gradient in 3D space).*

point of 3D space is computed by taking into account the influence of all of the field's components. In practice determining it is necessary only for the positions of particles.

Buoyant force is realized by a globally defined value for the acceleration vector with a nonzero y coordinate.

The wind vector is globally specified, too. The burning object's movement is considered on the base of virtual movement; glimmers are generated for a still source and wind vector is modified by a value opposite to the source's movement vector (Figure 4, Animation 4).

Figure 4: *A burning object in movement. For a more realistic effect, the number of flares and their bases' speed multiplier is increased.*

Gas flow around the scene's objects (particularly around fire sources) is realized by flow primitives: sources, sinks and vertices - like in [WH91].

Sinks and sources are characterized by their coordinates in 3D space, their power, and radius of influence. Vortex definition additionally requires supplying a vector of its rotation axis. The velocity induced by sinks and sources is a linear function of the points' distances from their center. For vortices it is a combination of linear and exponential functions

- like in [RR00]. Flow primitive attributes may vary in time. In particular, their coordinates may change due to movement of the object they shape gas flow around.

Turbulence is modeled with the use of Ken Perlin's noise [Per85]. The effect of turbulence animation is achieved by the technique of moving through the noise field in time (modifying the y coordinate of noise function argument by a value proportional to simulation time).

A different type of turbulence is obtained by introducing a varying vortex field realized by a particle system. Particles representing vortices are generated by a source of fire (or an independent source defined in similar way) in every simulation step and move in the velocity field consisting of components specified before. The vortex's influence radius, power multiplier and lifetime are randomly assigned at the moment of its activation. The vortex's power and rotation axis change during its lifetime in a way determined by the noise function. Its power is additionally scaled in a way that makes the vortex appear and disappear smoothly.

3.4. Visualisation

Each glimmer is a source of a density field. Density induced by a glimmer in point x of 3D space is determined by the Gauss function of x's distance to the broken line originating the glimmer (to the segment closest to it). This distance is disturbed in a way that makes the glimmer attached to burning surface wider at its base and narrowed at the top. The glimmer drifting in air is wider in half of its length and narrowed at both of its ends. The disturbance is linear, and depends on the glimmer's segment closest to the considered point of space, and on the distance of that point's projection on the segment to the segment's beginning.

The disturbed distance is then scaled - to give glimmers the desirable thickness.

The amplitude of the Gauss function is proportional to the glimmer's mass and decreases with the glimmer's age. Simultaneously, the Gauss function's parameter σ increases, so the glimmer does not get narrowed to a thin line but instead disappears smoothly.

The value of the single glimmer's density function in point x, $d(x)$, is added then to a function defining a complete fire in that point, $D(x)$, in the way that prevents values of $D(x)$ from saturation: $D(x) + = d(x) * (1 - D(x))$.

The density field's visualisation is realized by an independent program (POVRay) and necessitates probing the field in the points of the regular grid. This operation is performed only for the closest neighbourhood of each glimmer and within it - for the closest neighbourhoods of its segments, so it doesn't require calculating a distance from a considered point of the grid to every segment of glimmer.

The density field is raytraced with adaptive sampling. The resultant colour of the medium representing fire is density

dependent: in high density areas it is bright orange or yellow, in lower density areas it is red. The flames' contours are more clear if the threshold value of density which maps to nonzero colour intensity is bigger than zero.

Medium particles emit light (they are visible without any illumination shining on them), they absorb it, which increases opacity of the flames, and scatter it in a direction-independent way.

The problem of global illumination is solved with the use of a 3D table of point light sources. Each source stirs slightly in the center of its cell. Its intensity is proportional to a sum of values from the density table's cells found in that area.

Best effects are achieved if the number of light sources is high, but that obviously increases the costs of visualisation. A better solution is to place a table of a few lights in the center of the fire (Animation 5).

4. Model controlling and modelling costs

The model is open to defining different scales and dynamics of phenomena. The fire's scale is determined by the number of glimmers, their size (length, thickness and mass) and the scale of turbulence. Fire dynamics is stated by time step value, amplitude of turbulence, and turbulence change rate; the tempestuous character of the phenomenon is marked by increasing the number of flares and their speed multiplier's value.

The main costs of modelling the phenomenon are the cost of moving the glimmers (proportional to the number of particles originating them and the number of vortex field elements) and the cost of filling the density table (proportional to the number of glimmers, their length in particles and table resolution). These costs are negligible in comparison with rendering time (a couple of seconds and a minute (or a couple of minutes), respectively, for high quality images: created with use of a few hundreds of glimmers with average length of about 4 particles, and 128^3 grid resolution).

5. Conclusions and future work

The presented model gives significant freedom in shaping fire; determining its scale and dynamics is intuitive and does not involve a large number of parameters. We have considered issues that are very important for image realism: turbulence, clear contours of flames, differentiation in their colours, flares thrown off by a fire, and a proper illumination of the scene.

The model's components, proposed here, that proved especially effective in obtaining convincing images are: the role of particle chains (their size is small, which results in a more fluid-like character of phenomena), density field and vortex field definitions. The definition of the density field is a proposition of efficient metrics for the function describing density distribution around a single particle chain, and

the way this function changes and affects the resultant density field. The vortex field definition is an idea of using the particle system (with particles representing flow primitives) and noise function in order to secure compelling vortex-like turbulence.

A natural extension of the model would be the ability of defining gas flow around the scene's objects with 3D tables containing solutions of Navier-Stokes equations.

The problem that wasn't considered in this work is a fire propagation model. We plan to develop one that would take into account burning object deformation.

References

[BPP01] BEAUDOIN P., PAQUET S., POULIN P.: Realistic and controllable fire simulation. In *Proc. Graphics Interface '01* (2001), pp. 159–166. 1

[CMTM90] CHIBA N., MURAOKA K., TAKAHASHI H., MIURA M.: Two-dimensional visual simulation of flames, smoke and the spread of fire. *Journal of Visualisation and Computer Animation 5*, 1 (1990), 37–54. 1

[LF02] LAMORLETTE A., FOSTER N.: Structural modelling of flames for a production environment. In *Proc. SIGGRAPH '02* (2002), pp. 729–735. 1

[NFJ02] NGUYEN D. Q., FEDKIW R., JENSEN H. W.: Physically based modelling and animation of fire. In *Proc. SIGGRAPH '02* (2002), pp. 721–728. 1

[Per85] PERLIN K.: An image synthesizer. In *Proc. SIGGRAPH '85* (1985), vol. 19, pp. 287–296. 3

[PP94] PERRY C. H., PICKARD R. W.: Synthesizing flames and their spreading. In *Proc. 5th Eurographics Workshop on Animation and Simulation '94* (1994), pp. 56–66. 1

[Ree83] REEVES W. T.: Particle Systems - A Technique for Modelling a Class of Fuzzy Objects. *ACM TOG 2*, 2 (Apr. 1983), 91–108. 1

[RR00] RUDOLF M. J., RACZKOWSKI J.: Modelling the motion of dense smoke in the wind field. *Computer Graphics Forum 19*, 3 (2000), 371–372. (Proc. Eurographics'00). 3

[SF95] STAM J., FIUME E.: Depicting fire and other gaseous phenomena using diffusion processes. In *Proc. SIGGRAPH '95* (1995), pp. 125–136. 1

[WH91] WEJCHERT J., HAUMANN D.: Animation aerodynamics. In *Proc. SIGGRAPH '91* (1991), vol. 25, pp. 19–22. 3