10. The Surface Environment on Asteroids

The goal of many space missions to small bodies, such as the Hayabusa mission to Itokawa and the forthcoming OSIRIS-REx mission to asteroid 1999 RQ36, are to take samples from the surface of the body. The prospect of designing a transfer to an asteroid surface and choosing where on the surface to sample begs several questions related to the flow of material across an asteroid surface, possible regions of stable resting points, and the surface forces and slopes that a landing spacecraft will encounter. The detailed design of surface encounters rests heavily on the capabilities and design of the proposed spacecraft. A series of interesting case studies for the Hayabusa spacecraft and its successful touchdowns on the asteroid Itokawa surface were summarized in [81, 201, 64, 84]. In the following we take a more dynamics and mechanics oriented approach and describe the surface environment due to gravitational and rotational effects, describe measures of surface stability, and discuss some simple characterizations of the ballistics of bodies from the surface of an asteroid. This chapter does not probe the interesting question of how surface rovers should be designed and operated in order to achieve specific goals (see [85]).

10.1 Surface Specification

The physical surface of the asteroid to be specified can be defined by a constraint function $S(\mathbf{r}) = 0$, where $S > 0$ corresponds to a positive altitude above the surface and $S < 0$ would be below the surface. On the surface of the asteroid the gradient of $S$ is defined as the surface normal, $S_{\mathbf{r}} = \hat{n}$, and is itself a function of position on the asteroid surface. If the asteroid shape is specified as a polyhedron, then the constraint consists of a series of flat plates with constant normal vectors that become discontinuous at edges and vertices. The second partial of $S$ is identically zero if on a flat facet, and is not defined as the surface point changes from facet to facet. If the surface is specified as a smooth function, such as the popular Gaussian random shape models [113], the second partial can be non-zero and would describe the local topography. An actual asteroid surface will, of course, consist of a highly discontinuous function as asteroid surfaces are often covered with boulders,
cobbles and blocks [108]. Thus, the use of a flat or smooth surface is an obvious simplification that describes macroscopic properties of the surface while ignoring its small-scale features.

10.2 Surface Geopotential

A quantity of interest for the surface environment is the effective potential, defined by the combined gravitational potential and rotational potential terms. For a uniformly rotating body this is just the Jacobi integral discussed earlier, evaluated at rest on the asteroid surface. This provides a relative measure of the available energy that can be converted to kinetic energy (and hence easily dissipated) based on the location of a particle in the asteroid frame. The effective potential energy function of an asteroid is:

\[ V(r) = \frac{1}{2} r \cdot \tilde{\omega} \cdot \tilde{\omega} \cdot r + U(r) \]  

(10.1)

where \( \omega \) is the angular velocity vector of the body and can be time-varying. Uniform rotation is generally assumed in this chapter (see [173, 165] for a discussion of surface slopes on a non-uniformly rotating body). Using this, the dynamical height of the asteroid surface can be computed, a relative measure from a locally defined average gravity [181].

A more direct interpretation of the surface geopotential is to link it directly to possible dynamical motion across the asteroid surface. Recall from the Jacobi integral that the quantity \( J = \frac{1}{2} v^2 - V(r) \) is conserved during ballistic flight, if the body is uniformly rotating (which is assumed for the current discussion). Here \( v \) is the speed of the particle in the body-fixed frame. Thus, given two points at rest on the surface of the asteroid, \( r_o \) and \( r \), the ideal kinetic energy required for an object to move from one location to the other can be compared. Assume that the body is at rest at point \( r_o \) and that the two points will be linked by a ballistic trajectory (independent of the existence of a ballistic trajectory between these two points). Then the two Jacobi integral values can be equated to find:

\[ \frac{1}{2} v^2 - V(r) = -V(r_o) \]  

(10.2)

and solved for the speed required to link the two points on the surface

\[ v = \sqrt{2(V(r) - V(r_o))} \]  

(10.3)

To be defined, the quantity \( V(r) - V(r_o) \geq 0 \), and thus the point \( r_o \), must lie at a lower point in the geopotential. If this speed is to be defined everywhere on the asteroid surface relative to the rest point \( r_o \), the rest point must be taken at the lowest value of the geopotential on the surface. Then the geopotential across the asteroid surface can be defined in terms of the kinetic energy or speed required to boost a particle from the rest point to another point on the asteroid. Conversely,