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Enhanced Details for Smoke Animation

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***Abstract*—This paper introduces a novel method, called enhanced advection, for smoke simulation. The method delays dissipation introduced by interpolation of semi-Lagrangian advection. Enhanced advection can be implemented easily by two steps. First, advect the fluid field by semi-Lagrangian advection. Then convolve it with modified Laplace kernel for enhancement. This enhancement could compensate for the blurring effect of semi-Lagrangian advection, so as to reduce blurring and at last delay dissipation. We discuss how to choose a modified Laplace kernel for a certain kind of fluid field. Enhanced advection preserves details significantly, when it is used to enhance the velocity field of smoke's self-advection. Besides, we demonstrate the benefits of this approach by advecting smoke density and image.**

I. Introduction

In the recent past, researchers use incompressible Navier-Stokes equations to describe various fluid phenomena in computer graphics[13]. Incompressible Euler equations, the inviscid and incompressible form of Navier-Stokes equations[1], are more commonly used to describe an ideal fluid with no viscosity. Under initial conditions, solutions for that equations generate physically based fluid motions. This is done by a splitting strategy[11] which separates out advection part, body forces part, and projection part from the fluid equations. In each time interval, first advect quantity through velocity field, then add body forces into it, at last project the velocity field to a divergence-free component so as to conserve volume. In the advection part, Stam[11] introduced semi-Lagrangian advection to ensure stability. However, its interpolation step tends to do an averaging operation, which leads to numerical dissipation, and at last loses high frequency features of the fluid, such as vortices and turbulences.

So how to deal with losing of high frequency details? Considerable techniques have been developed to fix this problem. One strategy is to increase computing accuracy, i.e. using higher order interpolations such as monotonic cubic interpolation[3] and BFECC[6], or using higher resolution grids like octree [8]. These methods increase the fidelity of animation. But they either consume more CPU and memory resources or increase the complexity of data structures. Another strategy is to compensate for the error of interpolation by adding noise. It comes into two steps: looking for where to add noise, and choosing a kind of noise to fill in. Stam[12], Lamorlette[7], Rasmussen[10] and Kim[5] choose Kolmologorov noise, and Bridson[2] uses curl noise. Meanwhile, Kim[5] and Narain[9] described how to find places where details are missed. This strategy brings details of fluid simulations visually but nonphysically, because the details added are noises that bring high frequency signals together with artifical effects.

These two strategies are both based on generating new details, while our method focuses on delaying dissipation. We try to preserve existing details, and let them dissipate slower, rather than replace them by artificial details. The advantages of doing this are that the details would behave more naturally and computing resources could be saved by using existing details rather than creating new ones. So, how to delay dissipation? As mentioned above, interpolation step of semi-Lagrangian advection leads to dissipation such as high frequency features missing. This dissipation smooths out details visually. Thus to delay dissipation is to let blurring happen, but to find an inverse process to compensate for the lost. According to image processing theory[4], details of image could be emphasized by enhancing, and be smoothed out by blurring. So enhancing could be taken as the inverse process of dissipation.

Our advection iterates like this: input a field, semi-Lagrangian advect it, enhance the field, and re-input the field into next iteration. This process could preserve details that still exist after semi-Lagrangian step. Because after enhancement, details are strengthened, and extra energy would be decreased by semi-Lagrangian step in the next iteration, and at last maintains a constant energy. The total energy change behaves like decrease, increase, decrease, increase and so on, while the standard semi-Lagrangian advection behaves like decrease, decrease, decrease and so on. So the latter ultimately smooths out most details, while the former delays dissipation.

In particular, this paper claims the following novel contributions over previous work:

- A practical implementation of enhancing fluid field in advection step for delaying dissipation.
- A feasible example of treating fluid field as image and dealing with it by image processing.

II. Enhanced Advection

In order to delay dissipation, we compensate for the blurring effect by enhancing fluid field, see Figure 1. In the n-th time interval, there is an input field F_I^n, we advect it using standard semi-Lagrangian method and get F_{sL}^n:

$$F_{sL}^n = L(F_I^n) \tag{1}$$

Then enhance F_{sL}^n and get F_E^n:

$$F_E^n = E(F_{sL}^n) = E[L(F_I^n)] \tag{2}$$

At last, output F_E^n as F_O^n, then input F_O^n to the next time interval:

$$F_I^{n+1} = F_O^n = F_E^n \tag{3}$$

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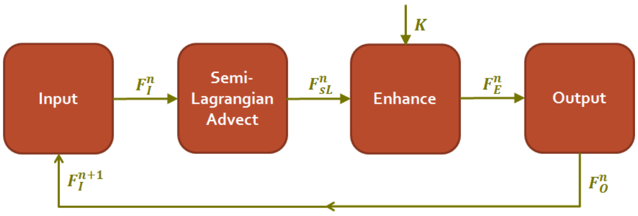

Fig. 1. Process of enhanced advection. First semi-Lagrangian advect the field, then enhance it with kernel K, at last input the result to the next iteration.

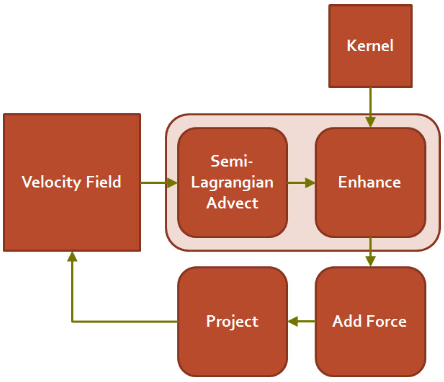

Fig. 2. Solver with an enhanced advection. Replace semi-Lagrangian advection in standard solver with our enhanced advection for velocity field.

For semi-Lagrangian advection $F_{sL}^n = L(F_I^n)$, it back traces each point in the field through velocity field over a time interval, obtains an old location, calculates its value by interpolating the field of previous iteration, then sets the result as the new value.

For enhancement $F_E^n = E(F_{sL}^n)$, we convolve the field with a modified Laplace kernel K in space domain and then add the result to F_{sL}^n, as the inverse process of blurring:

$$E(F_{sL}^n) = F_{sL}^n * K + F_{sL}^n \tag{4}$$

According to image processing theory[4], Laplace kernel represents a differential operation that finds out the sharply changing regions of F_{sL}^n, and returns their variations. After adding the variations to F_{sL}^n, the original field is enhanced. How to choose a modified Laplace kernel will be discussed in the next section. A lot of experiments[4] show that enhancing an image with Laplace kernel emphasizes its details and forms a "clearer" result. In this paper, we treat fluid field as image. Figure 5 shows the fluid details are enhanced using our advection.

The enhanced advection could be applied to solvers that solve Navier-Stokes equations, illustrated by Figure 2.

For each time interval, we firstly advect velocity field using semi-Lagrangian method, then enhance its output with a modified Laplace kernel, add force to the field, and ensure incompressibility by projection. Then this incompressive velocity field is finally evolved into next iteration.

III. Modified Laplace Kernel

The modified Laplace kernel K derives from standard Laplace kernel with a slightly change, because it is inappropriate to apply the standard kernel to fluid field whose distribution of values varies a lot. Here is an example; we enhance a field with modified Laplace kernel,

$$\begin{bmatrix} a_1 & a_2 & a_3 \\ a_4 & a_5 & a_6 \\ a_7 & a_8 & a_9 \end{bmatrix} * \begin{bmatrix} 0 & -l & 0 \\ -l & 4l & -l \\ 0 & -l & 0 \end{bmatrix} + \begin{bmatrix} a_1 & a_2 & a_3 \\ a_4 & a_5 & a_6 \\ a_7 & a_8 & a_9 \end{bmatrix}$$

After enhancing, a_5 would change to

$$\begin{aligned} a_5' &= a_5 + l * [(a_5 - a_2) + (a_5 - a_4) + (a_5 - a_6) + (a_5 - a_8)] \\ &= a_5 + l * \nabla a_5 \end{aligned}$$

For fluid field whose value a_5 is commonly small such as density field that varies from 0 to 1, and ∇a_5 is also small, then $\nabla a_5 \approx a_5$. If $l = 1$ which is standard Laplace kernel, then $a_5' \approx 2 * a_5$. Thus applying Laplace kernel once would double or greatly change the values of the whole field, and ultimately disorder it. In this case, it is wise to apply a small value to l such as 0.05, so that $l * \nabla a_5 < a_5$, then $a_5' \approx a_5$, the field maintains its structure and enhances details at the same time.

IV. Results and Analysis

Enhanced advection can advect many kinds of fields. Here we apply it to smoke density advection, image advection and velocity self-advection.

Figure 3 shows the advection of a square density field along an up-going velocity field on 64×128 grids. The left two images show initial locations of density field. The upper four are advected using standard semi-Lagrangian advection where the blurring effect is significant on the top and bottom edge of the density square and the mass dissipates away. The lower four images are with enhanced advection, where the blurring effect is largely decreased and the mass could stay close.

Figure 4 shows the advection of a 64×64 image along the same up-going velocity field on 128×256 grids. This example illustrates that our enhanced advection can delay dissipation of details. The left two images show initial locations of the image. The upper four are advected using standard semi-Lagrangian advection. After a few iterations, the image is smoothed out, and details are blurred due to the averaging operation in semi-Lagrangian advection. The lower four images are with enhanced advection. Compared with the lower first image, the lower fourth one does blur a little after several iterations. But in the same column, the lower image is "clearer" that the upper one and features of the lower image can be identified. Details do dissipate, but dissipate slower, so the enhanced advection successfully delays dissipation.

Figure 5 and 6 are solutions of fluid solvers that animate smoke on 64×128 grids. The left three images show initial locations of density field. For the upper nine images, we use s-tandard semi-Lagrangian method for velocity's self-advection, while the lower two rows are with enhanced advection, $l = 0.03$ for the middle nine, and $l = 0.05$ for the bottom nine. Figure 6 places a solid sphere in the smoke's up-going path, and figure 5 does not. As these images illustrate, smoke with standard semi-Lagrangian advection behaves smoother than

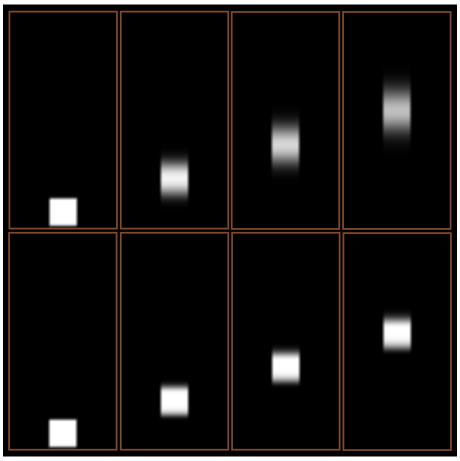

Fig. 3. Advection of a square density field along an up-going velocity field on 64×128 grids. The left two images show initial locations. The upper four are advected using standard semi-Lagrangian method, while the lower four are with enhanced advection(l=0.05).

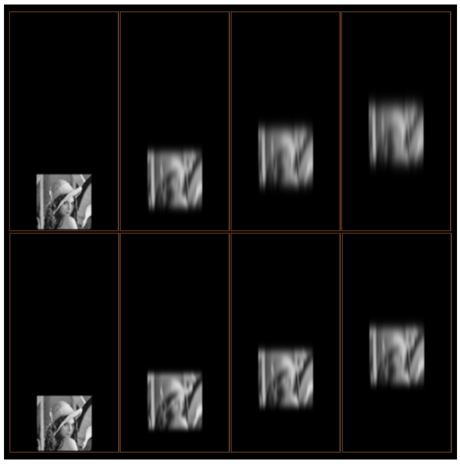

Fig. 4. Advection of a 64×64 image along the same up-going velocity field as Figure řefBoxDens on 128×256 grids. The left two images show initial locations. The upper four are advected using standard semi-Lagrangian method, while the lower four are with enhanced advection(l=0.05).

that with enhanced advection. In the starting iterations of the upper scene(the 3rd image form the left) details have already been lost. As iteration goes on, more details are smoothed out, and that results in significant numerical dissipation. In contrast, the lower two scenes preserve details at the beginning. Then these details are enhanced step by step, and blurring effect is compensated by this enhancement along, so that dissipation of details is delayed.

However, a small l(0.03) maintains the smoke shape but enhanced details are not that clear, and a large l(0.05) contributes to clear details in the beginning(the 3rd and 4th images from the left) but the smoke edges are unnatural at last(the 7th to 9th images from the left). This may be caused by the modified Laplace kernel. Larger l brings more obvious enhancement effect. As the kernel convolves with fluid field again and again, a slight change in the beginning affects the field tremendously in the end. When iterating with a smaller l, the impact of the initial slight change is limited. So, a better kernel that both maintains shape and clearly enhances detail may solve this problem. We could use machine learning technologies to generate this kernel in the future.

V. Future Work

The enhancement in our enhanced advection is done by convolution, which consumes a lot of computing resources and time in the space domain. According to signal processing, this could be done by multiplication in the frequency domain using FFT. Since multiplication is cheaper than convolution and there is a great amount of stable and fast implementations of FFT, it makes sense to port our enhanced advection to frequency domain.

In Section III, we've discussed how to choose a modified Laplace kernel that is fit for a certain kind of fluid field. But this is done manually and the result needs to be tuned. We seek to find a way that generates a suitable kernel automatically. Besides, it is tempting to introduce more techniques of signal processing or image processing to fluid animation. Our experiments in this paper show the connection of these two fields and the feasibility of this introduction.

Acknowledgment

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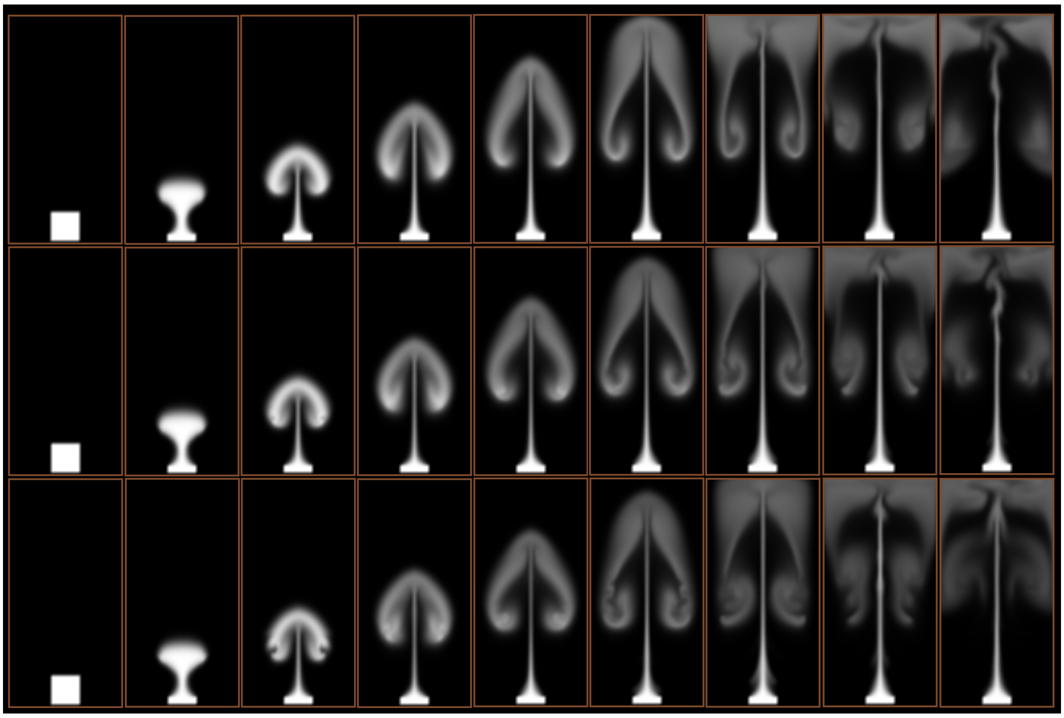

Fig. 5. Solutions of fluid solvers that animate smoke on 64×128 grids. The left three images show initial locations of density field. In the upper nine images, we use standard semi-Lagrangian method for velocity's self-advection, while the lower two rows are with enhanced advection, $l = 0.03$ for the middle nine, and $l = 0.05$ for the bottom nine. No obstacles are placed in the scene.

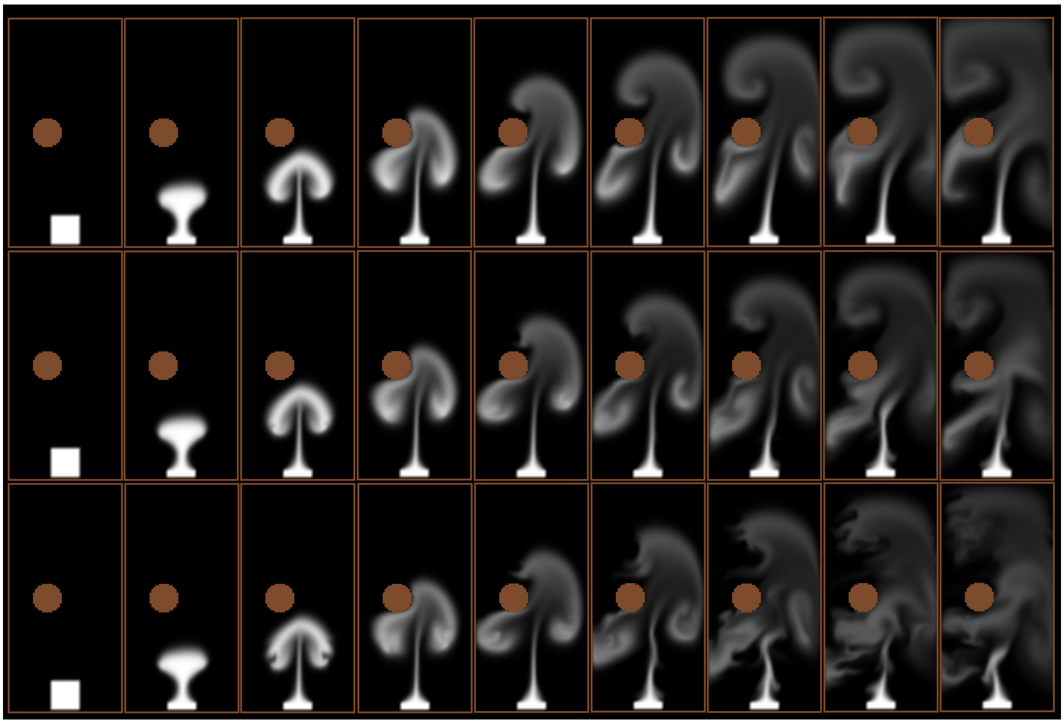

Fig. 6. Solutions of fluid solvers that animate smoke on 64×128 grids. The left three images show initial locations of density field. In the upper nine images, we use standard semi-Lagrangian method for velocity's self-advection, while the lower two rows are with enhanced advection, $l = 0.03$ for the middle nine, and $l = 0.05$ for the bottom nine. A solid sphere is placed in the scene.