Small-Body Lander/Hopper Simulations using the GPU

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Keyword: asteroid, comet, lander, hopper, simulation

Asteroids and comets, known collectively as the *small bodies* of our Solar System, have been receiving ever-increasing attention as potential targets for both Discovery- and New Frontiers-class space missions. They are expected to provide a window through time into the conditions of the early Solar System, and may teach us about its formation and evolution. Similarly, these missions may provide a proving ground for planetary defense strategies and in-situ resource utilization techniques. The science returns from past missions were provided primarily through remote sensing operations from an orbiting spacecraft; this return may be increased significantly by including a lander and/or surface mobility operations. The delivery of a lander to the surface of a small body is often challenging, however, as experienced by both the *Philae* and *Minerva* landers. To convince future mission designers to include landers/rovers as primary payloads, we require methods to predict the settling statistics for various deployment strategies. Similarly, to demonstrate controlled mobility of a surface hopper and the effectiveness of on-board autonomous planning, high-fidelity simulation software is required.

Previous work on the motion of small-body landers has established techniques to model the complex gravitational field and surface of a small body at high resolution and low numerical burden. The presence of rocks on the small-body surface, as observed on asteroid Itokawa by the Hayabusa spacecraft, is accounted for using a procedural geometry generation technique. The previously developed software can be used to validate lander deployment strategies and to investigate sensitivities to uncertain parameters. Significant effects due to the lander mass distribution and shape, density of rocks on the surface, and surface interaction coefficients on the resulting deployment statistics have been identified. Although our CPU-based implementation of this software is effective, its performance is limited.

In this work, we present techniques to perform lander/hopper simulations using graphics processing units (GPUs) instead, as they provide massive parallelization compared to a CPU. Furthermore, the GPU's architecture enables various novel modeling strategies. We voxelize the small-body gravitational field and pre-compute it offline using a polyhedron model, and then perform inexpensive linear interpolations online. Instead of representing the surface with an explicit polyhedron, it is *implicitly defined* by a signed distance field (SDF), which allows for fast spatial queries, such as collision detection. Furthermore, the SDF is well-suited to the addition of detailed surface features, such as rocks, craters, and small cracks, by procedurally distorting the SDF with multiple octaves of fractal noise. The amplitudes and frequencies are chosen to match orbital observations; see Fig. 1. We evaluate both collisions and continued contact of an arbitrary-shaped lander/hopper with this surface using a distributed penetrating contact model. Changes in the local surface in response to collisions/contact are captured through local modifications of the surface interaction coefficients.

The resulting comprehensive lander/hopper simulation software enables full life-cycle simulations: from mothership release, to bouncing and settling on the surface, and to hopping surface mobility operations. We present the methodologies used in and first results provided by this novel technique.

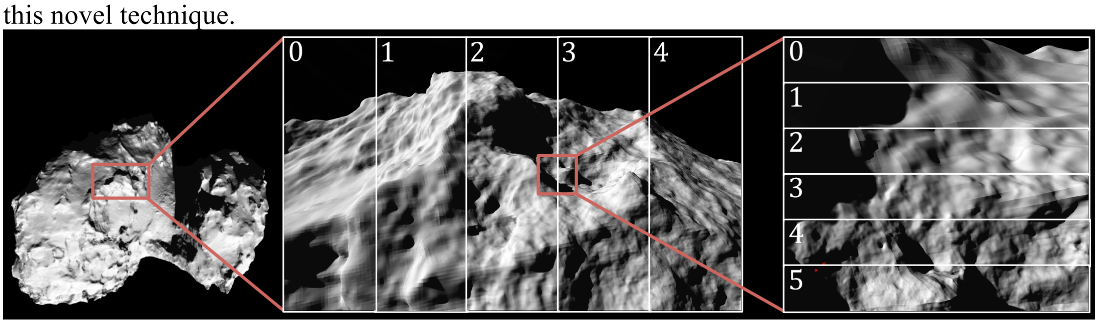

Fig. 1. Artificially generated features on the surface of comet 67P/C-G at increasing noise levels.