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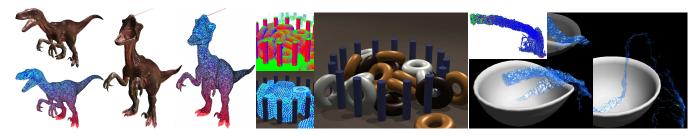


Figure 1: We combine GPU methods for detailed deformable objects (left), image-based collisions (middle), and SPH fluids to simulate a two-way fluid-deformable coupling (right) at interactive rates.

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Abstract

We present a method to implement on the GPU an implicit FEM 2 solver which is fast and stable enough to handle interactions and 3

collisions. We combine this method with GPU-based fluids [Zhang

et al. 2008] and collision detection [Allard et al. 2010] to achieve

interactive multiphysics simulations entirely running on the GPU. 6

Introduction 1 7

The Finite Element Method (FEM) is widely used to simu-8 late deformable materials in mechanical simulations. Recently 9 co-rotational linear FEM was applied successfully in interactive 10 games [Mendoza and Garcia 2010] and medical simulations, how-11 ever CPU methods are limited to coarse meshes due to performance 12 constraints. GPU-based FEM methods have been proposed [Comas 13 et al. 2008], but they rely on explicit schemes and thus require pro-14 hibitively small time-steps. We overcome these limitations by im-15 plementing an implicit integration scheme on the GPU. GPU colli-16 sion handling methods for rigid [Tonge et al. 2010] and deformable 17 bodies [Allard et al. 2010] are available, yet an interactive simula-18

tion of two-way fluid-deformable coupling is an open problem. 19

Methods 2 20

Implicit FEM Solver on GPU 2.1 21

To implement implicit FEM, we rely on an iterative Conjugate Gra-22 dient (CG) solver. However, in contrast to existing GPU-based 23 sparse solvers [Krüger and Westermann 2005; Buatois et al. 2009], 24 we do not explicitly build the system matrix, but instead parallelize 25 the required matrix-vector products directly on the original mesh. 26 This considerably reduces the number of operations required, and 27 more importantly the consumed bandwidth, enabling the method to 28 be fast enough for interactive simulations of soft bodies. The paral-29 lelization, detailed in [Allard et al. 2011], relies on first computing 30 the contribution of mesh elements using one thread per tetrahedron, 31 followed by a parallel gather to accumulate contributions at ver-32 tices. Further optimizations include mesh ordering, compact data 33 structures, memory layout, and changing sequences of operations 34 to reduce synchronization points. 35

2.2 Fluid Coupling using Image-based Collisions 36

An image-based collision method [Allard et al. 2010] has been pro-37 posed to handle complex deformable objects. It computes inter-38 section volume gradients which are discretized on pixels and accu-39 mulated on vertices. To handle fluid coupling, we extend this ap-40

proach to compute pixels directly from the SPH fluid density field

using ray-tracing. When intersections are detected, contributions are accumulated to the fluid particles based on their relative contribution as given by the SPH kernels evaluated at the pixel. As ray-tracing can be expensive, an important optimization is to test rays only when an existing pixel is within the fluid, which requires only a simple evaluation of the SPH density field.

Results 3 48

All timings given below exclude rendering as the cost of this step can vary greatly depending on the desired visual quality and complexity. Our CUDA-based FEM solver is able to simulate a deformable object with 45k tetrahedral elements (Fig. 1 left) at 212 FPS on a Nvidia GeForce GTX 480, 18× faster than our most optimized sequential implementation on an Intel Core i7 975 3.33GHz CPU. The fluid simulation (Fig. 1 right) demonstrates two-way coupling between the fluid and a soft cup, achieving 25 FPS using 2k FEM elements and 32k SPH particles on a GeForce GTX 280 GPU.

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