Tap, squeeze and stir the virtual world: Touching the different states of matter through 6DoF haptic interaction

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"Tap, Squeeze and Stir" the Virtual World: Touching the Different States of Matter Through 6DoF Haptic Interaction

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Abstract

Haptic interaction with virtual objects is a major concern in the virtual reality field. There are many physically-based efficient models that enable the simulation of a specific type of media, e.g. fluid volumes, deformable and rigid bodies. However, combining these often heterogeneous algorithms in the same virtual world in order to simulate and interact with different types of media can be a complex task. In this paper, we propose the first haptic rendering technique for the simulation and the interaction with multistate media, namely fluids, deformable bodies and rigid bodies, in real-time and with 6DoF haptic feedback. Based on the Smoothed-Particle Hydrodynamics (SPH) physical model for all three types of media, our method avoids the complexity of dealing with different algorithms and their coupling. We achieve high update rates while simulating a physically-based virtual world governed by fluid and elasticity theories, and show how to render interaction forces and torques through a 6DoF haptic device.

Index Terms: I.3.5 [Computer Graphics]: Computational Geometry and Object Modeling—Physically based modeling; H.5.1 [Information Interfaces and Presentation]: User Interfaces—Haptics I/O; H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, Augmented, and Virtual Realities

1 Introduction

The computer graphics community has developed many different physically-based models to recreate materials with which we interact on a daily basis: smoke, fire, water, clay, plastic and metal, to name a few. We are used to see these simulations in movies or video games, but what about touching them? Haptic rendering algorithms compute force feedback in real-time, and allow to feel the objects in a virtual world through a haptic device. Due to the high complexity of physical simulations and the high update rate required for haptics, these algorithms often focus on enabling the haptic interaction with a single type of matter: either rigid, deformable or fluid media. However, even the most common activity in real life often involves interacting with more than one type of media: walking on pavement, parquet and puddles, having a meal on a plate with meat and a beverage, washing our hands by touching the faucet, the soap and the water. In order to bodily interact with such virtual worlds, we currently need to use different algorithms for each type of media, and set up coupling interfaces between these heterogeneous models. This supposes to increase the complexity and the computational cost of an already highly complex and time consuming simulation.

In this work, we propose a single model with a single haptic rendering technique to simulate and interact simultaneously with rigid, deformable and fluid media in real-time with 6DoF haptic feedback. This novel approach is the first to tackle the problem of physically-based multistate haptic rendering. Based on a Smoothed-Particle Hydrodynamics (SPH) model [8] brought to high update rates through a GPU implementation, we are able to simulate fluid volumes, deformable and rigid bodies in real-time. Using a novel coupling scheme that takes advantage of the SPH model, we show how to render interaction forces and torques through a 6DoF haptic device. We measure the performance of our technique in terms of computation time and haptic feedback.

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2 Previous Work

Previous work on haptic interaction with deformable bodies [2] or fluids [4] only allow the interaction with rigid bodies on top of another state. The CORDIS-ANIMA [3] simulation framework was the first to simulate different states with haptic feedback, although using a mass-spring formalism and not the physically-based approach of continuum mechanics. To the best of our knowledge, there is no haptic rendering technique that provides haptic feedback for fluid, deformable and rigid states of matter in the same simulation. Recent work on physically-based simulations has used the SPH model [8] for the simulation of multiple states of matter in a unified framework. However, update rates are usually not real-time, or fall short for haptic interaction. In [10], deformable bodies are modeled in real-time with SPH and the Moving Least Squares (MLS) algorithm to compute the elastic forces. The approach is improved in [7], allowing solid, deformable and fluid animation and interaction in a unified approach. A fully SPH-based approach is presented in [12], later corrected in [1] for a rotationally invariant formulation. Although these approaches allow a certain degree of interaction, they are not fast enough and do not solve the haptic rendering issue.

Our approach is the first to achieve multistate haptic rendering. Previous haptic rendering techniques were focused on a single state, e.g. fluid, deformable or solid, making it difficult to have different types of media coexist in the same simulation while providing convincing haptic feedback. Inspired by our previous work presented in [4], and bringing [12] and [1] for deformable bodies to the required speeds, we are able to simulate simultaneously fluid volumes, deformable bodies and rigid objects in a physically-based manner and at high update rates. Through the SPH model, we enable the haptic coupling with 6DoF haptic devices and the force feedback interaction with matter in its differrent states.

3 Physically-based simulation for haptic rendering of multistate media

The seamless cohabitation of different theoretical models for different states of matter within the same virtual world is made possible through the use of a single common computational approach: the SPH model. With all three states of matter simulated with the same data structures and the same algorithmic, the coupling between the different media becomes a straightforward task, and is included in the simulation. Figure 1 illustrates this principle. Any virtual object of the virtual world can be either fluid, deformable or rigid, and the state is hidden inside the model. The interactions between the different states are also computed seamlessly based on the same model. In the end, a virtual world is populated by defining the state of each virtual object together with its corresponding physical properties (stiffness for deformable bodies, viscosity for fluids). Users can interact with the virtual world through a haptic device using the interaction forces, without ever dealing with the models behind.

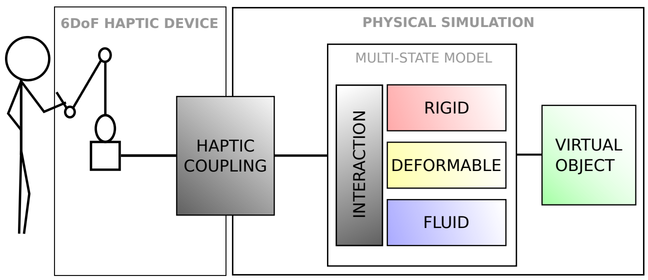

Figure 1: Global view of our approach: a user seamlessly interacts with a virtual world populated with objects of different states of matter.

In this section, we describe the foundations of our physically-based simulation algorithms.

3.1 SPH-based Physical Simulation

The SPH model [8] computes the smoothed quantity A_i of a particle i at any position $\mathbf{x}$ in space through the general formula:

$$A_i = \sum_j A_j V_j W(\mathbf{x} - \mathbf{x}_j, h) \tag{1}$$

where A_j is the discrete quantity A sampled for neighboring particle j at position $\mathbf{x}_j$, V_j is the volume of j, and W is the smoothing kernel of support h, where particles beyond h are not taken into account.

3.1.1 Fluid and Rigid Body Model

The motion of fluids is driven by the Navier-Stokes equations. Using the SPH model as presented in [9] and used in [4], pressure and viscosity forces are computed at each time step:

$$\mathbf{f}_i^{pressure} = -V_i \sum_j V_j \frac{P_i + P_j}{2} \nabla W(\mathbf{x}_i - \mathbf{x}_j, h) \tag{2}$$

$$\mathbf{f}_i^{viscosity} = \mu V_i \sum_j V_j (\mathbf{v}_j - \mathbf{v}_i) \nabla^2 W(\mathbf{x}_i - \mathbf{x}_j, h) \tag{3}$$

where P is the pressure, $\mathbf{v}$ the velocity, μ the viscosity coefficient and $\mathbf{g}$ the gravity field. ∇ and ∇^2 are respectively the gradient and Laplacian of the physical quantities. Parameters such as the viscosity can be changed to obtain different fluid behaviors, from smoke (no viscosity) to honey (very high viscosity).

Rigid bodies are modeled with the same SPH particles used in the fluid simulation, creating a unified particle model as described in [12]. This simple rigid body model has the main advantage of being meshless: since the overall shape of the rigid body is not important, it allows the seamless use of arbitrary-shaped rigid bodies, including concave objects. Moreover, it provides a gain in efficiency by computing a single model, since it makes the approach unified with fluid and deformable bodies. Additional collision detection techniques are avoided, since collision computations are included in the neighbor search.

3.1.2 Deformable Body Model

In order to simulate a deformable body with SPH governed by the elasticity theory, we compute elastic forces as in [12] using the improvements proposed in [1] to make the computations rotationally invariant by using a corotational approach. For more details, we refer the reader to the respective articles, as well as to [10].

The elastic force exerted on a particle i is computed from the gradient of the locally rotated displacement field, $\nabla \bar{\mathbf{u}}_i$. Using an SPH formulation, this gradient is defined as:

$$\nabla \bar{\mathbf{u}}_i = \sum_j V_i^0 \bar{\mathbf{u}}_{ji} \nabla W(\mathbf{x}_i^0 - \mathbf{x}_j^0, h)^T \tag{4}$$

where $\mathbf{x}_i^0$ and $\mathbf{x}_j^0$ are the initial positions (in the undeformed state) of particles i and j respectively, and $\bar{\mathbf{u}}_{ji}$ is the locally rotated displacement difference between neighboring particles j and i. Then, the strain ε can be computed from $\nabla \bar{\mathbf{u}}_i$, using a Green-Saint-Venant strain tensor formulation.

The elastic force $\mathbf{f}_{ji}$ exerted on a neighboring particle j by particle i is defined as the negative gradient of strain energy with respect to displacement, and can be computed as:

$$\mathbf{f}_{ji} = -2V_i^0 (\mathbf{I} + \nabla \bar{\mathbf{u}}_i^T) \sigma_i V_j^0 \nabla W(\mathbf{x}_i^0 - \mathbf{x}_j^0, h) \tag{5}$$

where V_i^0 is the initial volume of particle i and σ is the stress. σ is computed from the strain ε through the linear relation $\sigma = \mathbf{C}\varepsilon$, where $\mathbf{C}$ is defined by only two parameters, the Young modulus and the Poisson ratio.

The elastic force $\mathbf{f}_i^{elasticity}$ exerted on particle i is symmetrized and computed as:

$$\mathbf{f}_i^{elasticity} = \sum_j \frac{-\mathbf{R}_i \mathbf{f}_{ji} + \mathbf{R}_j \mathbf{f}_{ij}}{2} \tag{6}$$

where $\mathbf{R}$ is the rotation matrix computed through the corotational approach.

3.1.3 Interaction Forces

In a unified, parallel and time-critical framework, unified interaction forces fit well for computation time reasons. Using the same interaction forces as in a fluid-fluid case, namely pressure and viscosity forces, improves the gain of parallel computation, while providing a reasonable amount of control over the forces through density and viscosity values. Hence, as in [4], interaction forces $\mathbf{f}_i^{interaction}$ are computed between particles belonging to different bodies as:

$$\mathbf{f}_i^{interaction} = \mathbf{f}_i^{pressure} + \mathbf{f}_i^{viscosity} \tag{7}$$

Moreover, by using the SPH model for the computation of interaction forces between fluid, deformable and rigid body particles, it removes the need of additional collision detection algorithms.

3.2 Integration and Simulation Loop

The different models previously described are run simultaneously under the same SPH framework, improving the efficiency of the simulation compared to having three heterogeneous models. Hence, the simulation loop runs in four consecutive steps:

1. Compute corotational matrices $\mathbf{R}_i$ for each particle belonging to a deformable body;
2. Compute new density and elastic properties;
3. Compute new internal forces (between particles of the same body) and new interaction forces (between particles of different bodies);
4. Integrate (compute new velocity and position) through Leap-Frog integration for fluids and deformable bodies. For rigid bodies, integrate by applying rigid body dynamics.

The entire physical model is implemented on GPU using the CUDA framework, extending our previous implementation [4] to support deformable bodies. Space is subdivided in a 3D uniform grid, so that search for neighbors is limited to the surrounding cells. We compute the different physical quantities and forces related to fluids and elastic theories, as well as interaction forces. In order to further accelerate computations, we use texture lookups to retrieve the different data arrays to benefit from texture data caching. We also use an OpenGL Vertex Array Object for the particle position array, allowing the graphic rendering algorithm to access position data without copying it back to CPU memory.

4 MULTIMODAL RENDERING

4.1 6DoF Haptic Rendering

We base our force feedback computation on interaction forces and on an SPH rigid body as proxy. By using an SPH proxy, we avoid additional computations for haptic coupling: the proxy is an object of the virtual world, and it interacts with all other media around it through the unified interaction forces described in section 3.1.3. When the proxy interacts with different media on the virtual world, the simulation computes the corresponding interaction forces as any other body from the virtual world. In this way, the user can feel the virtual world through an arbitrary-shaped rigid body.

Once the interaction forces are computed on the proxy, they are fed to the rigid body dynamics algorithm to perform the haptic coupling between the proxy and the 6DoF haptic device. In the rigid body dynamics step, all the interaction forces exerted on the proxy rigid body *body* are summed to obtain a total force $\mathbf{F}_{body}^{haptic}$ and a total torque τ_{body}^{haptic}. The force and torque feedbacks coming from the haptic device are then added as external forces. Hence:

$$\mathbf{F}_{body}^{haptic} = \sum_{i_{body}} \mathbf{f}_{i_{body}}^{interaction} + \mathbf{f}^{device} \quad (8)$$

$$\tau_{body}^{haptic} = \sum_{i_{body}} \tau_{i_{body}}^{interaction} + \tau^{device} \quad (9)$$

Then, the new position and velocity are computed by integrating the forces over the simulation time step. They are sent to the haptic device, closing the haptic loop in admittance mode. A Virtual Coupling mechanism [5] is introduced between the haptic device and the rigid body, reconciling a high update rate haptic device with a lower rate simulation, leading to an increase of stability.

The resulting 6DoF haptic coupling scheme is unified, in the sense that it allows the interaction with different media (fluid, deformable and solid) without distinction, since the haptic forces are computed in a unified way.

4.2 Graphic Rendering

As for the physical simulation, we use a unified visual rendering algorithm for fluid and deformable bodies. Previous work [4] has shown how to render fluids with a screen-space technique based on [13], with a trade-off between quality and performance. A three-step approach first computes per pixel fluid data (front and back fluid volume depth from view), then smoothes the front surface depth in screen space using a fast bilateral filter, and finally composes the frame.

We follow the same procedure to render deformable bodies. However, since most bodies are not transparent, as opposed to fluids, we do not handle transparency for deformable bodies, which leads to an increase in performance. In order to achieve a correct occlusion between the different media, we perform a depth test in the fragment shader.

5 PERFORMANCE

In this section we measure the performance of our haptic rendering technique, in terms of computation time and haptic feedback.

The simulations were carried out using a Virtuose 6DoF force-feedback device from Haption Company, and a laptop computer with a Core 2 Extreme X7900 processor at 2.8GHz, 4GB of RAM, and a Nvidia Quadro FX 3600M GPU with 512MB of memory.

5.1 Computation Time

We measured the computation time of three scenes with an increasing number of particles. Each scene has either a fluid volume, a deformable body or a rigid body, all of the same size and shape (a cuboid with a square base of 0.5m side and a variable height according to the number of particles). We only measured the physical simulation computation time, without taking into account graphic rendering. The simulation ranges from 2,000 to 30,000 particles. Figure 2 plots the measurements for the different types of media.

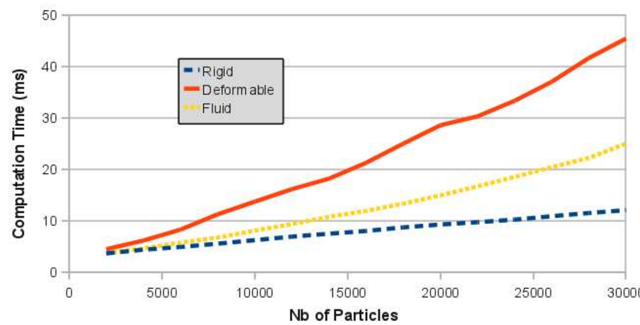

Figure 2: Computation time for scenes made of either a rigid body (dashed curve), a deformable body (continuous curve) or a fluid volume (dotted curve), according to the number of particles.

The higher complexity of the elastic theory implementation compared to the fluid theory and the rigid body dynamics is clearly visible: when the number of particles increases, the computation time for deformable bodies increases roughly 2 times faster than for fluids, and 6 times faster than for rigid bodies.

A determinant factor of our approach is its computation time, since haptic feedback requires update rates higher than the usual 30Hz of real-time visual rendering. It has been shown that, for fluids, update rates of 70Hz are satisfactory for haptic rendering, since forces due to fluids do not change rapidly [4]. Our implementation allows to simulate large volumes of fluid (around 20,000 particles) above 70Hz, as shown in Figure 2. In the case of deformable bodies, low update rate simulations (30-50Hz) use interpolation [11], and faster models rely on pre-computed data and small deformation approaches [6], or limit the complexity of the virtual objects [2]. Our model is an efficient trade-off between these approaches, with a fast simulation with complex deformable bodies (150Hz for 5,000 particles) and a virtual coupling mechanism for a smooth haptic rendering.

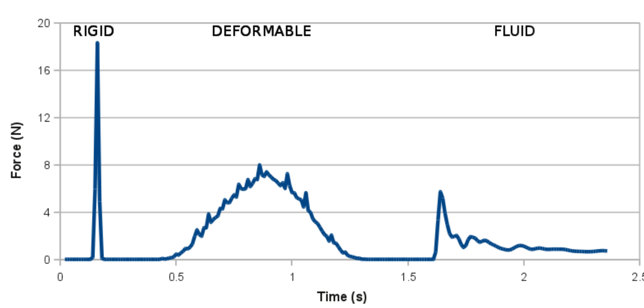

Figure 3: Forces exerted on a sphere successively dropped on rigid, deformable and fluid media.

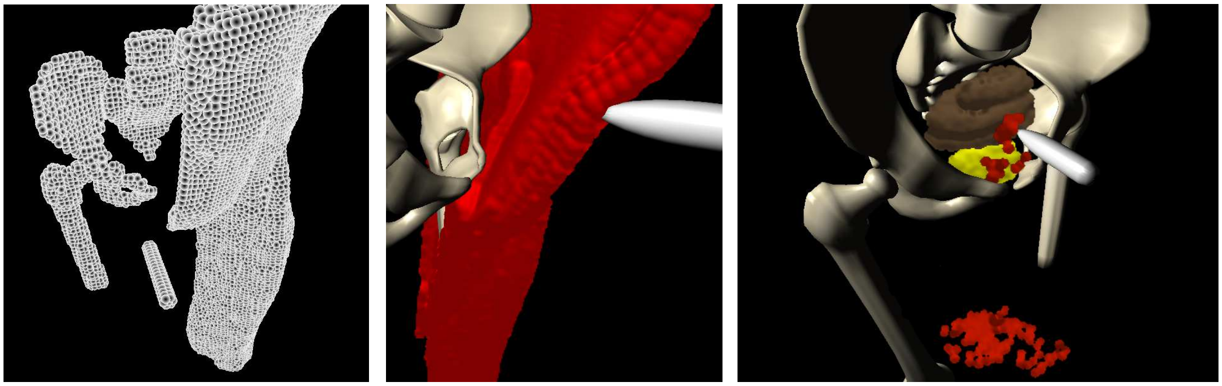

Figure 4: 6DoF haptic interaction in a medical scenario. Left: rendering of the particles composing the multistate virtual world. Middle: the user examines a deformable muscle. Right: fluid blood pours from the deformable intestine when the user penetrates it with the rigid probe.

5.2 Haptic Feedback

We provide a visual feedback of the forces exerted on a coupled rigid body interacting with the three types of media, in order to show the correspondence of the simulation behavior with the expected physical behavior.

A 20cm radius sphere, coupled to a 6DoF Virtuose, is dropped onto a 50x50x20cm block of particles, representing a volume of fluid, a deformable body or a rigid body. Figure 3 shows the forces involved in the interaction between the coupled sphere and the media. The three interaction patterns are computed and recorded individually, but are shown on the same graph for comparison purposes.

When the media is solid, the sphere bounces quickly, generating a force peak. When the media is deformable, the sphere compresses the media's surface until its elastic behavior pushes the sphere back into the air. When the media is fluid, the sphere penetrates the fluid until pressure makes the sphere rise to the surface and float.

6 Application Scenarios

Our multistate haptic rendering technique can be applied to different fields, with haptic feedback enhancing the interaction experience. The medical field can substantially benefit from our approach, since surgeons are in constant interaction with fluids (blood), deformable bodies (organs, tissues) and rigid bodies (bones). We designed a medical simulation scene as an illustration of potential application, as shown in Figure 4, with these three states. The user can interact with the different body parts through a rigid probe, and experience haptic feedback through a 6DoF haptic device. Where interactive medical simulations of this kind were restricted to deformable bodies only, we enable haptic feedback on virtual worlds with complex rigid and deformable objects, together with volumes of fluid, without dealing with different models and their coupling.

Other potential application areas include the entertainment field (exploration of virtual worlds), training (manipulations of dangerous materials) and industrial simulations (virtual prototyping).

7 Conclusion

This paper introduces the first multistate haptic rendering approach, allowing haptic interaction simultaneously with media in fluid, deformable and rigid states. Based on the SPH physical model for all three types of media, our method avoids the complexity of dealing with different algorithms and their coupling. We achieve high update rates while simulating a physically-based virtual world governed by continuum mechanics theories, and show the multimodal rendering of the interaction, with forces and torques displayed through a 6DoF haptic device and with an optimized visual rendering algorithm. Preliminary tests with novice users were promising, with users giving positive feedback. Future work will focus on decoupling graphic and haptic rendering loops for an increased simulation performance. We will then conduct a perceptual evaluation in order to assess the capability of users to recognize the different states of matter.

Acknowledgements

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