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FluidPlaying: Efficient Adaptive Simulation for Highly Dynamic Fluid

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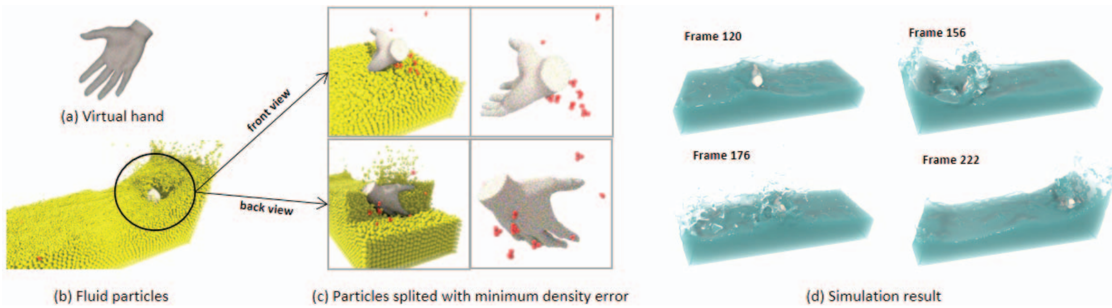

Figure 1: Fluid playing with a virtual hand. In (c), the newly-generated children particles is highlighted in red according to the 1 : 3 splitting template, where the splitting orientation is determined by the minimum density error.

Abstract

We present FliudPlaying, a novel dynamic level-based spatially adaptive simulation method that can handle highly dynamic fluid efficiently. To capture the subtle detail of the fluid surface, the high-resolution simulation is performed not only at the free surface but also at those regions with high vorticity levels and velocity difference levels. To minimize the density error, an online optimization scheme is used when increasing the resolution by particle splitting. We also proposed a neighbor-based splash enhancement to compensate for the loss of dynamic details. Compared with the high-resolution simulation baseline, our method can achieve over 3× speedups while consuming only less than 10% computational resources. Furthermore, our method can make up for the loss of high-frequency details caused by the spatial adaptation, and provide more realistic dynamics in particle-based fluid simulation.

Index Terms: Computing methodologies—Computer graphics—Animation—Physical simulation; Computing methodologies—Modeling and simulation—Simulation types and techniques—Interactive simulation

1 Introduction

Free interaction with natural phenomenon in virtual environments can enhance the user experience in virtual reality (VR) systems (see Fig. 1). However, physical simulation of the natural interaction behavior such as playing in the water relies on high-resolution discretization to afford sufficient details, making the simulation of highly dynamic scenes time-consuming. Therefore, achieving realistic simulations of highly dynamic fluids with limited computing resources is difficult. This limits the use of free interaction with the simulated natural environments in virtual reality applications.

By applying different resolutions to different positions, spatially adaptive methods [4] are able to focus computational resources on regions of interest. Local regions with higher visibility levels, such as free surfaces, are typically simulated at high resolution, while secondary regions are simulated at lower resolutions. These methods improve efficiency while ensuring high-fidelity presentation of some important details.

We choose the classical smooth particle hydrodynamics (SPH) solver to solve the fundamental motion of the fluid [2]. Most prior approaches to adaptive SPH particles are based on the camera's perspective, but the complex motion inside the fluid is ignored [1]. This will result in a loss of dynamic details, especially vortex and splash. This cannot be compensated by simply increasing the resolution near the surface. In a particle-based framework, the resolution is adjusted by means of particle splitting, merging, and mass redistribution [3]. The information transfer between particles of multiple scales will inevitably lead to numerical dissipation, which makes the calculated results deviate from the ground truth [5]. Therefore, the density error should be minimized to ensure the stability of the simulation. Besides, optimization measures are required to enhance the dynamic details, thereby alleviating the detail loss.

In this paper, we propose FluidPlaying, a highly dynamic spatially adaptive method, which takes into account both the visibility level and the dynamic level of the flow field to achieve high-fidelity and efficient simulation of particle-based fluids. The dynamic level of the flow field is determined by the vorticity field and the velocity difference between the particles. The resolution of the entire flow field is modulated through a newly designed particle splitting, merging, and mass redistribution scheme, where density error is calculated and minimized to improve the stability of the simulation. A post-processing optimization step is proposed to further enhance the splash details efficiently. Compared with these existing approaches, our method can achieve detailed fluid simulation with

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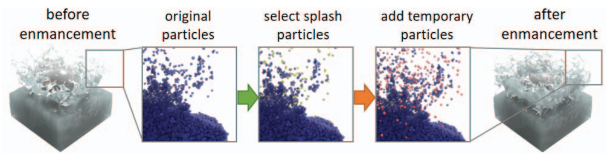

Figure 2: Splash enhancement process. Splash particles and temporary particles are marked by green and red respectively.

high efficiency, and the computational overhead is negalible.

2 Method

In this paper, both the surface level and dynamic level of fluid particles are taken into account to comprehensively identify the region that requires high-resolution simulations. For a particle i, we calculate its distance to the free surface ϕ_j using the Level-Set function. Then we calculate its vorticity ω_i using the curl of its velocity $\mathbf{v}_i$, and obtain its velocity difference v using the velocity of its neighbor particles. Next, we mapped the above three variables into three user-defined intervals, and obtain three level parameters that limit the ease of resolution adjustment, including visible level R_i^{ϕ}, vorticity level R_i^{ω} and velocity difference level R_i^{v}. Finally, the optimal mass of particle i is determined by $m_i^{opt} = m^{fine} + (R_i^{\phi}/R_i^{\omega} \cdot R_i^{v})(m^{base} - m^{fine})$, where m_i^{opt} is the optimal mass of particle i, m^{base} and m^{fine} denote the largest and smallest mass in the simulation, corresponding to the lowest and highest resolution respectively. We adopt $1:n$ splitting, $n:(n-1)$ merging, and mass redistribution operations to adjust the resolution to achieve the ideal level [4]. To ensure stability, we calculate the density error [5] when adapting the resolution and choose the best pattern with minimum error for each splitting particle.

To alleviate the detail loss caused by coarse simulation, we proposed an efficient post-process splash enhancement scheme to obtain a more dynamic visual effect (see Fig. 2). If surface particle i has neighbors less than a user-defined parameter N^{splash}, n_i^{splash} temporary particles will be created surrounding it. The position of temporary particle t is set based on its parent splash candidate i using $\mathbf{x}_t = \mathbf{x}_i + \alpha \cdot \left(\frac{\hat{\mathbf{x}}_i}{\|\hat{\mathbf{x}}_i\|} + \mathbf{n}_r\right) / \left(\left\|\frac{\hat{\mathbf{x}}_i}{\|\hat{\mathbf{x}}_i\|} + \mathbf{n}_r\right\|\right)$, where $\hat{\mathbf{x}}_i = \sum \mathbf{x}_{ij} \frac{m_j}{\rho_j} W_{ij}$ is the position difference of particle i and its neighbors, α and $\mathbf{n}_r$ are random parameters to make the result more nature.

3 Experiments and Conclusion

Comparison and Performance. As shown in Fig. 3, we set up a fulfilled container with a spinning propeller into it. We perform the simulation of the same scene multiple times using high resolution, low resolution, our method, and the state-of-the-art adaptive method [4]. High resolution and low resolution correspond to the highest and lowest particle sizes in the adaptive simulation, respectively. The initial particle number of the spatially adaptive simulation is the same as that in the low-resolution simulation, and it changes over time due to splitting and merging operations.

The dynamic details are more obvious by using a higher resolution, while most of the high-frequency details are lost under low-resolution simulation. Compared with the surface-based adaptive method [4], our result shows a higher splash height, which means our method can preserve more dynamic effects. Compared with high-precision simulations, our method achieves the same visual effect using less than 10% particle number (see Fig. 4), greatly saving computational resources. Besides, the speedup of our method and the surface-based adaptive method [4] are 3.319× and 3.316×, respectively. This means that we achieves more realistic and highly dynamic fluid simulations with negligible computational overhead. We also observed that the speedup of our method is prone to increase along with the increment of the particle numbers.

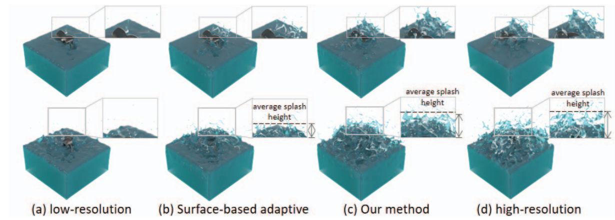

Figure 3: Fluid played by spinning the propeller under water, which is simulated under uniform low-resolution [2] (a), surface-based adaptive resolution [4] (b), our highly dynamic adaptive resolution (c), and uniform high-resolution [2] (d), respectively.

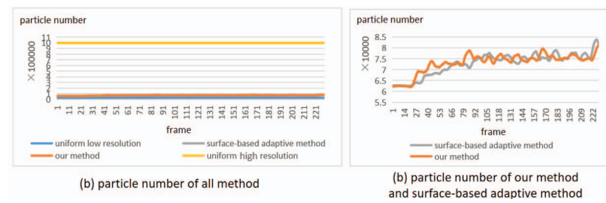

Figure 4: Our method uses less than 10% particles of the uniform high-resolution simulation method, but outcome the similar results, indicating significant savings in computational resources.

Interactive Application. As shown in Fig. 1, a tank of water is played with a virtual hand, showing the performance of our method in VR applications. As hand stirring, some particles split and generate high-resolution children. It could be seen that the $1:3$ splitting shows up in multiple positions, but the orientations of the template are different. This is because we calculate the density error during simulation, and only the best orientation with minimum error will be used in a specific split. During the whole simulation, the average density error after error minimizing decreases 15.468%.

Conclusion and Future Work. FluidPlaying is a spatially adaptive SPH method designed specifically for the simulation of highly dynamic fluids efficiently, which can provide a high-fedility result with less than 10% computational resources and over 3× speedup. In the future, we will consider temporal adaptation and improve the data structure to further improve simulation efficiency.

Acknowledgments

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