EG UK Theory and Practice of Computer Graphics (2009)
Wen Tang, John Collomosse (Editors)

A Framework for Physically Based Forest Fire Animation

Odd Erik Gundersen[1,2] and Jo Skjermo[1]

[1]Department of Computer and Information Science, Norwegian University of Science and Technology, Norway
[2]Verdande Technology, Norway

Abstract

In this paper, we propose a conceptual framework for animating physically based forest fires. Animating forest fire is a computationally demanding task as trees are intricate structures and fire is a highly complex process. The framework is divided into three conceptual levels, which are a large scale forest fire simulation, a small scale tree fire simulation, and an intermediate level connecting the two. Problems with and possible solutions to all three levels are discussed. Based on this discussion, a complete framework is proposed.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism, Animation

---

1. Introduction

Natural phenomena are chaotic and complex in contrast to man-made structures that more often than not are smooth, organized, and systematic. Hence, rendering of man-made structures are easier to achieve than rendering of natural phenomena, even when the latter is well defined through the laws of physics. Often, the challenge of rendering natural phenomena is not that their behavior is not well understood, but the vastness of the nature. For instance, the number of trees in a forest is immense. Despite the very large number of trees in a forest, no duplicates exist. In addition to the large number and difference between objects, interaction is imperative when animating. For instance, one must not only consider waves interacting with other waves when animating a shore, but also waves interacting with stones and boats. All this makes animating natural phenomena on a large scale hard to achieve.

Still, it is becoming more and more common to experience synthetic natural environments both in films rendered offline and games rendered in real-time. Forest fires are a natural phenomena that has been given little attention both in animated movies, games, and scientific literature because of its obvious complexity. Animating forest fire is a computationally demanding task as trees are intricate structures and fire is a highly complex process. While research has been done on both rendering trees and simulating fires, the interaction between the two phenomena has not been thoroughly investigated. The only reference to forest fire animation in the scientific literature that we have been able to find is a sketch published in Siggraph proceedings on utilizing sprites when animating a 'wall' of fire for the Dreamworks movie *The Road to El Dorado*. In the recent game *Far Cry 2* by *Ubisoft* a procedural approach is used to render real-time spreading of fire. Physically based methods have not been proposed or described in the computer graphics literature.

Goal: The goal of the research presented in this paper is to propose a conceptual framework that can handle the computational load of animating a physically based forest fire. The scientific basis of the framework in regard to forest fire is found in scientific literature on fire. Properties of forest fire are discussed in relation to the applicability of different methods for animating fire and rendering trees. So are the identified problems and their solutions.

Contribution: This paper is a first step towards animating physically based forest fire with a goal of interactive frame rates. The main contribution is a conceptual framework that animates forest fires both on a small and on a large scale. Other contributions are the identification of problems related to such a framework, a discussion of possible solutions, and a presentation of the properties of fire that needs to be addressed in order to animate forest fire realistically.

This paper is structured as follows: Chapter 2 presents related works. Chapter 3 delves into the inner workings of the

DOI: 10.2312/LocalChapterEvents/TPCG/TPCG09/085-092

natural processes behind forest fires. Chapter 4 considers the overall problems of simulating and rendering forest fires. Chapter 5 and 6 consider possible approaches to solve the defined problems on a large (entire forest) and small (individual tree) scale, respectively. Chapter 7 considers the interaction between these. Chapter 8 concludes with a proposed framework.

2. Related Work

Historically, forest rendering has been done using image-based approaches such as billboards. A billboard, as defined by Jones [Jon94], is a four-sided polygon (quad) that has a partial transparent texture mapped on to it (analogous to cardboard cut-outs). The orientation of the billboard can be set to always face the observer. An alternative to orient the billboards is to use several quads to represent each tree object and then blend them together to generate a good result from the observers point of view. Although many billboards usually share the same texture (of the same tree), the overall forest still looks convincing on a large scale, as the overall complexity reduces our abillity to recognize individual trees.

A newer approach is to use billboard clouds [DDSD03]. A billboard cloud is usually generated by rendering a triangle mesh into a set of billboard planes that are nearly co-planar with the triangles in the mesh. Billboard clouds have a range of improved properties compared to normal billboards. For instance, in the work by Lacewell et al. [LEST06] it as possible to achieve both good motion parallax and smooth transition between recursive level of details.

Another approach is to use geometry based models where tree models are rendered directly using polygon meshes. Meshes can, for instance, be generated using parametric tree models [Hon71,WP95] or Lindenmayer systems [Pru86, PL96]. However, as a tree model might require hundreds of thousands triangles to be truly realistic, some form of LOD management is required to achieve any form of real-time performance.

In the work of Bromberg-Martin et al. [BMAMJMM04] and Rebollo et al. [RRC*07] hybrid approaches were suggested. Hybrid approaches use both billboard clouds (particularly for leaves) and mesh simplification (for stems and branches). For such hybrid methods the amount of mesh data is kept low, while the most complex parts are handled using billboards or billboard clouds. These methods can produce more detail when observing trees up close, while still remaining highly efficient for rendering (especially if LOD methods are used to switch out mesh parts with billboards at distance).

The dynamic and highly turbulent behavior of fire makes the traditional polygon models unsuitable. Also, the physics of fire is modeled using fluid dynamics, which is computationally demanding. Computationally cheap particle systems [Ree83] are still the most preferred way of modeling fires in real-time environments such as games, although the particles often are both textured an animated [Ngu04]. Another procedural method utilizing stochastic models in combination with Kolmogorov noise and physically defined wind was introduced to animate fire in the movie Shrek by DreamWorks Animation [LF02].

While the procedural methods for fire animation are computationally less demanding and also easier for an animator to control, interaction with the environment and the turbulent effects are better modeled using fluid dynamics. Fluids are simulated using the Navier-Stokes equations, which were assumed to be too computationally demanding for animation until Stam introduced Stable fluids – a fast and stable method to solve them [Sta99]. This method revolutionized fluid dynamics for computer graphics and several techniques for counteracting the numerical dissipation inherent in the method have been proposed. These methods include vortex particles [SRF05], vorticity confinement [FSJ01] and the MacCormac scheme [SFK*08].

Principally, the simulation domain of the fluid is divided into equally sized volume cells when using the Stable Fluids method. The quantities of each of the modeled variables, such as heat, fuel, exhaust gas, and velocity for fires are then stored in each simulation domain cell. The motion of the fluid is modeled by convecting all the variables, including velocity, using the velocity. For a thorough survey of physically based fluid animation the work by Tan and Yang is recommended [TY]. Realistic fires utilizing the Stable Fluids method for simulation and volume rendering methods for visualization purposes are presented by [NFJ02] and [MM07]. These methods are far from being able to achieve real-time frame rates. To achieve real-time frame rates [KW05], particle systems are being used to visualize the physically based simulations, although volume rendering has been applied [CLT08] as well.

3. Understanding Forest Fire

Fire is the result of a combustion process in which a fuel and an oxidant react to produce heat and exhaust. Often, a hydrocarbon is the fuel and the oxygen in air is the oxidant. The heat radiates and increases the temperature of its surroundings and, in cases where the surroundings are a fuel source with access to oxygen and the temperature is high enough, the fire will spread. The heat also raises the temperature of the surrounding air and, as hot air rises, it lifts the exhaust gases creating buoyancy effects. The yellow color emitted by a fire is radiation from exhaust gas heated to high temperatures. When the exhaust gas cools, it stops radiating yellow light and can nucleate into larger particles that we recognize as smoke. Both the air and the exhaust gases can be modeled using fluid dynamics as they are both gases. Smoke is particles that are moved by the gases they are enclosed by, and therefore their behavior can also be modeled using fluid dynamics.

Fire can be described through the interplay of three phenomena: (i) the chemical combustion reactions, (ii) the physical phenomena of mass and heat transfer, and (iii) the mechanical gas flow. *The chemical combustion reaction* describes the combustion process, which specifies how much oxidant is needed to burn a given amount of fuel and the amount of heat produced. *Mass and heat transfer* are regulated by conductivity and diffusion. *Gas flow* is described by fluid dynamics and the Navier-Stokes equations.

Flames are categorized on the basis of whether the fuel and oxidant are premixed or not when the combustion occurs and, as with fluids, whether it is laminar or turbulent. Premixed flames are flames that mix gaseous fuel and air before ignition such as bunsen burners while diffusion flames heat up the nearby fuel so that it vaporize and mixes with air before the combustion takes place, like candles [Dry07]. It is the flow of fuel and oxidant gases in which the combustion occurs that defines whether the flame is categorized as laminar or turbulent. An essential feature of turbulent flow is that the fluid velocity varies significantly and irregularly with respect to both position and time, and the result is that a turbulent flow mixes the fluid much better than a comparable laminar flow [Pop00].

The lifespan of the fire can be divided into three different stages:

Ignition: Ignition is typically divided into two different categories, which are self-ignition and pilot ignition [Dry07], and it is achieved by providing energy to a volume of premixed fuel and oxidants over a limited period of time [BD98]. Often, ignition is defined by a temperature, but this is only a simplification [Cox95].

Spread: Spread of fire can be thought of as the advance of ignition in which the burning fuel provides both the heat to vaporize the fuel and the pilot ignition. Several factors are important for affecting the rate of flame spread [Dry07]. The factors are both the chemical and physical properties of the material, but also the environment plays a role.

Extinction: Extinguishing a flame can be done through stopping the supply of fuel or oxidants and lowering the temperature in the reaction zone. This can be done through providing a chemical suppressor, cooling the fire zone using water, or distorting the reaction zone through a *blowout*. A blowout reduces the thickness of the fuel so that the fuel vapors have too little time to react [Dry07].

Forest fires are a large scale natural combustion process fueled by forests in which large scale buoyancy effects play a significant role [Dry07]. A forest is not only comprised of trees, but also the underbrush, and thus a forest fire is both burning trees and underbrush. Forest fires spread most rapidly at the ground level and at the treetop level where the fuel is denser.

According to Borghi and Destriau [BD98], forest fires most resemble a premixed fire propagation over a surface when observed at a large scale, while at a small scale it most resembles diffusion flamelets surrounding each tree or group of trees. As mentioned above, in a premixed flame the reactants - the fuel and the oxidant - are mixed on beforehand, and this is true for a forest fire in which the trees (fuel) are mixed with the air (oxidant). At a small scale, the forest fire is comprised of lots of smaller diffusion flames situated on all the burning trees in the forest. A diffusion flame is defined as a flame that mixes the vaporized fuel and oxygen in the air during the combustion process through diffusion and the buoyancy of the hot air rising.

In [Dry07], the important factors affecting the rate of fire spread are listed in a table and grouped according to material and environmental factors. The material factors are again divided into the two subgroups chemical and physical factors. Several of the factors listed are more important for understanding small scale flames and specific situations. We will assume that the chemical composition of the fuel is suitable for sustaining a fire and that retardants are not present. Also, the physical aspects of the fuel such as the initial temperature, the thickness, thermal capacity, and thermal conductivity will not be considered. The composition and the pressure of the atmosphere and the imposed heat flux are also ignored.

The factors affecting the rate of fire spread that will be given consideration when simulating forest fires are discussed below. While the first five items listed below are physical factors relating to the fuel material, the last two are environmental factors.

Direction of propagation: The direction of the fire propagation is an important factor, as the direction will determine the future destiny of the fire. For instance, if the fire propagates in a direction where no fuel exists, the fire will extinguish.

Surface orientation: A fire will spread much faster with an upward propagation direction on a vertical surface than for the exact same flame with a downward propagation direction. This is because of buoyancy. Buoyancy makes the hot gases spread upward in the same direction as the flame, and thus the fire spread rate is enhanced. Conversely, downward spread on a vertical surface will go even slower than horizontal spread.

Density: Fire spreads faster in materials with low density. This is because a very small mass of material on the surface, relatively to the flame size, needs to be heated in order for the fire to spread. However, a fuel that is too dense will not create enough heat to sustain the flame and thus quenched.

Geometry: Fires having a substantial width will spread faster. The effect is related to the size of the flame. Radiative heat transfer can dominate larger flames as the fuel in front of the flame front will be preheated to a higher temperature faster. Thus, the fire will spread faster.

Continuity: The continuity of fuel will, of course, affect the spread rate. This is why broad streets are effective for

Figure 1: *Left: Close view of forest fire. Right: Overview of forest fire. Photos by Jon Marshall.*

stopping fire spreading in cities. As far as heat transfer is concerned, the fire will not spread beyond gaps in the forest larger than the part of the preheating zone that heats the surrounding forest above the ignition threshold. Pilot ignitions can move further and can ignite areas further away.

Ambient temperature: The ambient temperature is the temperature of the surrounding atmosphere. Higher ambient temperatures result in higher spread rates as the preheating of the fuel will take a shorter time.

Wind: Confluent air movement will a enhance the rate of spread over a surface, and the rate will increase quasi-exponentially up to a critical level at which point extinction or a blowoff will occur. The rate of fire spread affected by wind in the opposite direction will vary with the wind velocity. For faster velocities of wind, the fire spread will decrease and the fire extinguish while, for slower velocities, thewind will increase the spread rate.

Another environmental factor important for forest fires is weather. Snow and rain will cool down the reaction zone. The result is decreased spread rate and, in some cases, the fire can extinguish. Sunny and dry weather will, on the other hand, provide better conditions for the fire.

4. A Framework for Forest Fire Animation

A physically based framework for animating forest fires must take into account both the simulation and the visualisation of the forest fire. Simulation must deal with the three stages of fire for the forest fire simulation while visualisation must deal with rendering both a large number of trees and a large scale fire.

As described in the section about related work, physically based simulation of fire is done through solving the Navier-Stokes equations in a discrete and bounded simulation domain with a relatively small number of cells. The intuitive solution for simulating a forest fire is to expand the simulation domain and increase the number of cells in the simulation domain until it is large enough to enclose the complete forest. However, a large number of cells in the simulation domain will make the computational demands of the simulation too high while reducing the number of cells and increasing their size will remove the detail and turbulent effects of the simulation. Thus, a compromise must be reached. For the simulation, the key is the differing behavior of forest fires at a small scale versus a large scale. As described in [BD98], large scale forest fires resemble premixed fire propagations while forest fire on a small scale must be treated as a set of trees enclosed by diffusion flamelets. Hence, forest fire should be simulated differently at different scales. This corresponds with how forest rendering is done through the use of level of detail. At a long distance the forest is rendered using billboards while detailed tree models are used at a short distance. A forest fire seen from a distance must take into account a large scale simulation that simulates the large scale propagation of the forest fire, propagating from one area to a neighboring one. Such a large scale simulation is less important when looking at a forest fire close up. Close up, fewer trees are observed and the details of the fire are more important, which demands a more detailed simulation.

Although dividing between a large scale and a small scale simulation, the simulations cannot be completely separated. There has to be some form of interplay as the large scale simulation must communicate the state of the forest at a given area. A non-burning forest can be considered static in the sense that the number of trees in the forest is constant and their structure does not change. By contrast, a burning forest is dynamic, as trees are burned down and turned into heaps of ash. Thus, both the structure of a tree and the number of trees in the forest changes. This dynamic property of a burning forest poses a challenge of visual consistency. When visiting a section of the forest that has been ravaged by a forest fire, the current state of the forest must reflect this situation. Also, the number of trees should not change over time and, likewise, the degree of damage on the trees. Visual consistency between the different scales is crucial. What is observed close up must be reflected when observed from a distance at a later time. As with tree rendering, level of detail is needed for rendering the two different simulation scales, in which the small scale rendering will need to render more detailed while the large scale rendering must cover a larger area of the forest fire. Level of detail for the rendering introduces another visual consistency issue, which is popping. Popping is the visual effect of switching between the different detail levels of the visualized phenomena. A good solution for how to solve the switching between different levels of detail must be researched.

Because of the computational load of both simulating and rendering a forest fire, the complexity should at all times be kept as small as possible while achieving a good enough visual result. The large scale forest fire simulation will have to run whether observed or not. A feasible solution must avoid simulating the forest fire at the small scale in the complete fire zone as this would be too computationally demanding. At a minimum, the forest fire simulation on a large scale will run. At maximum, both the large and small scale forest fire simulation will run in parallel, but the small scale simulation and tree rendering will only run for the nearest region of forest - with only a small group of main actor trees. Main actor trees are trees for which a fire simulation is done and rendered in detail.

A forest fire simulation should address the important factors of fire spread to a certain degree. Obviously, the fire should only be able to propagate in directions in which there exist fuel. When the forest stops, the fire should not propagate any further, at least if the gap is larger than a given threshold that can be determined dynamically according to the temperature of the fire front. The rate the fire spreads should be adjusted according to the direction of the propagation, together with the surface orientation. Fires spreading upwards should propagate faster than fires spreading horizontally or downwards. Hence, the surface on which the forest fire burns needs to influence the rate of propagation.

Also, the density of fuel should affect the forest fire. Thus, the amount of trees and underbrush in an area should affect the rate of spread and whether the fuel level is high enough to sustain the fire. The ambient temperature will not vary to a large degree as the temperature on the surface of the Earth is quite stable and low in comparison to the temperature inside a forest fire. However, as the ignition temperature of wood is around 300 degrees Celsius, the ambient temperature is not negligible and should be considered in the simulation. Global wind change is often simulated when animating trees and, as wind is important for the spread of a fire, wind simulation should be supported by the forest fire framework.

5. Large Scale Forest Fire Animation

The large scale forest fire simulation simulates the complete area covered by the forest fire while the large scale forest fire rendering renders a large set of burning trees. At this scale, the forest fire behaves as a premixed flame on a surface, which means that it will spread outwards in a perfect circle if located on a planar bed of fuel with no wind affecting it [BD98].

5.1. Forest Fire Propagation

The velocity of the forest fire propagation is quite slow in relation to the size of the forest. Thus, the simulation need not run several times a second in order to propagate in a realistic manner. Additionally, the number of cells in the simulation domain need not be large in order to capture the turbulence in the simulation. Therefore the number of cells in the simulation domain can be kept small. Hence, the computational demands of the large scale simulation are not very high.

For a forest located on a planar surface, a two-dimensional simulation domain suffice. The complete set of variables needed to represent the simulation domain can be stored in an image with the same dimensions as the simulation domain. The terrain, for the most part, is not completely planar. As surface orientation is an important factor for fire propagation, the fire simulation should account for a third dimension. This can, for instance, be done by simulating the fire in a three-dimensional simulation domain. A drawback with this solution is that the number of cells in the simulation domain will increase, as will the computational load. Another possible solution is to simulate the fire in a two-dimensional simulation domain and correlate the fire simulation with a height map. For instance, after each simulation step, the temperature in neighboring cells is adjusted according to whether they lie above or below the flame front. For neighboring cells that are located above a cell representing the flame front, the temperature rises according to the height difference while the opposite will be the case for a cell located below the flame front. This effect can also be correlated with the flame direction.

Figure 2 illustrates the situation described above. The uppermost image illustrates how a forest is situated in the terrain, while the middle image in the row below illustrates the fuel map. The terrain with a fuel map texture is shown in the lower right corner of the upper terrain image. The fuel map is created using a shadow map of the trees in the forest. In the bottom middle image, the trees are indicated by completely

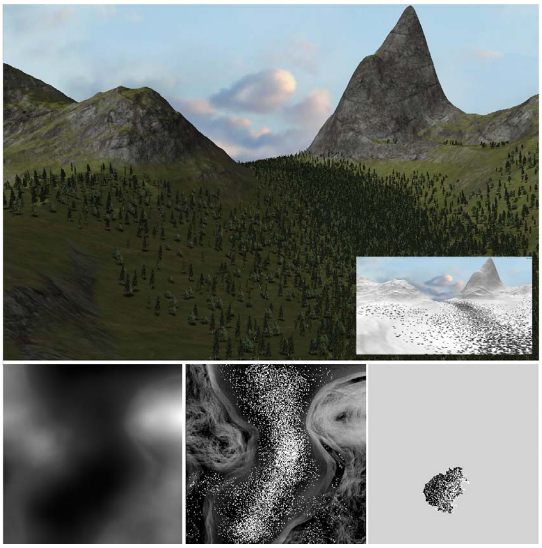

Figure 2: *Top: A forest scene with the fuel map in lower right corner. Bottom row: Height map, fuel map with landscape details, and forest fire spread simulation.*

white dots while the shading indicates the variation of the terrain. The height map is illustrated in the bottom leftmost image while the bottom rightmost image illustrates the fluid simulation domain. The fire will spread faster to the North as the forest climbs upwards in the terrain at that point and the forest has a high tree density in that direction.

5.2. Visualizing Large Scale Forest Fire

Figure 1 shows two images of a real forest fire. The leftmost image shows a small scale view while the rightmost image illustrates a large scale view of a forest fire. Several points can be made from the image illustrating the large scale view. Firstly, the forest has three different states when it comes to the forest fire: (i) burning, (ii) before burning, and (iii) burned-out. Secondly, the fire creates a large amount of smoke, which masks the background. Finally, the fire seems to have no depth.

Forests with a large number of trees, such as the one illustrated in the top image of Figure 2, are usually rendered using billboard trees. The states of the forest mentioned above can be directly mapped on to billboards. The two states, (i) and (iii), are static states, at least if wind interaction is not considered. The billboard representing the burned out tree should reflect where the stem was located so that the forest can be recognized to some degree even after being burned. The burning state (ii) of the billboard should be dynamic and reflect the result of the devouring fire. The colors of the billboard can reflect the amount of fuel left in the simulation domain. Green and brown pixels can be transformed into grey first, then black, and finally becoming fully transparent, indicating that this part of the tree has been burned out.

Several possibilities exist for how to render the fire. One is to visualize the fire using particle systems located in the terrain as specified by the fuel and temperature map. The particles can be animated in order to imitate turbulence, and colored according to the temperature and amount of exhaust gas in the zone they are expelled from.

A three-dimensional fluid simulated fire can be placed in terrain where the large scale fire front is located according to the large scale fire spread simulation. Such a simulated fire can be used for visualization purposes while the spread is controlled by the large scale fire spread simulation. The simulation domain can be dynamic and adapt in the direction of the fire spread using methods as described by [SCP*04].

As indicated by the picture of the real forest fire, the depth dimension of the fire is not necessary. Thus, the simulation can be limited to two dimensions. The obvious advantage is that one large or several smaller simulations covering a larger area can be performed. Then, the fire can be visualized through texturing billboards using Planck's formula for black-body radiation.

For moist forests like the one depicted in Figure 1, a large amount of smoke will be produced. Smoke is one of the two products of the combustion, and the amount of smoke produced is accounted for by the exhaust parameter of physically based fire simulations. One way of visualizing the smoke is to render in grey scale the amount of exhaust in a cell in the simulation domain. The problem with this method is that the simulation domain has to be large enough to contain the complete smoke cloud. This will, of course, be a computationally demanding solution. A less computationally demanding solution is to render the smoke as a textured particle system. The cells in the large scale fire spread simulation domain can all be sources for the particle system and generate smoke according to the amount of exhaust gas in each cell. Since even large particles will produce visually good results [USKS06], the number of particles needed can be kept low. A fog function can be used to make the smoke cover a larger volume.

6. Small Scale Forest Fire Animation

The small scale forest animation simulates and renders a small group of burning trees. The group of trees consists of a main actor and a small set of supporting actors. When moving around in the forest, the main actor will change. The main actor will always be the tree dominating the camera view. Being the main actor means being rendered in detail and thus both the tree model and the fire simulation will be more detailed for the main actor.

We consider two alternatives for animating a small scale forest fire. One alternative is to enclose the tree model of the main actor in a simulation domain volume. The other is to animate two-dimensional fire textures and visualize them as billboard clusters on the main actor tree already using this method for the leaves.

A tree model enclosed in a simulation domain is illustrated by the left part of Figure 3. The idea is that the simulation domain is a volume enclosing the complete tree. As described in [CLT08], the cells in the simulation domain can contain obstacles, and this information is decoded in an *inside-outside texture*. However, in contrast to the method they describe, the inside-outside texture needs to be dynamically updated in order to keep track of fuel depletion.

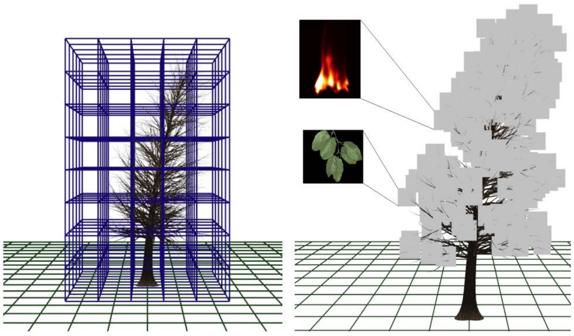

Figure 3: *Left: Simulation domain enclosing a tree. Right: Tree rendered using billboard placers, some for leaf clusters, others for animated fire textures.*

A tree rendered using billboard clusters is illustrated in the right part of Figure 3. This is a common way of rendering trees, but we propose the use of animated fire textures in addition to the leaf clusters. The animated fire textures are animated using the same method as proposed for the large scale fire animation. The animated textures are used as billboards on the main actor tree. Fires spread to neighboring textures and branches. Branches burn down after being in flame for a given period of time. The fuel source of the two-dimensional fire simulation is co-located with the attachment point to the branch, and it needs not necessarily be a point source.

7. Bridging Large and Small Scale

The two scales of fire simulation described in the previous sections need coupling as the forest fire spread simulation directs which parts of the forest has been burned down or is burning. A two-way communication between the small scale and large scale fire simulation is needed. The large scale simulation needs to tell the small scale simulation what state it is in. Is it burned and how much? However, the communication need not be continuous. When the camera observes a small scale forest fire simulation after not observing it, the small scale forest fire simulation needs to ask the large scale simulation what the current state is. After getting the current state, the small scale animation continues to develop the simulation from the state it was in to begin with. Then, when moving the camera away from that specific small scale simulation, the last observed state of the simulation must be communicated to the large scale simulation. The large scale simulation then continues to evolve the forest fire spread, but from now on it uses the last observed state of that exact small scale simulation. This scheme is repeated for every small scale simulation that the camera observes.

A tree in the small scale simulation is represented as a texel in the two-dimensional large scale simulation domain. Each texel contains information about the temperature, the amount of exhaust gas, and the amount of fuel. Thus, the state of each tree is stored in the large scale fire spread simulation domain.

Popping effects are usual when moving from one level of detail to another. We intend to apply level of detail techniques that reduce the popping effects for rendering both the fire and the trees. Methods for where to attach the animated fire billboards on the trees when closing in on the forest fire must be researched. Techniques developed for adding and removing the leaf clusters on the trees will be adapted for fire animation.

8. Conclusion

In this paper several factors one has to account for when considering simulation and rendering of forest fire have been considered. Also, several main problems to be solved have been identified. We consider the following selected solutions to be the most appropriate to achieve our goal of a conceptual framework for physically based forest fire animation.

On a large scale, we propose the use of a shadow mapping approach to generate a two-dimensional map indicating fuel density. The fuel map, together with other data such as a height map, will serve as data for a two dimensional fluid simulation of fire propagation at this scale. The large scale simulation will indicate to each tree its present situation. However, on a small scale, a fire in a tree is only simulated by the spread between texture clusters.

For the rendering of the forest fire at a large scale, image based approaches such as billboards should be used. Using billboards one can render both trees, trees on fire, and trees after fire, relatively inexpensively. On a small scale, we propose using a similar approach, but with smaller billboards for distinct parts of the tree. This is similar to the way leaves on trees close to the observer are often rendered using one billboard per leaf cluster. To achieve a good transition between rendering on a large and a small scale, we propose the use of similar level of detail handling as used for tree rendering done with hybrid image and polygon based approaches. As the distance between a tree and the observer increases, some leaf cluster billboards are faded out while other increases in size to maintain the overall tree volume. The same approach can be used for the fire billboards.

Using the proposed framework we hope to approach interactive frame-rates for rendering forest fire. Although the intrinsic complexity of the subject is staggering, we consider the proposed framework to give a clear direction for future work.

References

[BD98] BORGHI R., DESTRIAU M.: *Combustion and flames : chemical and physical principles*. Editions Technip, 1998.

[BMAMJMM04] BROMBERG-MARTIN E., ÁRNI MÁR JÓNSSON, MARAI G. E., MCGUIRE M.: Hybrid billboard clouds for model simplification. In *SIGGRAPH '04* (New York, NY, USA, 2004), ACM, p. 30.

[CLT08] CRANE K., LLAMAS I., TARIQ S.: Real-time simulation and rendering of 3d fluids. In *GPU Gems 3*, Nguyen H., (Ed.). Addison-Wesley Professional, 2008, pp. 633–676.

[Cox95] COX G.: *Combustion Fundamentals of Fire*. Academic Press, 1995.

[DDSD03] DÉCORET X., DURAND F., SILLION F. X., DORSEY J.: Billboard clouds for extreme model simplification. In *SIGGRAPH '03* (New York, NY, USA, 2003), ACM, pp. 689–696.

[Dry07] DRYSDALE D.: *An introduction to Fire Dynamics - Second Edition*. Wiley, 2007.

[FSJ01] FEDKIW R., STAM J., JENSEN H. W.: Visual simulation of smoke. In *SIGGRAPH '01* (New York, NY, USA, 2001), ACM, pp. 15–22.

[Hon71] HONDA H.: Description of the form of trees by the parameters of the tree-like body: Effects of the branching angle and the branch length on the shape of the tree-like body. *Journal of Theoretical Biology* (1971), 331–338.

[Jon94] JONES M.: Lessons learned from visual simulation, 1994. Siggraph 94 Course Notes.

[KW05] KRÜGER J., WESTERMANN R.: Gpu simulation and rendering of volumetric effects for computer games and virtual environments. *Computer Graphics Forum 24*, 3 (2005).

[LEST06] LACEWELL J. D., EDWARDS D., SHIRLEY P., THOMPSON W. B.: Stochastic billboard clouds for interactive foliage rendering. *journal of graphics tools 11*, 1 (2006), 1–12.

[LF02] LAMORLETTE A., FOSTER N.: Structural modeling of flames for a production environment. In *SIGGRAPH '02* (New York, NY, USA, 2002), ACM Press, pp. 729–735.

[MM07] MIN K., METAXAS D.: A combustion-based technique for fire animation and visualization. *Vis. Comput. 23*, 9 (2007), 679–687.

[NFJ02] NGUYEN D. Q., FEDKIW R., JENSEN H. W.: Physically based modeling and animation of fire. In *SIGGRAPH '02* (New York, NY, USA, 2002), ACM Press, pp. 721–728.

[Ngu04] NGUYEN H.: Fire in the "vulcan" demo. In *GPU Gems*, Fernando R., (Ed.). Addison-Wesley Professional, 2004, pp. 87–105.

[PL96] PRUSINKIEWICZ P., LINDENMAYER A.: *The algorithmic beauty of plants*. Springer-Verlag New York, Inc., New York, NY, USA, 1996.

[Pop00] POPE S. B.: *Turbulent Flows*. Cambridge University Press, Cambridge, UK, 2000.

[Pru86] PRUSINKIEWICZ P.: Graphical applications of l-systems. In *Proceedings of Graphics Interface '86 / Vision Interface '86* (1986), pp. 247–253.

[Ree83] REEVES W. T.: Particle systems: A technique for modeling a class of fuzzy objects. *ACM Trans. Graph. 2*, 2 (1983), 91–108.

[RRC*07] REBOLLO C., REMOLAR I., CHOVER M., GUMBAU J., RIPOLLÉS O.: A clustering framework for real-time rendering of tree foliage. *JOURNAL OF COMPUTERS (JCP) 2*, 4 (June 2007), 57–67.

[SCP*04] SHAH M., COHEN J. M., PATEL S., LEE P., PIGHIN F.: Extended galilean invariance for adaptive fluid simulation. In *SCA '04* (Aire-la-Ville, Switzerland, Switzerland, 2004), Eurographics Association, pp. 213–221.

[SFK*08] SELLE A., FEDKIW R., KIM B., LIU Y., ROSSIGNAC J.: An unconditionally stable maccormack method. *J. Sci. Comput. 35*, 2-3 (2008), 350–371.

[SRF05] SELLE A., RASMUSSEN N., FEDKIW R.: A vortex particle method for smoke, water and explosions. In *SIGGRAPH '05* (New York, NY, USA, 2005), ACM, pp. 910–914.

[Sta99] STAM J.: Stable fluids. In *SIGGRAPH '99* (New York, NY, USA, 1999), ACM Press/Addison-Wesley Publishing Co., pp. 121–128.

[TY] TAN J., YANG X.: Fluid animations: A survey. In *Science in China (in press)*.

[USKS06] UMENHOFFER T., SZIRMAY-KALOS L., SZIJÁRTÓ G.: Spherical billboards and their application to rendering explosions. In *Graphics interface 2006* (Toronto, Ont., Canada, Canada, 2006), Canadian Information Processing Society, pp. 57–63.

[WP95] WEBER J., PENN J.: Creation and rendering of realistic trees. In *SIGGRAPH '95* (New York, NY, USA, 1995), ACM Press, pp. 119–128.