Geophysical Research Abstracts
Vol. 12, EGU2010-12233, 2010
EGU General Assembly 2010

Complex fluid flow modeling with SPH on GPU

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We describe an implementation of the Smoothed Particle Hydrodynamics (SPH) method for the simulation of complex fluid flows. The algorithm is entirely executed on Graphic Processing Units (GPUs) using the Compute Unified Device Architecture (CUDA) developed by NVIDIA and fully exploiting their computational power. An increase of one to two orders of magnitude in simulation speed over equivalent CPU code is achieved.

A complete modeling of the flow of a complex fluid such as lava is challenging from the modelistic, numerical and computational points of view. The natural topography irregularities, the dynamic free boundaries and phenomena such as solidification, presence of floating solid bodies or other obstacles and their eventual fragmentation make the problem difficult to solve using traditional numerical methods (finite volumes, finite elements): the need to refine the discretization grid in correspondence of high gradients, when possible, is computationally expensive and with an often inadequate control of the error; for real-world applications, moreover, the information needed by the grid refinement may not be available (e.g. because the Digital Elevation Models are too coarse); boundary tracking is also problematic with Eulerian discretizations, more so with complex fluids due to the presence of internal boundaries given by fluid inhomogeneity and presence of solidification fronts.

An alternative approach is offered by mesh-free particle methods, that solve most of the problems connected to the dynamics of complex fluids in a natural way. Particle methods discretize the fluid using nodes which are not forced on a given topological structure: boundary treatment is therefore implicit and automatic; the movement freedom of the particles also permits the treatment of deformations without incurring in any significant penalty; finally, the accuracy is easily controlled by the insertion of new particles where needed.

Our team has developed a new model based on the SPH meshless method. In comparison to other particle methods, SPH also provides additional benefits such as the automatic preservation of mass. The direct computation of most physical quantities (e.g. pressure) without resorting to large, sparse implicit systems makes SPH particularly favorable to implementation on highly parallel computational hardware such as modern video cards.

The graphical processing units (GPUs) on modern video cards often surpasses the computational power of the CPU that drives them. The CUDA architecture, introduced by NVIDIA in the spring of 2007, allows generic GPU programming with an extension of the C language, making it easy to write highly parallelized code.

Our lava simulation model uses the SPH method with a pure GPU implementation in CUDA to achieve high computational performance, modeling both the dynamic and thermal aspects of a lava flow.

The dynamic parts of the SPH algorithms are based on the ones of the SPHysics simulator, enhanced to include the treatment of non-Newtonian fluids, the integration of thermal effects including temperature-dependent rheological parameters, and an optimal handling of large-scale natural topographies. For the non-Newtonian rheologies priority is given to the power law recently brought into light by physical modeling of lava flows.

For the thermal part of the model, the SPH model has been compared with classical finite elements to simulate a lava lake solidification, a problem for which an analytical solution is known. The comparison shows the significantly higher accuracy of the SPH method in proximity of the contact area of two or more solidification fronts.