Real-time haptic display of fluids

Mauricio Vines
University of Ottawa
800 King Edward Ave.
Ottawa, Ontario, K1N 6N5 Canada
+1 613 562 5800
mvine059@site.uottawa.ca

Javier Mora
University of Ottawa
800 King Edward Ave.
Ottawa, Ontario, K1N 6N5, Canada
+1 613 562 5800
jmora091@uottawa.ca

Won-Sook Lee
University of Ottawa
800 King Edward Ave.
Ottawa, Ontario, K1N 6N5, Canada
+1 613 562 5800
wslee@uottawa.ca

ABSTRACT
We present a novel interactive computer system based on integrating fluid simulation and haptic force feedback. Our system allows the user to interact with a fluid simulation in real time, producing flows and allowing the user to feel the fluid properties such as viscosity and velocity. Differently from solid or deformable objects found in most haptic applications, we interact with a pool of liquid where the shape cannot be defined using conventional polygons. We base our approach on the Navier-Stokes equation and a mass-spring system to represent the fluid surface. We solve the problems associated to real time rendering of haptic forces.

Categories and Subject Descriptors
H.5.2 [**Information Interfaces and Presentation**]: User Interfaces – *Haptic I/O*; I.3.7 [**Computer Graphics**]: Three Dimensional Graphics and Realism – *Virtual Reality*; I.6.3 [**Simulation and Modeling**]: Applications.

General Terms
Algorithms, Theory.

Keywords
Fluids, Simulation, Computer Interfaces, Haptics.

1. INTRODUCTION
Currently, an important trend in application development is to increase realism and interactivity levels with virtual environments. Methodologies based on physically accurate simulations, realistic graphic rendering and new technologies for interactivity enhancement have gained much attention recently. Among these technologies, Haptics have been developed to stimulate the sense of touch, by allowing the user to perceive material properties of virtual objects, like roughness, stiffness or viscosity. Most of the research in this field has been conducted on haptic interaction with solids, or deformable objects [7][10], whereas fluids have received less attention.

Fluids, such as liquids and gases, are substances that continuously deform under shear stress. Although this may seem simple, this occurs due to the interplay of several complex phenomena, such as advection, diffusion and turbulence. Simulating these phenomena is computationally expensive. Real-time simulations often focus on producing plausible visual results largely simplifying the fluid dynamics [5][6]. The high complexity of simulating fluids makes a challenging problem to provide smooth haptic feedback from interaction with fluids. Fluid simulations can be updated up to a rate of 50 Hz, while smooth haptic force feedback requires rates of about 1 KHz. Few interactive applications have been developed which allow the real-time fluids force feedback. Baxter and Lin [1] simulate the solid interaction with a viscous liquid for a painting application by filtering fluid forces. Dobashi et al [2] generate real-time haptic fluid forces from a large database of precomputed results.

We are motivated by devising simple and efficient ways to compute haptic forces from interaction with fluids. Our contribution is a real-time system which integrates fluid simulation with haptic force feedback. We focus on haptically displaying the fluid to the user in real-time. These features make our system suitable for applications where high interactive rates are required, such as computer games. We base our system on a previous application for haptic fluid simulation [8]. We evaluate the quality of our results based on a user study to assess the effectiveness of our methods.

2. THE SYSTEM
2.1 Overview
In our system, haptic interaction takes place at the tip of the probe location, or *Haptic Interface Point* (HIP). This is the place where the user introduces perturbations in the pool of fluid and where the fluid forces are calculated for haptic rendering.

Our system is organized in two main processes. The first is the fluid flow processing, where the effects of the introduced forces and substances are simulated by solving the fluid equations. The second process corresponds to the hapto-visual rendering, where simulation data is used to visualize the fluid, and fluid forces are computed. A schema of our system is shown in Figure 1.

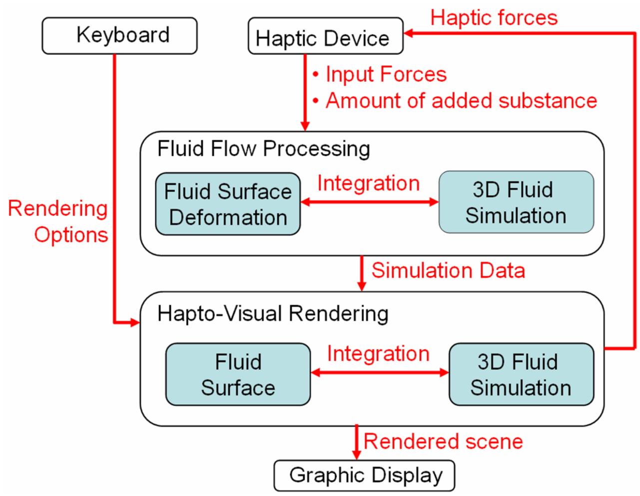

Figure 1. High Level Architecture of our system

2.2 Fluid Flow Processing

Fluid behavior is characterized by the Navier-Stokes equation which expresses the conservation of momentum in a body of fluid, and can be written as:

$$\frac{\partial V}{\partial t} = -(V \cdot \nabla)V + \nu\nabla^2 V - \frac{1}{\rho}\nabla P + \frac{1}{\rho}F \qquad (1)$$

Here V is the fluid velocity, ν is the fluid kinematic viscosity, ρ is the fluid density, P is the pressure and F an external force. Incompressibility is enforced by the continuity equation, which is written as:

$$\nabla \cdot V = 0 \qquad (2)$$

The transport of a substance in the fluid is modeled by the following density equation:

$$\frac{\partial \rho_i}{\partial t} = -(V \cdot \nabla)\rho_i + \kappa_i \nabla^2 \rho_i + S_i \qquad (3)$$

Here, ρ_i represents the density of the substance i in the fluid, S_i represents a source of the external substance and κ_i is the constant of diffusion of the substance. We assume that the substance and the fluid have approximately the same density and viscosity, therefore the fluid density and viscosity are assumed to remain constant throughout the simulation.

The simulation space is modeled as an Eulerian grid, where each fluid property is measured at fixed locations in order to solve the above equations. To solve the fluid velocity field, equations (1) and (2) are discretized and solved in each time step. To achieve interactive rates we apply the method proposed by Stam [11], which consists on splitting equation (1) and solving each term sequentially, and projecting the resulting velocity field into the space of divergence-free vector fields.

Our system represents the fluid surface as a mass-spring network of connected particles. We consider this the most suitable representation that provides real-time haptic force feedback for contact of the HIP with the surface. Other representations like heightfields [6] are susceptible to numerical dissipation and cannot maintain high curvature areas. Also it is not trivial to compute haptic feedback from contact with a heightfield. Other alternatives like surfaces obtained from particles [3] require special attention to particles positions, as after several time steps their distribution may become uneven, leaving large portions of the surface unresolved. Also, extracting a smooth surface from particles is not a trivial task.

2.3 Haptic Rendering

To enable haptic force feedback from interaction with the fluid, simulation data must be mapped into forces at a high update rate which cannot be achieved by grid simulation algorithms. Baxter and Lin [1] compute forces directly from simulation data and filter the force output introducing delays in the force feedback with respect to the simulation. In this approach, force artifacts are introduced by discontinuous pressure changes due to the movement of a solid inside the fluid. Another approach, by Dobashi et al [2], consists on computing fluid forces on a small object in a large body of water from a database of pre-computed results of several rounds of simulation under uniform flow. In this approach, the user cannot introduce changes in the flow, and the assumption of uniform flow restricts the kind of interactions that can be properly represented, like object rotation. In our system we approximate the fluid forces from the haptic device motion and the fluid simulation in real-time.

In our system haptic feedback is generated from four sources: the bowl containing the liquid, which is treated using a rigid body approach; the fluid surface, which allows producing and perceiving waves and cripples; the inner fluid, allowing perception of the fluid velocity and viscosity; and adding substances in the liquid.

2.3.1 Fluid Surface

Each particle in the mass-spring network representation of the surface is aligned with the simulation grid, and spring constants of stiffness and damping can be adjusted to provide different haptic feedback on contact. The force displayed is proportional to the distance between the HIP and the state of the surface before contact, in opposite direction to the surface penetration, as shown in Figure 2. If the user applies a force above a predefined threshold, the HIP penetrates the surface. When the force applied is smaller than this threshold, and the probe is let loose, it will float on the surface, oscillating with the waves.

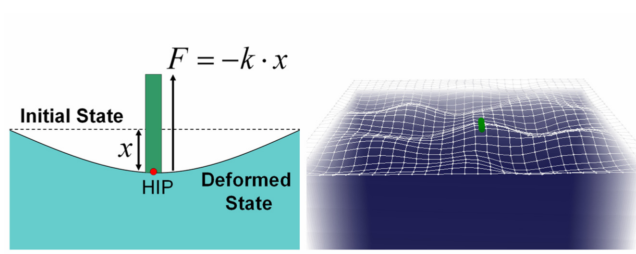

Figure 2. Left: Penalty based haptic force rendering for surface. Right: Waves produced by surface oscillation allowing haptic force feedback.

Figure 3. Schema of point mass simulation for flow resistance.

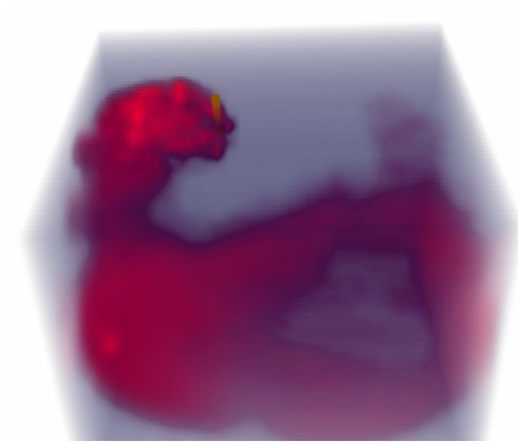

Figure 4. Example of simulation adding a red-coloured substance.

Figure 5. Samples of graphic rendering of our simulation.

2.3.2 Flow

For flow visualization, the HIP is represented as a particle in the fluid simulation. This allows the user to know the specific velocity of a particle that is being transported by the fluid flow. If the user lets the haptic probe loose, it will continue its trajectory along with the velocity field, allowing the user to perceive the evolution of the velocity field.

2.3.3 Viscosity

The user can perceive the viscosity of the fluid, this is, its resistance to motion by slowing it down. Whenever the user starts exploring the inner fluid, the user will perceive how the fluid tends to dampen the motion. The haptic force feedback f is computed as:

$$f = -kV_{probe} \quad (4)$$

Here f is the force displayed, V_{probe} is the velocity of the probe and k is a constant denoted *gain*. Different viscous fluids can be haptically represented by changing the gain value across the grid, and hence the resistance of the fluid to motion.

We employ this method to enhance the application interactivity and provide haptic feedback for the process of adding a substance to the liquid, as in the example shown in Figure 4. In this case, the gain is proportional to the amount of the substance in a grid cell. Although this process is not physically accurate, we have found that this feature improves the perception of the substance interaction with the fluid.

2.3.4 Flow Resistance

Flow resistance refers to the inertial forces in the fluid that opposes changes in motion. These forces may be computed from the velocity field in the simulation grid. However, the simulation update rate does not permit direct computation of smooth haptic force feedback. Hence we approximate this force by simulating the force produced by a mass point attached with a spring to the HIP. Then, when the HIP is moved, the point mass is dragged along the same trajectory, as shown in Figure 3.

The force is computed from the interaction of the HIP and the point mass. The velocity of the point mass acts as an approximation of the fluid flow near the HIP. If the user has induced a flow and decides to change the direction of the movement of the haptic probe, a force opposing this change will be rendered until the point mass has adapted to the new motion. This force is computed as:

$$f = K(Pos_{HIP} - POS_P) - DV_P \quad (5)$$

Here, K is the spring constant, Pos_{HIP} and Pos_P are the HIP and point mass positions respectively, D is the spring damping constant and V_P is the velocity of the point mass. In our system the spring is critically damped, so it does not oscillate.

The key aspects of fluid behavior for haptic perception of a viscous flow are the *viscosity* and the *flow resistance* since they represent the opposition of the fluid to motion. These can be combined to allow perception of the fluid accounting for both inertial and viscous forces. By changing the parameters for the force computation in each case, it is possible to simulate fluids with different densities and viscosities.

2.4 Graphical Rendering

To render the inner fluid and the substances that may be added, a 3D texture from simulation data is generated. From this texture slices are created, where each slice is perpendicular to the camera direction. Gradual alpha transparency is applied to the slices, which are sorted by the distance to the camera. Texture color and transparency are based on substance densities: higher densities produce brighter colors and less transparent areas. This method allows us to render the fluid from every viewpoint, since the texture is generated on each simulation time step. Our system also allows displaying the mass-spring network for better graphical display of the fluid surface, as shown in Figure 5.

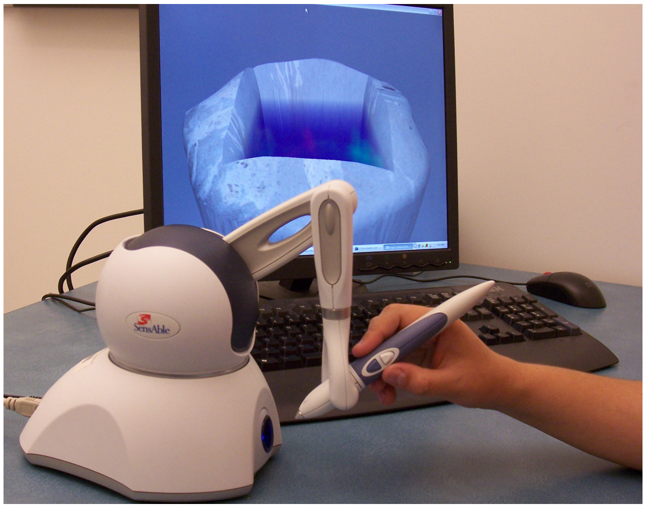

Figure 6. 3D fluid simulation with haptic probe in workstation environment.

3. RESULTS AND DISCUSSION

We implemented our system in C++, using OpenGL for the graphical environment, and the OpenHaptics™ [9] toolkit for haptic rendering. The latter was chosen due to simplification of the synchronization between haptics and graphics threads, and the possibility of reusing OpenGL code. For haptic rendering we used a Sensable™ Phantom Omni device with 3 DOF of force feedback as shown in Figure 6. We performed all our experiments in an IBM PC with and AMD Opteron™ processor with 2GB in RAM, and an NVIDIA Quadro FX 3400/4400 graphics card.

Our system simulates fluid in real-time with smooth haptic force feedback. The fluid simulation is updated at a rate of 30 Hz which does not interfere with the smooth haptic force feedback which takes place at a high rate. Our approach, however, has some limitations. We make a trade-off between physical accuracy and real-time rendering of both the graphical simulation and the haptic forces. We approximate the fluid behavior using a discrete grid; and we approximate fluid forces in order to obtain real-time computations without incurring in additional overhead on the simulation. Another issue in our approach is related to the liquid surface. A smooth liquid surface requires a high number of particles in the mass-spring network, however, this requires more computational power. Our tests for several grid sizes reveal that for a 15x15x15 grid, we can reach a frame rate of approximately 32 frames per second.

We conducted a user study to validate our approach and see how well our implementation represented fluid behavior. Ten adults of different backgrounds in fluid simulation and haptic technologies participated in the study. The participants were presented with a list of keyboard commands that they could use anytime to toggle between different functionalities and force rendering modes in our system. After a task was performed, users rated the hapto-visual experience from 1 to 5, being 1 the lowest, and 5 the highest ratings. Table 1 summarizes the user ratings.

Table 1. Summary of Survey Findings

Task	AVG	STD DEV
Colliding with bow walls	4.5	0.67
Colliding with deformable surface	4.3	0.78
Feeling the surface ripples	3.9	0.7
Feeling the viscosity of the fluid	4.5	0.5
Visualizing the motion of the fluid	4.6	0,49
Overall application as a tool for hapo-visually represent a fluid simulation	4.4	0.49

Users provided positive comments on the combination of graphic fluid simulation and haptic feedback for a realistic interaction with the scene. The highest average score was obtained by the visualization of the fluid, and the lowest average score was related to the feeling of surface ripples. However, this can be attributed to users not applying the required forces in order to produce surface ripples and oscillations, but smaller forces that produced little perturbation on the fluid surface.

4. CONCLUSIONS

Our main contribution is a novel human-computer system to extend human-computer interaction to real time fluid animation by displaying haptic forces according to the fluid simulation. We simulate the fluid flow from the Navier-Stokes equations and compute haptic force feedback in real-time from the interaction between a haptic probe and the fluid simulation. We solve the fluid surface using a mass-spring system which produces wave oscillations and generates haptic feedback for interaction with the surface, allowing feeling the waves and ripples. Our user study confirms that the methods employed are adequate for representing fluids in interactive applications. This system represents an important step towards enhancing real-time interaction with fluids, by integrating haptic force feedback and a fluid simulation. Future research directions include computation of haptic force feedback from splashing, merging and splitting bodies of liquid.

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