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自然現象的模擬與顯像技術之研究（I）

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摘要

長久以來對具有複雜表面的液體建模一直是艱鉅的挑戰，液體的模擬通常利用粒子系統或分子動力學的方法，這些方法需要非常大量的計算時間與儲存空間。除此之外，目前也沒有直接的方法由粒子資料建立平滑的液體表面。我們提出一個結合 VOF (Volume Tracking Method)與SPH (Smoothed Particle Hydrodynamics) 來對高度變形的流體表面建模的方法。並利用一包含三個步驟的方法來將粒子體積轉換成液體容積(Volume fraction)資料並利用marching cube方式建立液體表面。
關鍵字: 液體模擬，流體力學，水花，粒子系統

Abstract

Modeling liquid with complex surfaces is a great challenge in computer graphics. These liquids are often simulated by particle systems or molecular dynamics which requires a huge amount of computational cost and storage. Besides, there is no straightforward way to produce a smooth liquid surface from these particle skeletons. We proposed a hybrid approach combining the volume tracking method and smoothed particle hydrodynamics (SPH) to model liquids with highly deformable surfaces. A three steps method is used to convert the particle volumes into the volume fractions and an iso-surface extraction method for constructing the liquid surface.

Keywords: Liquid simulation, Fluid dynamics, Splashing, Particle dynamics.

1 Introduction

Producing realistic liquid animation is a great challenge in compute graphics due to the complex dynamics of flows.

We propose a method incorporating the volume tracking and smoothed particle dynamics to model complex fluid motion. Fluid surface is tracked by volume fractions and evolves over space and time. Particles are only generated in the area where the fluid motion is drastic, for example, when an object impacts the fluid surface. These particles move freely until they run into the volume fractions and are absorbed. The motions of particles are governed by smoothed particle hydrodynamics (SPH) [13]. Smoothed particles represent sample points that enable the approximation of the values and derivatives of local physical quantities inside a medium. SPH is favored than particle systems [17], which do not model inter-particle forces, and molecular dynamics [6], which does not model the coupling of pressure and velocity characterizing a real fluid.

To produce the smooth surface of realistic liquid, a three steps method that incorporates the interpolation of the original volume fraction, the conversion of particles to volume fractions, and the extraction of iso-surface is proposed. The volume fractions are interpolated only when rendering the liquid surface, they are not used in the future simulation process.

2 Previous Work

Early graphics work concentrated on modeling just the surface of the water body as a parametric function that could be animated over time to simulate wave transport. It ranges from Fourier synthesis methods [12] to parametric representation of the water surfaces [18].

O'Brien et al. [16] and Mould [15] used a spray particle system to model water drops which have broken free of the main body of fluid.

Globular dynamics, or molecular dynamics, is a connected particle system which uses a dynamics model for interactions between particles and with other environmental constraints. In [1], smoothed particle hydrodynamics (SPH) is modified to simulating high deformable bodies. Stora et al. [20] extended SPH to include a viscosity parameter depending upon temperature for each particle.

To provide a physical foundation for general fluid animation, Foster et al. [5] utilized the work of [7] in developing a 3-D Navier-Stokes methodology for the realistic animation of liquids, and the local surface elevation was computed using the vertical component of the fluid motion and the horizontal convection of the surface evaluation from adjacent cell columns. A semi-Lagrangian"stable fluids" treatment was introduced by Stam [19] in order to allow the use of significantly larger time steps without hindering the stability. Such a semi-Lagrangian advection has been used widely in recent researches [4, 2, 3, 10]. In Foster et al. [4], a hybrid liquid volume model for generating the geometry mode was used that combines an implicit surface generated from the level set method (LSM) and massless marker particles.

In [9], the problem of free surface of fluids was treated as a transport problem of volume fractions, and the high-resolution Marching Cubes algorithm [11] was used to extract the iso-surface.

To render the liquid, Watt et al. [21] used two-passed backward beam tracing to render caustics of polygon liquid surface. Photon map [8] can handle nonhomogeneous media and anisotropic scattering. It can simulate effects such as multiple scattering and volume caustics for both polygonal models and implicit surfaces.

3 Modeling Highly-Deformable Liquid

Figure 1 illustrates the computation flow in a timestep. Initially the physical domain is partitioned by a computation grid The fluid dynamic solver then calculates the velocities and pressures for the next time step. The volume fractions in current time step and the new obtained velocities are used to convect the fluid volume fractions. Particles are introduced in the area where the fluid surface is potentially exposed to large deformations, and the dynamics of particles is governed by smoothed particle hydrodynamics (SPH).

The fluid dynamics are solved by the marker and cell (MAC) method [7]. To track the free surface, the initial (known) fluid interface geometry is used to compute fluid volume fractions in each computational cell. Interfaces between liquid and air are subsequently tracked by evolving fluid volumes in time with the solution of a standard convection equation.

To compensate the motion under-resolved by the resolution of the Eulerian grid, we seed Lagrangian particles near the region in the flow field having drastic motion. Particles are generated only in the surface cells meeting any one of following conditions:

$$u\delta t > \gamma\delta x, \quad v\delta t > \gamma\delta y, \quad w\delta t > \gamma\delta z \quad (1)$$

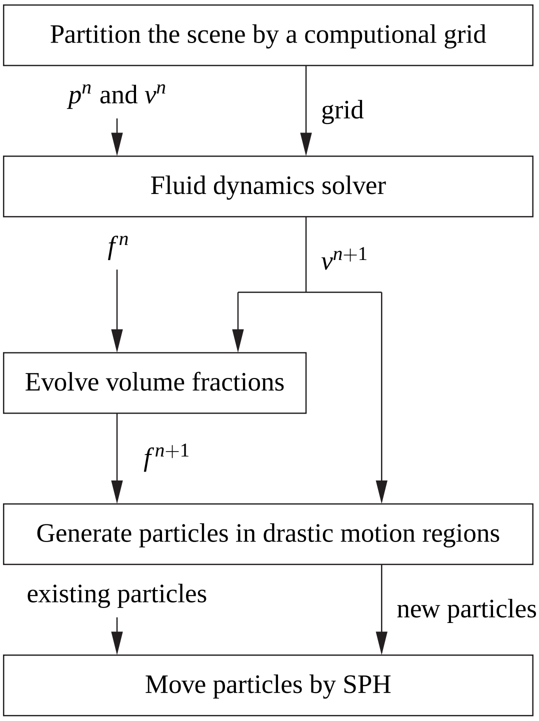


Figure 1: Simulation flowchart.

where δx, δy, δz are cell sizes, δt is the time step, u, u, w are velocity components, and $\gamma \in (0,1)$ is the convection threshold.

To seed particles in the a surface cell, the interface in the cell must be reconstructed. We approximate the interface for seeding particles by a Piecewise Linear Interface Calculation (PLIC) method [22] and particles is randomly placed below the interface constructed by the PLIC method.

Initially, each particle carries a fixed mass and will not split or merge with other particles. The total volume of particles in a cell should not excced the volume of liquid in the cell indicated by the volume fraction. The mass carried by a particle can be arbitrarily defined. The less the mass, the more particles are necessary to approximate the same volume of liquid in the cell.

Once the particles are generated, they may escape the liquid surface and their trajectories and acceleration are governed by Smoothed Particle Hydrodynamics (SPH). We use the extended SPH method proposed by Morris et. al [14] for controlling the tranectories and accelerations of the particles.

The liquid in the simulation is represented by both volume fractions and smoothed particles. To produce the smooth surface of realistic liquid, a three steps method is proposed as following:

1. Interpolate the original volume fractions.

2. Convert particle volumes to volume fractions.

3. Iso-surface extraction.

Figure 2 illustrates the rendering procedure.

First, the original volume fractions (the ”coarse” density volume) are interpolated adaptively to produce higher resolution volume fractions(the ”higher” density volume) based on the position of smoothed particles.

Then, the volumes of smoothed particles are converted to volume fractions of the occupying cells in the ”fine” density volume. For cells where both volume fractions and smoothed particles exist, the converted volume fractions of smoothed particles always predominate under the assumption that particles should give accurate values in the regions with drastic fluid motion, since they tracks the fluid surface independent of the resolution of the computational grid. Smoothed particles are eliminated when they fall back into the liquid volume or outside the simulation domain.

Finally, an iso-surface extraction alogrithm (Marching Cubes [11]) is employed to extract a smooth surface.

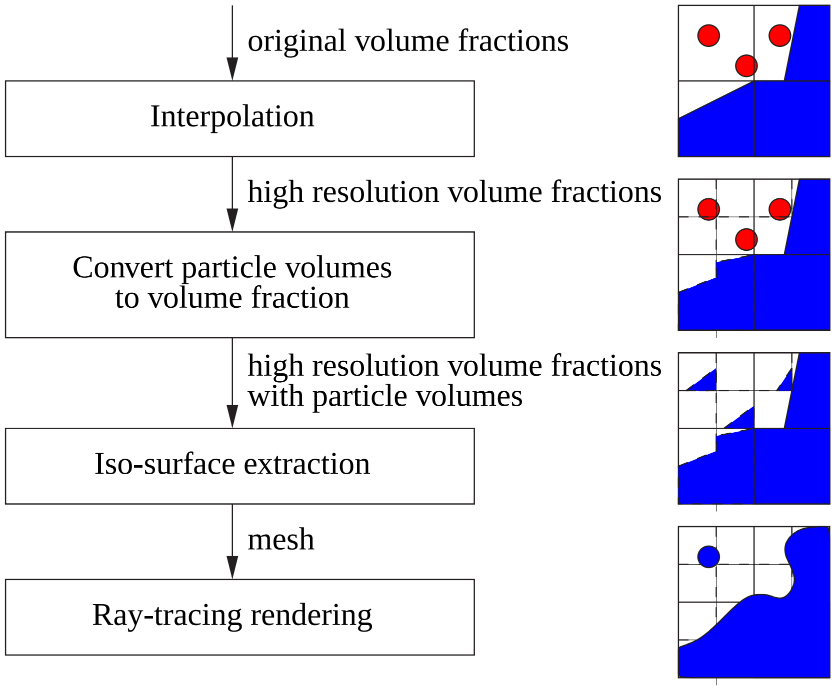


Figure 2: Rendering flowchart.

The interpolated volume fractions are used only when rendering the liquid surface, they are not used in the future simulation process. Figure 3 demonstrates the surface constructed in each step.

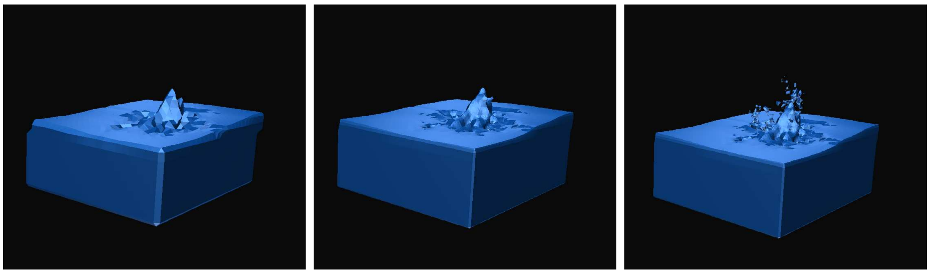
4 Results

All images are rendered by a ray-tracer at the resolution of 640×480 pixels. All computation and rendering are performed on a PC armed with an AMD 1000 MHz processor and 512 MB RAM.

Figure 4(a)-(c) shows an orange liquid is discharge from a pipe at the speed of 1.8 into a container of size $6 \times 5 \times 5$ with resolution $30 \times 24 \times 24$ at roughly the 42th, 92th and 124th minute of the simulation.

Figure 5(a)-(c) show a sequence of selected frames of throwing a sphere into a tank of water at the 79th, 118th, and 138th minute of the simulation, respectively. The sphere has a initial horizontal 1.1 and vertical velocity of -0.8. The size of the computational grid is 8 in width and height and 12 in depth. The computation time depends upon the complexity of the scene and varies substantially throughout the simulation, more time is needed to reach the second frame when the sphere just hits the water surface. However, the computation time is short after the water surface is getting calm.

Figure 6 shows a sequence of selected frames of throwing a cube. The cube has a initial horizontal and vertical velocity of -2.5. The size of the computational grid is 7 in width and height and 6 in depth. The computation time for each frame is 30 seconds in average.



(a) Original volume fractions (b) Interpolated volume fractions (c) Converting particles to volume fractions

Figure 3: Process to form a smooth fluid surface

(a) Frame 16 (b) Frame 32 (c) Frame 48

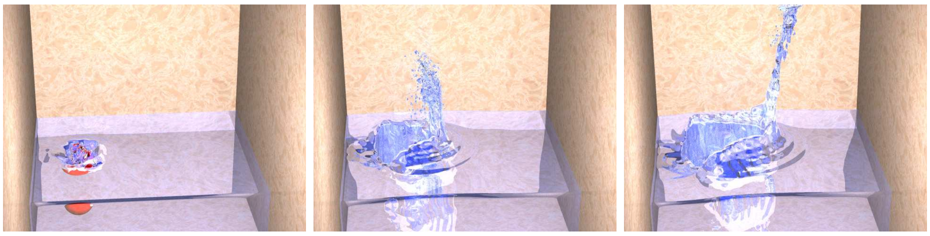
Figure 4: Liquid discharged from a pipe ($30 \times 24 \times 24$ gridl cells)

The calculation time grows more than cubicly with the resolution of the grid. When the cell size decreases, the simulation time-step also need to decrease to satisfy the CFL condition and therefore more cycles are needed for a frame than in the grid of a lower resolution.

5 Conclusion

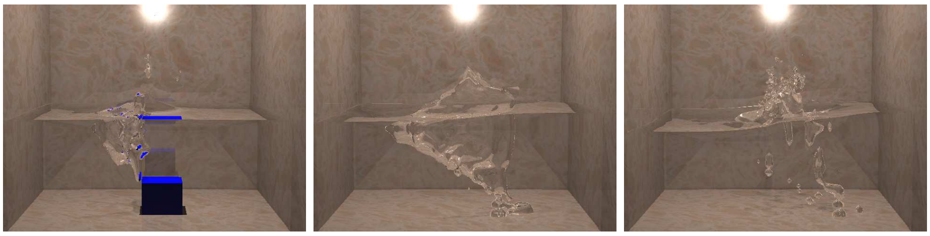
To model liquid with dramatic deformation, a hybrid approach combining the volume tracking method and smoothed particle hydrodynamics (SPH) has been proposed. The 3-D Navier-Stokes equations are solved by the marker-and-cell (MAC) method and a density volume representing the liquid is evolved over time and space by the volume-of-fluid (VOF) method. To add fidelity of the particle trajectory, the dynamics of the particles are governed by SPH, while previous methods treated splash as interaction-less particles. A smooth implicit surface is extracted from the liquid density volume which interpolates the volume fractions in a higher resolution and converts particle volumes to volume fractions.

The high realism of the animation is enabled by the coupling of pressure and velocity in 3-D Navier-Stokes equations. Under-resolved subtle features are captured by smoothed particles that are adequately placed in the neighborhood of the highly-deformable regions. SPH provide more physically-correct particle motions because it approximates the Navier-Stokes equations. Consequently, it can continue to take into account the coupling between pressure and velocity terms, which is lacked in other particle simulation methods.



(a) Frame 2 (b) Frame 12 (c) Frame 24

Figure 5: Selected frames of throwing a shpere into a tank of water ($32 \times 32 \times 48$ grid cells)



(a) Frame 19 (b) Frame 71 (c) Frame 103

(d) Frame 127 (e) Frame 159 (f) Frame 197

Figure 6: Selected frames of throwing a cube into a tank of water ($28 \times 24 \times 28$ grid cells)

When rendering, particle volumes are incorporated into the interpolated volume fractions before an unified iso-surface is extracted. As a result the liquid surface is more smooth than those of previous researches which rendered the splash by coating the particles with a field functions or as hard spheres.

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