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Short communication

Quasi-real-time simulation of rotating drum using discrete element method with parallel GPU computing

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ABSTRACT

Real-time simulation of industrial equipment is a huge challenge nowadays. The high performance and fine-grained parallel computing provided by graphics processing units (GPUs) bring us closer to our goals. In this article, an industrial-scale rotating drum is simulated using simplified discrete element method (DEM) without consideration of the tangential components of contact force and particle rotation. A single GPU is used first to simulate a small model system with about 8000 particles in real-time, and the simulation is then scaled up to industrial scale using more than 200 GPUs in a 1D domain-decomposition parallelization mode. The overall speed is about 1/11 of the real-time. Optimization of the communication part of the parallel GPU codes can speed up the simulation further, indicating that such real-time simulations have not only methodological but also industrial implications in the near future.

1. Introduction

Simulation of granular flow using discrete element method (DEM) (Cundall & Strack, 1979) is playing an increasingly important role in elucidating a variety of phenomena in processing industries. However, due to its major disadvantage of high computational cost, most simulations still focus on small systems with large particles. Although, for larger-scale systems, a coarse-grained or continuum-level description will be desirable and progress has been made in this direction (Pöschel, Salueña, & Schwager, 2001; Sakai & Koshizuka, 2009; Sakai et al., 2010), "direct" simulation in DEM is still meaningful as a virtual experimental tool to explore and verify those more efficient models, especially when complicated processes such as agglomeration and fragmentation have to be considered. With the development in high-performance computing, especially the emergence of GPU computing, simulating systems with hundreds of millions of particles is becoming realistic for engineering applications.

Acceleration of DEM simulations by special hardware has already been practiced. Using Field Programmable Gate Array (FPGA), Schäfer, Quigley, and Chan (2004) realized a speedup factor of 30 over an optimized software running on a fast personal computer. Radeke, Radl, and Khinast (2009) investigated size effect in granular flows using high performance GPUs. Shigeto, Sakai, and Koshizuka (2010) developed a parallel DEM simulation method on GPU and CPU, which achieved about three-fold speedup over one Intel Core i7 965 CPU (4 physical cores). However, real-time simulation of industrial systems has not been achieved yet.

In this paper, taking advantage of the intrinsic parallelism of DEM and the fine-grained parallelism of the GPU architecture, a simplified DEM model is implemented in an optimized algorithm on the newly available NVIDIA Fermi GPUs to realize quasi-real-time performance. Key simulating parameters such as the stiffness of the spring, the damping coefficient, the time step and the rotating rate, can be adjusted during simulations, to show the nature of real-time simulation. The simulation results from different types and numbers of GPU cards are compared and discussed. The simulation of rotating drums demonstrates that real-time simulation of industrial scale granular system is becoming feasible.

2. Model

The discrete element method (DEM), originally developed by Cundall and Strack (1979), is a soft particle model which assumes that two particles overlap when they are in contact. The interactions between individual particles are usually simplified by the spring, dashpot and friction effects. In our simulation, only translational motion is considered for simplicity, not accounting the

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friction between the particles, that is, the normal contact force exists only when two particles collide with each other. Among the many force models available, the following linear spring-dashpot model is used,

$$F = -k\delta_{ij}\eta_{ij} - \eta V_{ij}, \tag{1}$$

where k and η are the stiffness of the spring and the damping coefficient, respectively, δ_{ij} and V_{ij} represent the deformation and relative velocity between particles i and j, η_{ij} is the normal unit vector. The normal damping coefficient η is calculated according to Hoomans (2000),

$$\eta = -2\frac{\ln(e)}{\sqrt{\pi^2 + \ln^2(e)}}\sqrt{k\frac{m_i m_j}{m_i + m_j}}, \tag{2}$$

where e is the restitution coefficient of particle, and m_i and m_j are the mass of particle i and j.

In a general form, the governing equation for the translational motion of particle i of mass m_i and velocity V_i at time t, which can be described by Newton's second law of motion, is given by

$$m_i\frac{dV_i}{dt} = m_i g + \sum_{j=1}^{n} F_{ij}, \tag{3}$$

where $m_i g$ is the gravitational force, F_{ij} is the inter-particle forces between particles i and j. The forces are summed up for the n particles which are in contact with particle i. The simulation parameters are given in Table 1. The program is so designed that the last four parameters can be changed during the simulations.

Table 1
Simulation parameters.

Parameter	Case I		Case II
Solid density ρ_p (kg/m^3)		7860	
Particle diameter d_p (mm)		10.0	
Spring stiffness k (N/m)		7.0×10^4	
Restitution coefficient e		0.78	
Time step (s)	2×10^{-4}		1×10^{-4}
Rotating rate (rpm)		5.0	

3. GPU-based algorithm

The GPU-based algorithm for this simulation is developed at IPE on the basis of previous work (Chen et al., 2009) while using the new generation Fermi GPU and new version of CUDA 3.1 (NVIDIA, 2010), according to the general simulation procedure illustrated in Fig. 1. The codes can run either entirely on single GPU or on multiple GPUs with message passing interface (MPI) (Gropp, Lusk, Doss, & Skjellum, 1996). The interactions in DEM are local, so one dimensional domain decomposition method (Shaw, 2005) is used to divide the whole simulation system into small domains. The communication overlaps with force computation and particle update to save the data copy time between GPU and CPU.

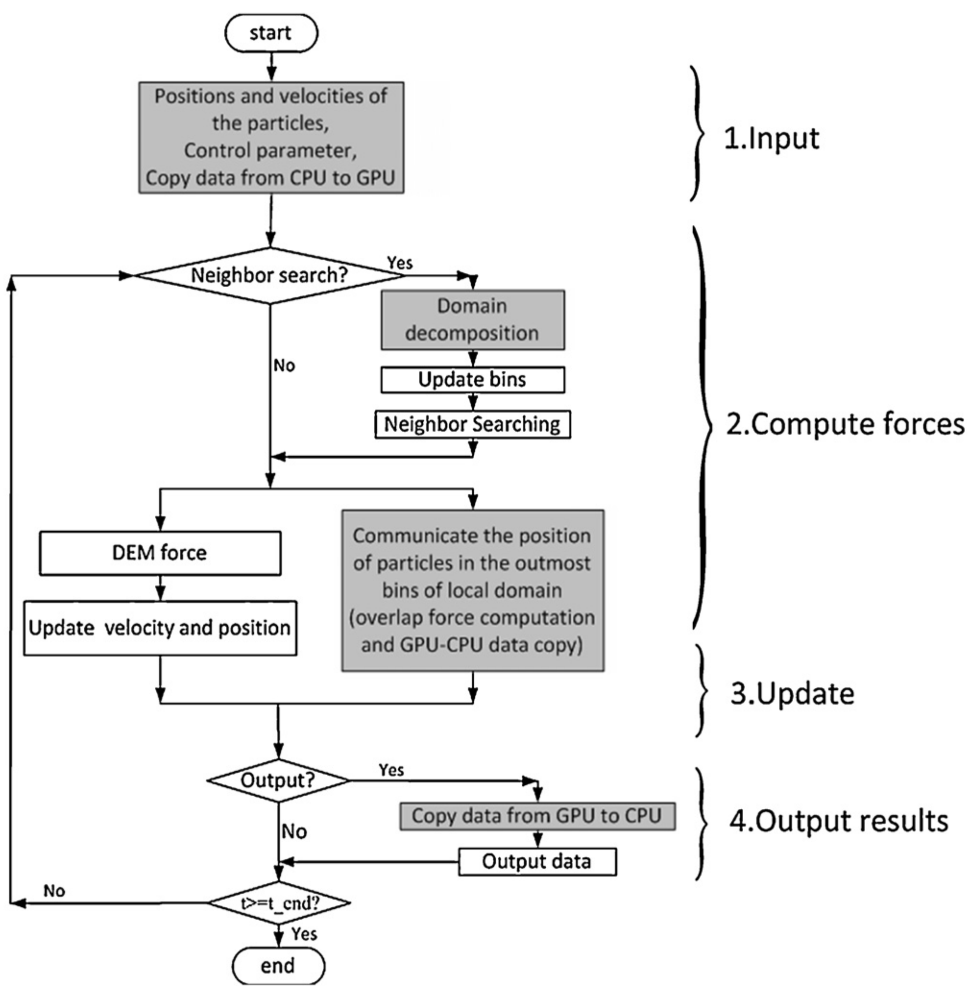

Fig. 1. Flow chart of the simulation procedure. (The grey boxes represent the steps involving communication or data copy between GPU and CPU.)