Target temperature driven dynamic flame animation

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Abstract

Fire/flame plays an important role in virtual environment. Controlling the flame behavior in an intuitive yet precise manner remains a challenging open problem. In this paper, a target temperature driven simulation method is proposed to control flame animation. The diverse descriptions of target flame are unified by temperature field. An adaptive control force is presented to control the degree of target-driven changing over the temperature field. A bidirectional iterative method is proposed to subdivide the final goal into a plurality of intermediate targets. We take geometric model, image, and temperature field as target flames to test our method. Experimental results show that this method allows complex flame animations to be controllably generated with very little additional cost compared to ordinary flow simulations.

Keywords: target-driven, adaptive control force, flame animation, temperature field

1. Introduction

Controlling animations of flame is a difficult and computationally expensive problem. A number of methods for controlling animated fluid have been developed in the past. Treuille et al. [TMPS03] propose a keyframe method for controlling smoke simulations, where a continuous quasi-Newton optimization solves for appropriate "wind" forces to achieve the desire smoke behavior. However, this method is highly computationally intensive. Methods like [FL04], [SY05], [ZSY05], [YLYJ13] add external force term to the standard flow equations for controlling the fluid. Those methods have produced many impressive results. However, the animator can not directly control how well a particular target is approximated at a specific instant in time. Yi Hong et al. [HZQW10] design a control blue core (CBC) to control the animated fire. This method is effective to model fire propagation along complex curves or surfaces, but the formation rate of CBC restricted the simulation speed. A.Bangalore and D.H. House [BH12] use a set of imported curves drawn by an artist to control the convection currents of fire simulation for obtaining a desired shape. This method is easy to implement, but only can deal with stick figures as targets.

Target-driven force methods have obvious advantages because it can rapidly generate visually realistic and controllable flame animations. However, they also have two significant problems. On the one hand, these methods [FL04] [YLYJ13] lack a unified description for the inputted target that can be image, hand-drawn curve, geometric model, density or temperature field. So we have to customize difference solutions for different inputted data, which will limit their applications. On the other hand, the animator can not directly control how well a particular target is approximated at a specific instant in time.

The motivation of this work is inspired by the observation that the changes of temperature can directly affect the flame on the vision [WZTW14]. A novel target temperature driven method is proposed to efficiently control the animated flame, the steps as shown in Fig. 1. As shown In Fig. 1, the diverse descriptions of target flame are unified with temperature field based on the user-defined properties. An adaptive control force is calculated to restrict the degree of target-driven changes over the temperature field. A bidirectional-driven method is presented to generate accurate and smooth intermediate targets. In the step of temperature-based flame simulation, one N-S equation governs the changing of target-driven temperature field, with another N-S equation used to simulate the combusted flame details based on the generated temperature field. Different flame scenes are tested to verify the efficiency of our method.

2. Calculation of adaptive control force

Considering flame as one special kind of incompressible fluid, its motion is controlled by solving the Navier-Stokes (N-

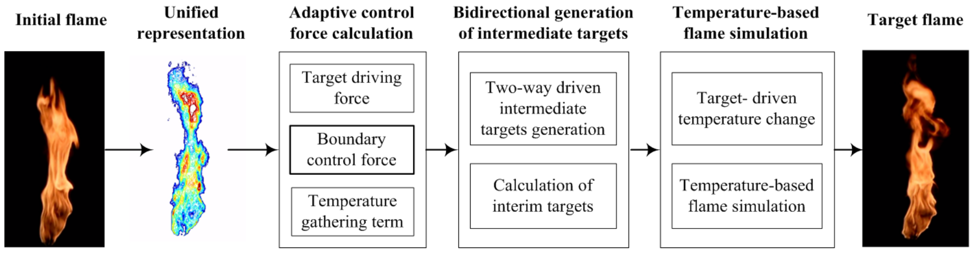

Figure 1: *Framework of the target temperature driven flame simulation method.*

S)equations:

$$u_t = -u \cdot \nabla u - \nabla p + f, \quad \nabla \cdot u = 0 \tag{1}$$

$$T_t = -u \cdot \nabla T. \tag{2}$$

where $u = u(x,t)$ is the speed field,$p = p(x,t)$ is the hydrostatic pressure, f is external force term, T_t is temperature field.

In order to get target-driven flame animation, our approach entails three modifications to the fluid flow equations present above. Based on the distinction between initial and target temperature field, a target driven force $F_{driving}(T,T^*)$, a boundary constraint force $F_{boundary}(T,T^*)$ and a temperature gathering term $G(T,T^*)$ are added to the governing equations, we rewrite Eq. (1) and (3) as:

$$\begin{aligned} u_t = & -u \cdot \nabla u - \nabla p + v_d F_{driving}(T,T^*) \\ & + v_b F_{boundary}(T,T^*) - v_a u, \end{aligned} \tag{3}$$

$$T_t = -u \cdot \nabla T + v_g G(T,T^*). \tag{4}$$

Where T is current temperature, T^* is the target temperature field, $v_a u$ is the momentum attenuation, which counteracts the increased momentum caused by the added external forces. v_d, v_b, v_a and v_g are the user-defined non-negative factors.

Follow Fattal and Dani Lischinski's [FL04] method [FL04], the target driving force is defined as:

$$F_{driving}(T,T^*) = \tilde{T} \frac{\nabla \tilde{T}^*}{\tilde{T}^*}. \tag{5}$$

A temperature gathering term [FL04] is employed to counteract numerical dissipation that causes temperature to diffuse, as shown:

$$G(T,T^*) = \nabla \cdot [T \tilde{T}^* \nabla (T - T^*)], \tag{6}$$

where $\nabla(T - T^*)$ is the error flux, $\tilde{T}$ and $\tilde{T}^*$ are the blurred current and targent temperature field with gaussian kernel, respectively.

A boundary control force is presented to restrict the flame to the appointed regions [YLYJ13]. The boundary constraint force is described as:

$$F_{boundary}(T,T^*) = \begin{cases} T \frac{|\phi_{boundary}(x)|}{dx}\left(-\frac{\nabla \phi_{boundary}(x)}{\|\nabla \phi_{boundary}(x)\|}\right), if \phi_{boundary}(x) > 0 \\ 0, \quad otherwise \end{cases} \tag{7}$$

where $\phi_{boundary}(x)$ is signed distance field.

2.1. Calculation of adaptive control force coefficients

To control the degree of target-driven change, an adaptive control force method is proposed to directly control the speed and degree of target-driven change by adjusting the target driving force coefficient v_d and boundary constraint force coefficient v_b. Let initial and target temperature field be A and B, respectively. And N steps is required from A change to B. The distinction between A and B is $Difference = \| A - B \|^2$. If the distinction between current state and next state is large, then the target-driven changing is too fast, the coefficients of control force are reduced adaptively. The pseudo code of this algorithm is shown in Alg. 1.

Algorithm 1 : Adaptive control force algorithm

Input: A, B, N.
Output: v_d, v_b.
Initialization: $Difference \leftarrow \|A - B\|^2$; $\varepsilon \leftarrow Difference/N$; $v_d \leftarrow 1$; $v_b \leftarrow 1$; $i \leftarrow 1$;
for *each time step* **do**
Compute $F_{driving}$, $F_{boundary}$;
$A_{i+1} \leftarrow A_i\left(v_d F_{driving}, v_b F_{boundary}\right)$;
$\varepsilon_i \leftarrow \|A_i - A_{i+1}\|^2$
  if $\varepsilon_i \leq \varepsilon - \Delta\varepsilon \,\|\, \varepsilon_i \geq \varepsilon + \Delta\varepsilon$ **then**
    Adjust v_d, v_b;
    Update A_{i+1}, ε_i;
  end if
$\mu_i \leftarrow \|A_{i+1} - B\|^2$
  if $i \leq N \,\&\&\, \mu_i \geq \varepsilon + \Delta\varepsilon$ **then**
    Save A_{i+1};
    $i++$;
  end if
end for

3. Bidirectional generation of intermediate target

In order to ensure the convergence of flame toward final target, we present a bidirectional-driven intermediate targets generation method to subdivide the global goal into plurality of partial targets. This method generates intermediate targets both from initial and target temperature filed. Take A and B as example, then we view A and B are each other source and target states. In each time step, we use adaptive control force to generate the next frame from both sides, A_i and B_i. If A_i and B_i are close enough, then we can link the generated frames from both side. The pseudo code of the bidirectional-driven algorithm is shown in Alg. 2.

Algorithm 2 :Bidirectional-driven intermediate targets generation

Input: A, B, N, M.
Output: $A_1, \ldots, A_i, B_i, \ldots, B_1$.
Initialization: $Difference \leftarrow \|A-B\|^2$; $\varepsilon \leftarrow Difference/N$; $i \leftarrow 1$;
for *each time step* **do**
// Compute A_i, B_i;
$A_i \leftarrow A_{i-1}\left(v_d F_{driving}, v_b F_{boundary}\right)$;
$B_i \leftarrow B_{i-1}\left(v_d F_{driving}, v_b F_{boundary}\right)$;
$\varepsilon_i \leftarrow \|A_i - B_i\|^2$;
  if $i \leq M$ && $\varepsilon_i \geq \varepsilon + \Delta\varepsilon$ **then**
    Save A_i, B_i;
    $i++$;
    Update A_i, B_i;
  end if
Return $A_1, \ldots, A_i, B_i, \ldots, B_1$.
end for

4. Temperature-based dynamic flame simulation

In our method, one N-S equations is used to describe the changing of temperature field. The generated temperature fields can be rendered directly by the Planck's law. To get richer flame detail, we view the temperature field as the distribution of combustion sources with different temperature, and use another N-S equations to simulate the flame combustion detail. In our implementation, the conjugate gradient projection [NFJ02] and MacCormack [SFK*08] advection solver are applied to decrease the numerical diffusion. We also employ divergence modification term [SKWL13] into the projection step to control expanding and compressing of flame.

In this work, we use ray-casting method to render 3D flame, the simulation results for two N-S equations as shown in Fig. 2. In Fig. 2 , (a) is the target-driven temperature field animation, and (b) is combustion flame simulation based on generated temperature field. It can be seen that our method preserves more details of flame animation, and it's more flexible for user to control the animated flame.

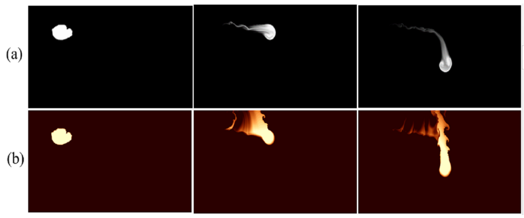

Figure 2: *Simulation results for two N-S equations.*

5. Results and discussion

Different target flame scenes were tested to verify our approach. Experiments were performed on a machine with dual core CPU 2.66GHz, 2.67GHz and 2GB of memory. We developed our approach with C++ and Open GL.

Fig. 3 shows the target-driven flame animation results when inputting images are the initial and target flames. In Fig. 3 , the first row shows the initial and target images, which come from dataset Torch [Art05]; the second row shows the flame animation results obtained by our method. It is shown that our method successfully achieved smooth animation from source toward target images.

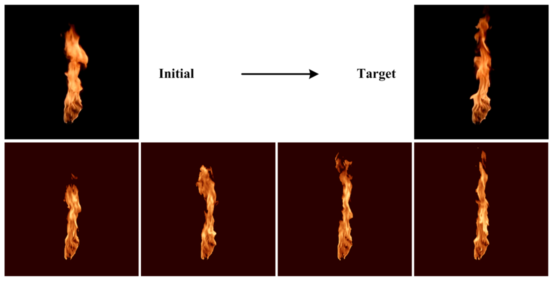

Figure 3: *Flame animation when inputting image is target.*

Fig. 4 shows the flame animation results when the initial and target flame are 3D temperature field. In Fig. 4, the first row is the visual hull representation of measured 3D temperature fields from an alcohol lamp flame; the second row presents the rendered results of temperature field animation sequence generated by our method. The results shows that our method restores the dynamic information between the reconstructed frames, and interpolates the reconstructed field data with the support of physical equations.

Fig. 5 shows the flame change results from a geometrical model of "elephant" toward "horse". We used a simple temperature field initialization method which assigns the temperature of voxels inside a model with a fixed value. The results show that our method is effective when inputted 3D geometrical models are target flames.

Fig. 6 shows the flame animation sequence from a word "FIRE" to "EG2015" obtained by our method. It can be seen

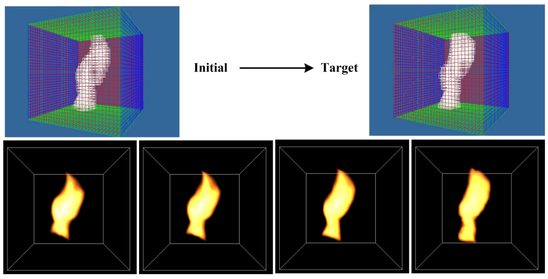

Figure 4: *Flame animation when inputting temperature field as target.*

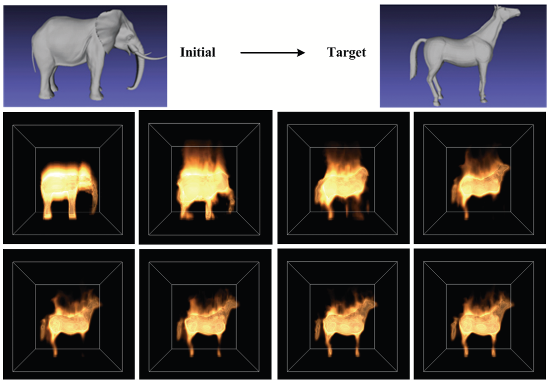

Figure 5: *Flame animation from "elephant" to "horse".*

that the change from initial to target state is uniform and smooth, and combustion details were preserved in flame animation.

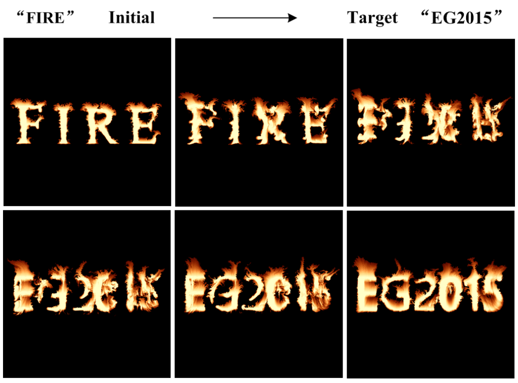

Figure 6: *Flame animation from "FIRE" to "EG2015".*

6. Conclusions and future work

In this paper we present a target temperature driven flame animation method to unify different target flames into the temperature field. We use self-adaptive control force and bidirectional iterative method to directly control how well a particular target is approximated at a specific instant in time. We tested our method with different forms of target flame: image, geometry model and temperature field. The experiment result shows that our self-adaptive method achieved direct control of convergence toward target flame. The bidirectional iterative method decreased the numerical diffusion of simulation and ensured the convergence toward final target.

7. Acknowledgments

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