EPSC Abstracts
Vol. 12, EPSC2018-1056, 2018
European Planetary Science Congress 2018

A code for the study of gravitational aggregates with non-spherical particles

Fabio Ferrari, Michèle Lavagna
Politecnico di Milano, Milano, Italy, (fabio1.ferrari@polimi.it)

Abstract

A recently popular way to study the internal properties and structure of "rubble pile" asteroids is to study them as gravitational aggregates, through numerical N-body simulations. These methods are suitable to reproduce aggregation scenarios after disruption and allow the study of the dynamical and collisional evolution of fragments up to the formation of a stable aggregate or to their dispersion. This work presents a numerical implementation of the gravitational N-body problem with contact dynamics between non-spherically shaped rigid bodies. The work builds up on a previous implementation of the code and extends its capabilities. The number of bodies handled is significantly increased through the use of a CUDA/GPU-parallel octree structure. The main features of the code are described and its performance are compared against CPU-parallel architectures and classical direct N^2 integration. Preliminary results and examples of scenarios that could benefit from such implementation are presented, with application to asteroid gravitational aggregation problems.

1. Introduction

The study of aggregation phenomena mostly relies on codes optimized for a large number of mutually interacting particles, including parallel N-body tree codes [9, 13, 12, 11], hybrid codes [1], adaptive algorithms of optimal orders [10], systolic algorithms [5], or more generally symplectic codes [14, 6, 4]. These handle a large number of particles regardless of their individual shape and rigid body motion. Although not relevant for many applications, this limitation could be relevant for the case of asteroids [8], as suggested by results of granular dynamics in terrestrial engineering applications. The latter are commonly studied using multi-body codes, able to simulate contact interactions between a large number of complex-shaped bodies, but not suitable for gravitational dynamics. The code presented here is developed to joint the advantages of both classes of codes into a single implementation, to reproduce N-body gravitational dynamics between a large number of complex-shaped rigid bodies.

2. Numerical implementation

This work builds on a previous implementation of the code [7] and extends its capabilities by including a parallel CUDA-GPU octree structure. The following paragraphs briefly summarize the main features of the code.

2.1. Contact dynamics

Concerning collision and contact dynamics, the N particles are treated as three-dimensional rigid bodies of arbitrary shape. Each body possesses rotational degrees of freedom, a tensor of inertia and a mesh to be used for collision detection. In our implementation, bodies can collide and re-bounce in collision types ranging from fully elastic to complete inelastic, depending on the selected restitution coefficient. Because we assume the rigid nature of bodies, contact forces are discontinuous and lead to a non-smooth constraint-based problem. In addition, the code provides the choice to select smooth penalty-based (soft-body) contact solver, which is best suited for high velocity impact dynamics. The interested reader can refer to [7] for further details.

2.2. GPU-parallel octree structure

Compared to direct N-body integrators, algorithms based on tree data structures rely on more dynamic and adaptive computations that allow for a significant reduction of time complexity from $O(N^2)$ up to $O(N\ \log(N))$. Our code implements the Barnes-Hut algorithm [2], which groups particles using a hierarchy of cube structures. A node in the algorithm corresponds to a cube in physical space. Because of the use of octrees, each node has eight child nodes obtained by a simple homogeneous spatial subdivision performed along the three principal axis of the system. The tree is therefore built by recursive sub-division until each node of the tree contains zero or one particle. The structure is adaptive, implying that the size of the tree is not fixed but comes as a result of the repartition of the particles in the 3D space.

The implementation of the Barnes-Hut algorithm on a GPU using CUDA language is inspired by the work of Burtscher and Pingali [3]. The physical domain is divided into sub-domains and the bodies are grouped following the octree structure. The numerical tasks to follow the Barnes-Hut algorithm have been divided among five kernels, to be executed sequentially on the GPU.

3. Numerical simulations

Numerical simulations are performed under many degrees of freedom. To reproduce asteroid aggregation scenarios, it is important to carefully select the physical properties of the N bodies and their initial dynamics. Initial conditions play a crucial role to the formation of the aggregates and their properties. As mentioned, bodies are modeled as complex-shaped bodies and their initial dynamical state includes relative position and velocity of their center of mass, angular position and spin rate. Other relevant simulation parameters include integration time step, to be chosen according to the characteristic time of dynamics [7]. These include gravitational dynamics (slow) and contact/collision dynamics (fast). Due to a more restrictive requirement, the latest drive the selection of the time step, which is tuned according to the fastest dynamics of the system. The number of bodies (10^4 in our simulations), their characteristic size and maximum initial distance between them are also key aspects. The physical properties of fragments (density and surface properties) are also to be chosen. Figure 1 shows an example of aggregation process.

4. Summary and Conclusions

The work presents a GPU-parallel numerical code for the study of collisional and gravitational evolution of “rubble pile” asteroids. At this preliminary stage, the code is able to handle up to 10^4 complex-shaped interacting bodies. Preliminary results on scenarios simulated are very promising and hint a good capability of the code to reproduce asteroid aggregation scenarios.

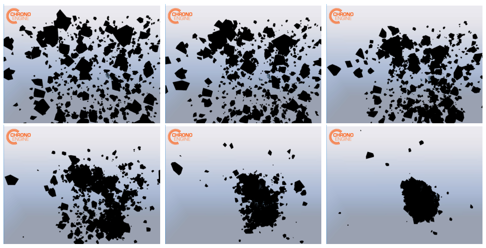

Figure 1: Aggregation sequence example with 1000 bodies

Acknowledgements

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 800060.

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