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Technical Section

A unified smoke control method based on signed distance field

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ABSTRACT

Smoke control involves shape and path. A unified framework able to deal with both of them will enable animators to manipulate the shape and path of smoke animation more effectively. In this paper, we develop such a unified framework. With our approach, path control, shape control, and mixed control of both can be handled satisfactorily in the same framework. In order to develop this framework, we use a signed distance field to provide three control forces: path control force, boundary control force, and shape control force based on medial axis point clouds. The path control force makes the smoke move along the appointed route, the boundary control force keeps the smoke moving through specified regions only, and the shape control force enables the smoke to form various given shapes. The boundary control force and the shape control force are two novel control forces developed in this paper. To make the smoke form the target shape more accurately, we develop an adaptive strategy to adjust the divergence field. We also employ a new hybrid vortex particle scheme to enhance the turbulence flow details. The examples given in this paper indicate that our proposed framework is advantageous over the existing shape control approaches and path control algorithms, and a naive combination of the two.

1. Introduction

The special effects industry has witnessed a greater emphasis on the use of physically based fluid animation to reproduce realistic fluid effects. Besides realism, the ability to control the fluid behavior is also very important and challenging. Smoke control is an important topic of fluid control. It has drawn the attention of many researchers, and some control algorithms for special effects simulation have been developed. These algorithms can be roughly classified into two groups: path control and shape control. Path control algorithms enable smoke to follow given paths, and shape control methods make smoke form the target shapes.

Since smoke control involves both shape and path, a unified framework able to tackle both of them will enable animators to manipulate the shape and path of smoke animation more effectively. Such a unified framework has not been developed, and the work carried out in this paper indicates that it cannot be achieved by a simple combination of the existing shape control methods and path control algorithms, even with the modifications given in Section 4 of this paper.

In order to address this issue, we propose a unified control algorithm to integrate shape control, path control, and mixed control into the same framework. Our control algorithm translates 3D surface geometry models and space curves representing paths into a signed distance field. Through the signed distance field, we provide two novel control forces: boundary control force and shape control force based on medial axis point clouds. The boundary control force restricts the smoke to the appointed regions, and the shape control force is used to drive the smoke into given shapes. In addition, we use the path control force presented by Kim et al. [1]. In order to improve the accuracy of shape control, we developed an adaptive strategy for divergence field adjustment. By combining the vortex particle method [2] and the Langevin particle method [3] together, we design a hybrid vortex particle scheme to enhance the turbulent flow details. This hybrid vortex particle can freely switch between two identities of vortex particles and Langevin particles depending on its spatial location.

The contributions of our work include: (a) a unified control framework, which integrates path control, shape control, and mixed control of both, (b) two new control forces, i.e., the boundary force restricting the smoke to appointed regions and the shape control force making the smoke form target shapes, (c) an adaptive strategy for the divergence field adjustment used in the shape control, (d) a hybrid vortex particle scheme to enhance turbulent flow details.

Our approach gives a solution to the problem of mixed control of shape and path which has not been addressed by the existing approaches. With our proposed approach, the shape and path of smoke animation can be controlled more effectively.

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Table 1
Performance comparison.

Examples	Grid size	Time for simulation per step (s)	Time for computing control forces (s)	Percentage (%)
Fig. 8	$128 \times 128 \times 128$	24.9	0.308	1.24
Fig. 11	$128 \times 128 \times 128$	25.4	0.337	1.33
Fig. 12	$64 \times 64 \times 64$	2.4	0.058	2.42
Fig. 13	$128 \times 128 \times 128$	26.5	0.508	1.92

The rest of the paper is organized as follows. Section 2 provides a brief overview of previous related work. In Section 3, the adopted algorithm is elaborated. Section 4 presents the experimental results. Finally in Section 5, the conclusion of the present work is drawn and a proposal for future work is given. Table 1

2. Related work

In 1997, Foster and Metaxas [4] introduced embedded controllers which enable animators to control fluid movement. Based on this algorithm, Foster and Fedkiw [5] proposed one modified algorithm, in which 3D parametric space curves are sampled to generate oriented points, and the velocity of these local points is further modified to control fluid movement. Three years later, Rasmussen et al. [6] presented a control algorithm based on particles, which were set accordingly to generate either hard or soft control to achieve user desired animation effects. Pighin et al. [7] introduced a new representation, radial basis functions carried by moving particles, to express fluids, and modified the moving track of particles to realize the control of fluid. Schpok et al. [8] proposed another algorithm which automatically extracts simulation features like vortices and uniform advection, and enabled users to manipulate and modify these features to realize fluid animation control. In addition, other researchers such as Angelidis et al. [9,10], and Weißsmann et al. [11] all used smoke control algorithms based on vortex filaments and rings. All the above studies provided a direct control algorithm, but failed in making the fluid form target shapes or follow specified paths.

In order to solve this problem, Treuille et al. [12] developed a control algorithm based on user-specified keyframes, which determines control forces through a continuous quasi-Newton optimization. By applying this algorithm, they succeeded in making smoke form any possible target shape. However, this approach is time-consuming. Therefore, Mc-Namara et al. [13] further improved it by adopting an adjoint method. Unfortunately, the adjoint method still requires much computation and storage. Although directly exerting a control force on fluids without considering optimization fails to ensure the fluid form a target shape at a specific moment in time, it is enforced in an easy manner and saves much computation expense as indicated in the existing literature, notably those by Fattal et al. [14], Hong and Kim [15], Shi and Yu [16,17]. Similar to these research studies, we also developed several control forces to make the fluid match various targets. Since the scaling parameter and the direction of our control forces do not change over time, their computation can be performed only once in the whole simulation process. Next to the algorithms based on Eulerian approaches [14–17], particle based Lagrangian methods, such as smooth particle hydrodynamics (SPH) introduced by Desbrun and Gascuel [18], are also very popular in computer graphics. Thürey et al. [19] used control particles based on SPH to drive fluid to a target shape while preserving small fluid details. The work focuses more on liquid rather than smoke. Liu et al. [20] proposed a cloud shape control method based on the ellipsoidal-blob approximations of 3D models. Compared to shape control, path control has not been addressed so much by researchers. Credit in this field goes to Kim et al. [1], who achieved path control of smoke animation by using a linear feedback control method. We are unaware of any work which integrates shape control and path control to obtain smoke animation. In this paper, we will address this issue.

3. Algorithm

Developed from Eulerian approaches, our control algorithm consists of two parts, pre-computation and simulation loop. First, we introduce the basic fluid solver in Section 3.1. Next, we investigate the precomputation in Section 3.2 with a main focus on the calculations of the signed distance field and the scaling parameter, and the determination of the direction of our control forces. Finally, we discuss the simulation loop in Section 3.3.

3.1. Basic fluid solver

The incompressible Navier–Stokes equations can be written as

$$\mathbf{u}_t + (\mathbf{u} \cdot \nabla)\mathbf{u} + \frac{\nabla p}{\rho} = \mu \nabla^2 \mathbf{u} + \mathbf{f}, \tag{1}$$

$$\nabla \cdot \mathbf{u} = 0, \tag{2}$$

where $\mathbf{u}$ is the fluid velocity, p is the pressure, ρ is the fluid density and μ is the viscosity. The term $\mathbf{f}$ represents external forces including gravity, buoyancy, and our three control forces: the boundary control force, the shape control force based on medial axis point clouds, and the path control force. In order to determine the unknowns such as pressure and velocity in the above fluid equations, Eqs. (1) and (2) are discretized on a regular Cartesian grid by applying the staggered MAC-grid arrangement for unknowns like pressure and velocity. We employ the methods presented in Refs. [21,22] to solve Eqs. (1) and (2).

3.2. Precomputation

Precomputation includes determination of the signed distance field and the three control forces. Since the signed distance field is a prerequisite of determining the three control forces, we investigate it first.

3.2.1. Computation of signed distance field

As discussed above, our fluid control can be divided into shape control, path control and mixed control of shape and path. The signed distance field is different for different fluid controls. Therefore, we will discuss below how to determine the signed distance field for each of the three controls.

For shape control, we load CG models, adopt the signed distance computing method proposed by Bærentzen et al. [23], and obtain the following signed distance function:

$$\phi_{shape}(\mathbf{x}) = \begin{cases} -d_t(\mathbf{x}) & \text{if } \mathbf{x} \text{ is inside the model,} \\ d_t(\mathbf{x}) & \text{otherwise,} \end{cases} \tag{3}$$

where $d_t(\mathbf{x})$ expresses the shortest Euclidean distance from the spatial point to the triangle meshes constituting the target shape. Note that, the CG model must be a closed mesh.

For path control, our algorithm uses a NURBS curve to represent the curve constraining the bulk flow path, which is similar to