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CATCHING A ROLLING STONE: DYNAMICS AND CONTROL OF A SPACECRAFT AND AN ASTEROID

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The National Aeronautics and Space Administration is currently investigating a conceptual robotic mission to collect a small Near-Earth Asteroid (NEA) or a small boulder resting on the surface of a large NEA, and transport it to an orbit in the Earth-Moon system. An object with a diameter of roughly 7 m is of interest. Such a mission would lead to greater scientific understanding of NEAs and serve as preparation for planetary defense. This paper is concerned with dynamics and control of the spacecraft (S/C) trajectory and attitude in the terminal phases of a rendezvous with the object, as well as the attitude of the S/C after its payload has been secured. We assume the method of collection imposes two requirements on the S/C motion. First, the S/C must approach by translating along a line fixed in the object. Second, the angular velocity of the S/C relative to the object must be eliminated prior to contact. Furthermore, we assume that the angular velocity of the S/C relative to an inertial reference frame must be made to vanish after the payload is collected. Exercise of control in these ways is just as important for asteroid deflection as it is for retrieval.

In the interest of simplicity, the heliocentric orbit of the NEA is taken to be circular, the NEA is treated as a rigid body, and the gravitational force exerted by the NEA on the S/C is neglected. Rotational motion of the NEA is modeled as torque-free, before it is captured. A NEA having three distinct central principal moments of inertia is referred to as unsymmetric, and its angular velocity can be expressed as a function of time in terms of Jacobian elliptic functions. In the special case of two identical central principal moments of inertia, the NEA is axisymmetric and its angular velocity can be described simply in terms of spin about the symmetry axis, together with precession about the angular momentum vector.

For the purpose of studying trajectory control, the S/C is regarded initially as leading or trailing the NEA in the same orbit, so that there is no relative translation between the two. From this station, the S/C moves to a point on a line passing through a target point on the NEA surface and fixed in the NEA (line of descent). A multi-impulse trajectory is used to reach the point on the line of descent; the total velocity increment (ΔV) is minimized with an interior-point optimization algorithm, which contains a collision-avoidance constraint consisting of a keep-out zone that envelops the NEA and has a simple geometric shape, such as a sphere or an ellipsoid. A set of target points distributed over the NEA surface is considered, and propellant consumption is reported for the corresponding multi-impulse trajectories. After reaching the point on the line of descent, the S/C remains there for a period of time and hovers above the target point. ΔV and propellant consumption required for hovering are reported. While the S/C hovers, additional observations of the target can be made.

Removal of relative angular velocity between S/C and NEA proceeds in two steps: first, there is an initial reorientation of the S/C, followed by spacecraft spin-up. The S/C is regarded as an axisymmetric rigid body, and it is assumed that operation of the capture mechanism requires the S/C symmetry axis to be parallel to the line of descent. The attitude maneuver required to reach this orientation can be accomplished slowly, by briefly firing Reaction Control System (RCS) jets at the beginning and end of the maneuver, and only a small amount of propellant is needed.

A spin-up feedback controller is designed to bring about and maintain a S/C inertial angular velocity that is identical to the inertial angular velocity of the NEA, which is presumed to be a known function of time. The controller makes use of a two-parameter description of the direction of the line of descent with respect to the S/C. It is assumed that effective use of the capture mechanism does not require any particular relative orientation, about the symmetry axis, between the S/C and the NEA. The controller works equally well for an unsymmetric or axisymmetric NEA.

Subsequent to spin-up, the S/C translates at a constant speed along the line of descent until the capture mechanism makes contact with the object of interest. ΔV and propellant consumption required for descent are reported.

Once the payload has been secured, the S/C must undergo de-spin. This is necessary, for example, to orient solar arrays properly or to aim thrust in the direction needed to return to the Earth-Moon system. During torque-free motion, the direction of angular velocity changes continuously with respect to the S/C. Certain angular velocity directions can be dealt with more efficiently than others because certain RCS jets have larger moment arms than others. In fact, it can be advantageous to perturb rotational motion by firing RCS jets briefly in order to create a more beneficial time-history of angular velocity. A feedback controller is designed to apply appropriate perturbations and use RCS jets in an efficient manner to minimize propellant consumption required for de-spin.

Numerical simulation results are illustrated in interactive animations with the aid of the Exploration Visualization Environment (EVE), which supports design and planning of space missions. Time histories of position, attitude, thrust direction, and thrust magnitude, for example, can be used to animate detailed graphical models of S/C and asteroids in a full-scale, three-dimensional solar system. EVE has been used in this effort to visualize relative motion with realistic scaling of the bodies. The tool can also be used to study clearance distance and detect a collision between, say, a solar array and the irregular surface of a NEA during sample collection.