Augmented Flow Simulation Based on Tight Coupling Between Video Reconstruction and Eulerian Models

Feng-Yu Li\textsuperscript{1}, Chang-Bo Wang\textsuperscript{1,∗}, Member, CCF, Hong Qin\textsuperscript{2}, Member, IEEE, and Hong-Yan Quan\textsuperscript{1}

\textsuperscript{1}School of Computer Science and Software Engineering, East China Normal University, Shanghai 200062, China
\textsuperscript{2}Department of Computer Science, State University of New York at Stony Brook, NY 11794-4400, U.S.A.

E-mail: li_fengyu@foxmail.com; cbwang@sei.ecnu.edu.cn; qin@cs.sunysb.edu; hyquan@sei.ecnu.edu.cn

Received January 8, 2018; revised March 20, 2018.

Abstract Hybrid approaches such as combining video data with pure physics-based simulation have been popular in the recent decade for computer graphics. The key motivation is to clearly retain salient advantages from both data-driven method and model-centric numerical simulation, while overcoming certain difficulties of both. The Eulerian method, which has been widely employed in flow simulation, stores variables such as velocity and density on regular Cartesian grids, thereby it could be associated with (volumetric) video data on the same domain. This paper proposes a novel method for flow simulation, which is tightly coupling video-based reconstruction with physically-based simulation and making use of meaningful physical attributes during re-simulation. First, we reconstruct the density field from a single-view video. Second, we estimate the velocity field using the reconstructed density field as prior. In the iterative process, the pressure projection can be treated as a physical constraint and the results of each step are corrected by obtained velocity field in the Eulerian framework. Third, we use the reconstructed density field and velocity field to guide the Eulerian simulation with anticipated new results. Through the guidance of video data, we can produce new flows that closely match with the real scene exhibited in data acquisition. Moreover, in the multigrid Eulerian simulation, we can generate new visual effects which cannot be created from raw video acquisition, with a goal of easily producing many more visually interesting results and respecting true physical attributes at the same time. We demonstrate salient advantages of our hybrid method with a variety of animation examples.

Keywords video reconstruction, velocity estimation, fluid simulation, volume modeling and re-simulation

1 Introduction

Flow/fluid simulation has received considerable attention in recent decades in computer graphics, thanks to its ubiquitous and powerful capability towards modeling a wide variety of natural phenomena with details such as vortex and splash. The model-centric numerical simulation is necessary in flow simulation, and the research on this subject has resulted in widespread applications, including special effects in movies and realistic environment in computer games. Especially in the most recent years, the uprising trend of virtual reality technologies in our everyday life gives a strong prospect for the broader application of flow/fluid simulation. Physically-based flow simulation mainly has offered two types of approaches: the Lagrangian\cite{1} method and the Eulerian method\cite{2}. Both approaches have their advantages and drawbacks. Since it is convenient to numerically approximate spatial derivatives on a fixed grid, the Eulerian method receives a lot of researchers’ attention\cite{3-5} with increasing popularity. In our paper, we mainly consider the Eulerian method. However, in order to obtain better results, the time consumption is enormous as resolution increases. Moreover, it is some-
times difficult to achieve a visual effect of a particular scene, due to the requirement for appropriate initial values and strict boundary conditions.

In contrast, as the inverse problem of flow simulation, the purpose of flow capture is to measure the flow state and its physical properties in the real world, such as velocity and density. With the rapid development of data acquisition hardware, it is convenient to obtain a sequence of flow in video data. However, some details of the flow may be lost due to the equipment and environmental constraints. Moreover, it is hard to obtain a particular phenomenon with varying boundaries and/or initial value conditions. Despite this, we can obtain a rough volume of the flow and its plausible density field and velocity field, which are what we wish to utilize towards possibly enhancing the physical simulation with correct and meaningful physical quantities.

The key motivation of this paper is to clearly retain prominent advantages from both video-based method and model-centric numerical simulation, while overcoming certain difficulties of both. With the guidance of the video data, including density and velocity, the simulation results shall match with the real scene. In addition, we can inject the lost yet interesting details and change the boundary condition through physical approaches, which are difficult in video reconstruction, with a goal of creating many more vivid effects. Since the Eulerian method relies on regular grids, it is a natural choice for us to explore the Eulerian method, which could be associated with volumetric video data on the same domain. Our goal is to seek realistic simulation results that are matching with natural scenes.

In the past few years, researchers have explored the connection of flow simulation and the inverse problems, providing a few novel ideas. Okabe et al.\cite{okabe2002fluid} used the modeled volume from videos as a guide and Gregson et al.\cite{gregson2004} used the reconstructed velocity field to restart fluid simulations. As a follow-up, Zhai et al.\cite{zhai2006} further estimated the physical parameters of the fluid and applied physical editing on existing flows. Nonetheless, the above methods lack a tight coupling. Quan et al.\cite{quan2007} combined image analysis and physical method to reconstruct fluid in real time but lacking follow-up interactions. Combining with multi-fluid simulation, Ren et al.\cite{ren2008} modeled real-world bubble phenomena. In addition, Wang et al.\cite{wang2009} combined video-based fluid surface reconstruction and SPH (smoothed particle hydrodynamics) simulation to re-animate fluid surface. But the connection between video reconstruction and SPH is not natural. Inspired by the prior research work, we wish to use the reconstructed velocity field and density field to guide the physical simulation with stronger connection and tighter coupling.

We propose a novel method for flow simulation that is tightly coupling physical simulation with fluid capture and making use of meaningful physical attributes during re-simulation. Given a single-view video, we reconstruct the density field first. Then we estimate the velocity field using the reconstructed density field as prior. During iterations, the pressure projection can be treated as a physical constraint and the results of each step are corrected by obtained velocity field in the Eulerian framework. Finally, we use the reconstructed density field and velocity field to guide the Eulerian simulation with anticipated new results. Within the framework, we conduct experiments for certain graphics applications, such as detail enhancement and solid-fluid coupling under different boundaries and/or initial value conditions. The contributions of this paper are as follows.

- **Fluid Density Field Reconstruction from a Single Video.** We make a reasonable assumption to reconstruct the approximate density field and obtain plausible volume from a single-view video.
- **Tight Coupling Between Video Reconstruction and Eulerian Models.** In our method, pressure projection can be treated as a physical constraint of the reconstruction of velocity fields, and the reconstruction results of each step are corrected by physical simulation. Then the final reconstruction results can be used to guide the simulation. In such a way, we are capable of coupling the two tightly towards hybrid modeling over pure numerical simulation and video data acquisition.
- **Augmented Flow Simulation with Controllable Details.** Matching with the real scene, we can also add a lot of interesting details, such as complicated solid-liquid coupling subject to new boundaries and/or initial value conditions.

In the following sections, we briefly discuss some related work. Section 3 gives an overview of our approach. Section 4 discusses the density field reconstruction, and Section 5 details the coupling of multigrid Eulerian simulation and reconstruction. We discuss some controllable details and demonstrate graphics results of our work in Section 6, and draw the conclusion and outline future work in Section 7.

### 2 Related Work

Our approach is mainly relevant to fluid simulation, volume modeling, and velocity estimation. We intro-