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Extended virtual pipes for the stable and real-time simulation of small-scale shallow water

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ABSTRACT

We propose an approach for real-time shallow water simulation, building upon the virtual pipes model with multi-layered heightmaps. Our approach introduces the use of extended pipes that are capable of resolving flows through fully flooded passages, which is not possible using current multi-layered techniques. We extend the virtual pipe method with a physically-based viscosity model that is both fast and stable. Our viscosity model is integrated implicitly without the expense of solving a large linear system. Despite the few simplifications necessary to achieve a real-time viscosity model, we show that our new viscosity model produces results that match the behavior of an offline fluid-implicit particle (FLIP) simulation for various viscosity values. The liquid is rendered as a triangular mesh surface built from a heightmap. We propose a novel surface optimization approach that prevents interpenetrations of the liquid surface with the underlying terrain geometry. To improve the realism of small-scale scenarios, we present a meniscus shading approach with a view-dependent adjustment of the liquid surface normals based on a distance field. Our implementation runs in real time on various scenarios of roughly 10×10 cm at a resolution of 0.5 mm, with up to five layers.

1. Introduction

In this paper, we focus on a real-time simulation of shallow water at small scales, such as in scenarios of spilled coffee or bleeding during surgery (Fig. 1). In such situations, thin layers of liquid flow on a surface and may also eventually fill up small cavities. At this scale, effects such as the viscous drag force exerted on the liquid by the surface of the obstacles, as well as the meniscus at the wet–dry boundary, are much more prominent.

In many real-time contexts, such as those involving medical applications and games, it is necessary to have a very efficient simulation since other systems are running on the same resources (e.g., haptic feedback, other physics, AI). A full 3D simulation is often too expensive; only very coarse resolutions can be achieved in real time. However, a coarse 3D resolution fails to represent thin films of liquids, such as blood or paint flowing over a surface. To reduce computation times, several methods focus on performing a 2D simulation on a heightmap; these methods include those of Dagenais et al. [1], Chentanez and Müller [2], and Mei et al. [3]. Such methods can simulate liquids that are arbitrarily deep or shallow, with no impact on the resolution of the simulation.

Our approach builds upon the virtual pipes (VP) method [4]. With the exception of the work of Dagenais et al. [1], previous papers do not use a physical model to handle the viscous drag force from the terrain. This force is non-negligible for various liquids such as blood and paint. To allow more complex terrain geometries that contain overhangs and holes, previous researchers extended virtual pipe methods to use a multi-layered heightmap [5] and created interconnections between the layers to allow the liquid to flow between them. Such configurations are important for different scenarios, such as when blood should flow below organs in a surgery simulation. Nevertheless, only the method of Dagenais et al. [1] handles the flow through fully flooded passages below obstacles, but is limited to axis-aligned passages. When passages get completely filled, previous methods stop the flow for these cells, preventing future flow while the passages remain filled. Additionally, current multi-layered VP methods have a limited surface representation, with some leading to discontinuities in the surface mesh, while others are unable to accommodate multiple

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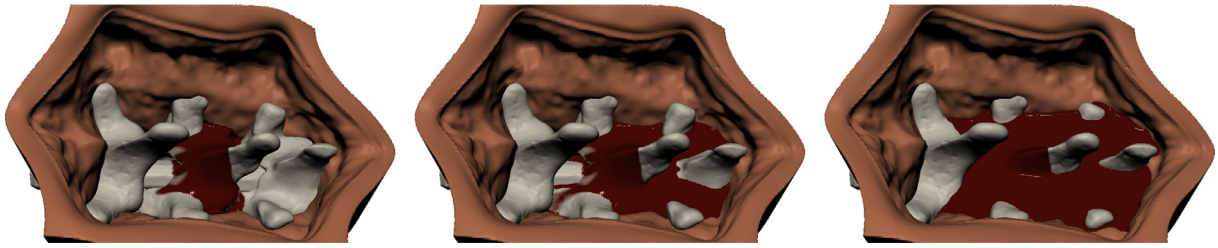

Fig. 1. Frames from an animation where blood flows from a vertebra. Note the multiple overhangs and holes.

overlapping layers. Finally, most related work typically aims for large-scale simulations and ignores the surface meniscus shading.

Our approach extends the work of Dagenais et al. [1], enhancing both the behavior and the shading. The behavior is improved using a physically-based viscosity model and by considering the flow below obstacles. Furthermore, our improved multi-layered surface reconstruction does not suffer from discontinuity issues. Our surface optimization approach provides a correction to the mesh surface, preventing interpenetrations with the underlying terrain geometry. We work on the simulation of moderate amounts of liquid, roughly in the 10 ml to slightly over 1 l range. At this scale, our new meniscus shading approach significantly improves the visual results of our simulations. To summarize, our contributions are as follows:

- We present a physically-based stable viscosity model and analyze its behavior compared to an offline simulation.
- We propose two approaches allowing flow through passages of any orientation and shape, including around corners.
- We perform independent multi-layered surface reconstruction with smooth boundaries.
- We use a surface optimization to prevent unwanted interpenetrations between the heightmap and an arbitrary surface.
- We propose a view-dependent correction of the normals to enhance the specular shading of the meniscus.

2. Related work

In the computer graphics field, most fluid animation efforts concentrate on offline simulations using either an Eulerian [6], particle-based [7], or hybrid [8] simulation. Some work focuses computation on areas with more details using adaptive grid structures [9], narrow band surfaces [10], or adaptive particle radii [7]. These methods are capable of generating astonishing visual results, but are unfortunately too slow for real-time applications. Macklin and Müller [11] were able to achieve impressive visual results by simulating and rendering more than 100,000 particles in real time using their position-based dynamics framework. While this method is real-time, its ability to reproduce smooth thin layers of liquid is limited.

To reduce memory and computational costs, it is more efficient to use a heightmap to represent the fluid and perform a 2D simulation to update the liquid's height. While methods using the heightmap as such cannot exhibit some more complex behaviors such as splashes and wave crests, they are adequate for a broad range of scenarios. For example, intricate wave patterns in shallow water can be encoded as height displacements by particles [12] or packets of similar wavelengths [13]. Furthermore, heightmap methods can simulate arbitrarily thin films of liquids with no impact on the simulation resolution. Lee and O'Sullivan [14] allowed some compressibility in their 2D simulation based on the Navier–Stokes equations and adjusted the liquid's height based on its density. While simple and efficient, this technique does not account for the underlying terrain elevation. By assuming a vertical anisotropy of the liquid's velocity, the Navier–Stokes equations can be simplified, resulting in the shallow water equations, which can be further simplified to the shallow wave equations [15]. Several papers focus on implicitly solving these equations on a regular grid [15,16] or on triangular mesh surfaces [17,18]. Methods with an implicit integration maintain stability at larger timesteps, but are prone to a lot of diffusion as well as volume gain when using a large timestep. Furthermore, faster-moving boundaries require a smaller timestep, which can considerably increase the computation time. On the other hand, Chentanez and Müller [2] showed that their explicit integration of the shallow water equations is able to simulate large-scale scenarios in real time. For their part, our experiments show that the explicit integration requires a considerably smaller timestep for small-scale examples because of the larger ratio between the liquid's velocity and the simulation cell size, which limits its use for real-time applications in that context.

A simpler model for simulating shallow water, the VP method, was introduced by O'Brien and Hodgins [19]. It is based on the hydrostatic pressure difference between neighbor cells of a uniform grid. Liquid is transferred between them through virtual pipes connected at their bottom, and the simulation uses an explicit integration. This method has been extended to support multi-layered heightmaps in order to allow simulations above partially submerged floating obstacles [5] and on more complex terrains with overhangs [20]. Furthermore, our experiments show that the VP method allows a considerably larger timestep than with the shallow water method of Chentanez and Müller [2] for small-scale scenarios. As such, our approach builds upon the VP method to simulate real-time, small-scale shallow waters. Dagenais et al. [1] introduced a physically-based viscosity model to the VP method. We show that this viscosity model produces results that are similar to those of a full 3D offline simulation based on the Navier–Stokes equations. Dagenais et al. [1] also introduced another novelty to the VP method: the extended pipes. These allowed flow below obstacles, but were restricted to axis-aligned passages. We improve the method of Dagenais et al. [1] by allowing extended pipes with any shape, eliminating the axis-aligned limitation.

Our goal is to simulate small amounts of liquids, with a millimeter to sub-millimeter resolution. Another feature is important at such scales: the meniscus, which is the effect of the capillary action at the fluid–solid boundary. Kerwin et al. [21] propose a real-time meniscus shading method relying on a pixel-based edge detection. Although fast, this method delivers limited realism, as it does not take into account the size of the meniscus, nor does it differentiate between a concave and a convex meniscus. The method of Dagenais et al. [1] greatly improved the meniscus shading, allowing control of the size of the meniscus, and included a physically-based curvature incorporating the contact angle. Nevertheless, their method did not account for the view direction, which then often produced spurious dark areas for convex menisci. Our approach accounts for the view direction by correctly masking these areas.

Prior VP methods often ignore effects that are visible at a smaller scale, such as the viscous drag force from the terrain and the meniscus near boundaries. Furthermore, multi-layered