ORBITAL AND LANDING OPERATIONS AT NEAR EARTH ASTEROIDS

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Abstract

Orbital and landing operations about near-Earth asteroids are different than classical orbital operations about large bodies. The major differences lie with the small mass of the asteroid, the lower orbital velocities. the larger Solar tide and radiation pressure perturbations, the irregular shape of the asteroid and the potential for non-uniform rotation of the asteroid. These differences change the nature of orbits about an asteroid to where it is often common to find trajectories that evolve from stable, near-circular orbits to crashing or escaping orbits in a matter of days. The understanding and control of such orbits is important if a human or robotic presence at asteroids is to be commonplace in the future.

Much of the difficulty in maneuvering very close to a small body stems from ignorance of the shape, spin state and gravity field of the target. For this reason, accurate *a priori* physical models of targets can dramatically reduce the cost and risk of asteroid missions.

Recent studies of orbital dynamics about asteroids deal with the dynamics of natural items such as ejecta ([3], [10]) and man-made objects such as spacecraft orbiters ([1], [9]). The results from these studies will be presented in a concise form, and applications of these results to engineering activities about near-Earth asteroids will be given. Specifically, different types of landing and rendezvous operations will be reviewed, and the basic problems of each approach discussed in brief.

In conjunction with this paper specific examples of orbiter and lander trajectories at asteroids are available in a video format. These examples use shape models obtained by inversion of radar images of asteroids 4769 Castalia and 4179 Toutatis ([4], [5], [6]) and highlight the process of landing a spacecraft on an asteroid.

1 Introduction

The most exciting aspect of orbital operations in an asteroid vicinity is dealing with the irregular shape and (potentially) complex rotational state of the body. Some aspects of classical orbital theory can be applied to these situations, yet in many other instances new orbital theories must be developed to describe the possible situations which arise, An item of great importance is the proper modeling of the asteroid environment, focusing mainly on the shape, gravity field and rotational dynamics. These issues are crucial if operations of any sort are to be carried out in the vicinity of asteroids,

Landing and orbital operations at asteroids can be categorized with respect to the strategies and intent of the encounter, The first phase, which is common to all the strategies, is the initial encounter and arrival of the spacecraft at the asteroid. The strategy taken after rendezvous will be a function of the type of landing envisioned: soft landing, hard landing, orbit only and high-velocity impact. Each of these strategies has peculiarities which will be briefly discussed.

2 Dynamics and Modeling

In terms of the orbital dynamics about them, asteroids may be divided into several classifications. Each of these classifications has a number of sub-trees which point either to increasing stability of orbits or to the increasing prevalence of unstable orbits. The first distinction is between a principal axis rotator and a non-principal axis rotator. The equations of motion and the relevant approximations which can be made differ significantly between these two cases, Currently, the theory indicates that principal axis rotators have a larger degree of orbital instability associated with them (note that in all references, orbital instability or stability refers to the orhits of a particle about an asteroid. and not to the asteroid orbit). Next, within the category of principal axis rotators, one may classify the asteroids in terms of density, rotation rate and shape irregularity, Although these are three different parameters which describe the asteroid geometry, composition and dynamics, they can be united theoretically into providing a single "measure" of the stability or instability of orbits about the asteroids ([1 I]).

Following these broad categories the stability or instability of certain classes of orbits can be used to further delineate between asteroids, these further delineations being a function of the specific asteroid shape, density and rotation rate. Retrograde, low altitude, near-equatorial orbits around principal axis rotators seem to he generically stable. However, as one increase-s orbital inclination from the equatorial plane the orbits will cross a stability boundary at some inclination and be subject to chaotic motion for larger inclinations. Such stability boundaries constitute an interesting area of current research.

It is of the utmost importance to acquire accurate physical models of" small asteroids. Recent efforts that use range-Doppler radar to image near-Earth asteroids has begun to furnish a crucial data base with which to understand the dynamics about asteroids ([8], [6]). Currently, all the shape and rotational state models which have been found have an ambiguous density associated with them and rely on constant, density assumptions. This will change with the NEAR mission to Eros ([2]), where an actual asteroid density will be measured to great accuracy, and its gravity field measured and inspected for density inhomogeneities ([7]). Such observations will provide further insight into these usually unobservable properties of asteroids.

3 Asteroid Encounter

The traditional approach for asteroid encounters would be to use radiometric tracking for spacecraft navigation, with optical navigation images prior to encounter with the asteroid. For an impact trajectory, the only concern may be that the S/C impacts the asteroid, although some control of the impact speed may he desired. Alternatively, for orbit and landing strategies the S/C-asteroid relative velocity must be nulled out to allow the S/C to become captured by the asteroid. This process of rendezvous can either be controlled by a series of impulsive maneuvers, or by a constant low-thrust maneuver over several days. The initial relative velocities will usually be on the order of 1 km/sec. With either approach it is important to design the control and orbit determination loop so that the maneuver execution and control errors are always under control.

It may also be possible to incorporate autonomous navigation operations for such a mission, with the S/C sighting on '<beacon)' asteroids during cruise. The total statistical fuel cost associated

with such an approach will be more than ground-based radiometric navigation, but will have the benefit of decreased ground operations. Depending on the specific goals of the mission, some form of autonomous navigation using optical imaging may be a necessity, as explained in the following sections.

The limiting error source for encounter will be the asteroid ephemeris uncertainty, which may be on the order of 100 km. Note that if the target body has been observed with radar, the ephemeris error may be appreciably smaller, even on the order of 1 km or less if the asteroid has been observed very recently. Potential target asteroids may be quite small, on the order of 1 km or less, so the absolute ephemeris uncertainty may make open-loop navigation to the target body impossible unless radar observations are carried out shortly before encounter ([8]).

4 Landing and Operation Strategies

The following subsections outline the different approaches and strategies for a variety of asteroid encounter scenarios. In increasing order of difficulty these are: high velocity impact, orbit, bard landing, soft landing and return.

4.1 High Velocity Impact

The intent is to impact the asteroid within a specified high velocity range. The impact velocity control is effected by performing a maneuver some days before impact to set the relative velocity to the proper level and to re-target the S/C toward the center of tile asteroid. Following this maneuver. a final correction and re-targeting maneuver will have to be made near closest approach using optical data,

Given an observation of an asteroid against, the star background the uncertainty of the S/C trajectory in the impact plane can be approximated as $\sigma_b \sim R\sigma_\alpha = V_I T \sigma_\alpha$, where σ_b is the uncertainty radius in the impact plane, R is the S/C range to the asteroid at the time of observation, σ_α is the pixel size of the opnav camera (or a fraction of the pixel size depending on the processing techniques used), V_I is the impact speed, and T is the time to impact. Let us assume an impact speed of 1 km/s and a desired uncertainty in the impact plane of 100 meters. Then one finds a simple relation between the time of data cutoff for the design of the final correction maneuver and the necessary camera accuracy:

$$T = \frac{\sigma_b}{V_I \sigma_\alpha} \quad (1)$$

$$\sim 0.1/\sigma_\alpha \quad (2)$$

Typical camera accuracies may range from 0.1 rnrad (for an inaccurate camera) to 1μrad for au accurate camera, providing data cut-off times which range from 17 minutes to 1.2 days, respectively Assuming an incoming targeting error of 10 km, this translates into a 10 m/s burn for the inaccurate camera and a 0.1 m/s burn for the accurate camera. Clearly, there is a fuel cost associated with a less accurate camera.

4.2 Asteroid Orbit

Following a rendezvous sequence and capture at the asteroid, an orbital phase will follow. This could be the only goal of the mission, or a prelude to a landing on the asteroid. If radiometric data is acquired during rendezvous, the mass of the asteroid may be determined.

If orbital operations are to take place far from the asteroid, say at a distance of 10 radii or further, than the body may be treated as a point mass for mission design and control purposes. In this regime, however, the solar radiation pressure may become a significant perturbation which, if left uncontrolled, could drive the S/C into the asteroid surface on the order of 100's of days. Note that there arc stable orbits available in the sun plane-of-sky which balance the solar radiation pressure force against the attractive force in such a way that the spacecraft orbit always faces the sun ([12]). This may be an attractive orbit for constructing a global map of the asteroid.

If orbital operations are to take place within a distance of 10 radii then it is necessary to have a shape and gravity field model of the asteroid. The shape model may be estimated from optical data, once preliminary mapping of the asteroid is complete, or may be obtained prior to encounter by range-doppler imaging of the asteroid ([6]). The latter will enable a far more specific mission plan, aid in identifying regions of interest on the asteroid, and enable a larger degree of navigation] autonomy.

The *a priori* gravity field may be based on the shape model under the assumption of constant density and a total mass estimate that would become refined during the encounter. Then, depending on the desired navigation accuracies and the orbit radius, the gravity field may be improved hy processing the radiometric tracking data. For irregularly shaped asteroids, it is critical that the gravity field be known rather accurately so that the mission avoids orbital instabilities which may cause the S/C to suffer either an unplanned impact with the asteroid surface or an unplanned escape from tile asteroid vicinity. There are some simple rules of thumb which may be used in designing stable orbits about asteroids ([9]), but additional analysis must be done to delineate and map out the stable and unstable regions of orbital motion and the necessary control for the mission.

The mapping orbit strategy will in general be constrained by the rotation pole of the asteroid and the configuration of the S/C. For example, if the S/C has fixed solar arrays and instruments, it must maintain its orbit plane in a specific orientation for it to be able to image the surface and illuminate its solar arrays simultaneously, Due to the irregular shapes of asteroids, there is usually a large secular nodal rate imparted to an orbit. which then may require frequent maneuvers to maintain an orbital orientation which enables mapping.

4.3 Hard Landing

A hard landing is a drop from orbit onto the asteroid surface with no braking maneuver prior to impact. This approach is attractive as it involves no thrusting maneuvers to control descent rate, and avoids some of the modeling issues by falling relatively swiftly down to the asteroid surface. The achievable landing accuracy on the asteroid surface will be a function of the orbit determination accuracy, maneuver execution errors and asteroid modeling errors. The orbit from which the lander is delivered will also play a role in the landing accuracy.

The impact, speed of such a lander may be approximated by a few simple formulae. First, assume that the S/C velocity with respect to the asteroid is nulled out at some radius r_o and the S/C is allowed to fall onto an asteroid of radius r_b. Then the impact speed is approximately:

$$V_I \sim \sqrt{2\mu}\sqrt{\frac{1}{r_b} - \frac{1}{r_o}} \tag{3}$$

where μ is the gravitational constant of the asteroid in question. Letting $r_o \rightarrow \infty$ and assuming an asteroid density of 3 g/cc, one sees that the impact speed will be limited to $V_I \sim 1.3 r_b$ (m/s) where r_b is measured in km.

For control purposes it may be desired to impart a non-zero speed to the S/C at the final maneuver before impact on the surface (this will provide angle of attack control at impact). To compute the new impact speed V_I, one must take the root-sum-square of the non-zero speed with the shove formula to find the new impact speed.

For any landing approach there is a trade-off between performing the impact maneuver at a higher altitude (which costs less fuel) and minimizing the landing error, Assuming a simple situation where a maneuver is performed at an apse to null out the orbital speed, setting up a hard landing on the surface of an asteroid, the control error in the impact site can be approximated as:

$$\delta e \sim f\sqrt{r_p r_a} \tag{4}$$

where f is the fractional error in the executed maneuver (typical values range from 0.001 to 0.01), r_p is the delivery orbit periapsis and r_a is the delivery orbit apoapsis. Note that this expression holds for both periapsis and apoapsis burns, indicating that the fuel efficient procedure would be to drop from the higher, apoapsis altitude, although this yields a larger impact speed. A thorough analysis of the question of delivery accuracy to the surface of a comet is addressed in [13].

4.4 Soft-Landing

A soft landing requires that the S/C perform at least one maneuver prior to impact to minimize the impact speed. If such a landing is to be flown open loop, it is prudent to perform only one or two such maneuvers, as the attendant, execution errors after these maneuvers will make it difficult to design additional such maneuvers without additional data.

A soft-landing strategy is a good candidate for incorporating some degree of S/C autonomous navigation and control. The simplest implementation would require a stable and accurate attitude control system, altimetry measurements during the descent phase and a good asteroid model for integration and prediction of the lateral motion of the S/C. Lateral closed-loop navigation would require some sort of imaging system with landmark tracking or a limb sensing instrument.

Accurate landings will need a closed loop system. The modeling of the asteroid gravity field close to the surface will be important if the S/C is to descend slowly enough to be subject to irregularity in the asteroid gravity field. The field estimated via radiometric tracking during the orbital phase will likely be inaccurate and divergent close to the surface, as it will be evaluated outside of its radius of convergence. This may be alleviated somewhat by only retaining low degree and order terms, or by using a constant density model, but the most effective approach would be to remove the gravity field errors by explicitly controlling the S/C to the target as sensed by the navigation instruments.

If the impact speed is to be limited to a low value, the final maneuver may have to be performed very close to the asteroid surface. Assume that the radial speed is nulled out at an altitude of h, where $h << r_b$, the average radius of the asteroid. Then the impact speed and time to impact are approximated by:

$$V_I \sim \frac{2}{r_b}\sqrt{\mu h} \tag{5}$$

$$T_I \sim 2r_b\sqrt{\frac{h}{\mu}} \tag{6}$$

Table 1 relates a desired impact speed to the altitude of the final maneuver and time to impact for a density of 3 g/cc and two different asteroid radii. Clearly, if the impact speed is to be limited to

	$R_b = 1$		$R_b = 10$	
V_I (m/s)	T_I (s)	h (m)	T_I (s)	h (m)
1.0	1194	299	119.4	29.9
0.1	119.4	2.99	11.94	.299
0.01	11.94	0.0299	1.194	0.00299

Table 1: Last maneuver altitudes and times to impact given impact speed and asteroid radius

much less than 1 m/s, accurate timing and execution of the final maneuver becomes important. For impact speeds less than 0.1 m/s (especially for larger asteroids) it is not clear if this approach would even be feasible.

The alternative to a soft, ballistic landing is a thrusting landing. For an asteroid of density 3 g/cc, the necessary thrust acceleration to null the gravitational attraction at the surface of an asteroid is approximately $85.5 r_b$ μg's. If continuous thrusting is applied during the final descent phase of the S/C, the dynamics are analogous to a free-fall onto an asteroid with a lower mass.

Of course the above formulae are useful only for order of magnitude design purposes. When considering an actual trajectory the role of the irregular shape and gravity field of the asteroid becomes very important, both from the standpoint of S/C dynamics and from the standpoint of reducing any measurements taken during descent. Improper modeling of either of these may lead to an incorrect maneuver or thrust level being set during descent, and a consequent escape or "harder" landing on the asteroid surface.

once on the surface, if the S/C *is to roam* it will be important that a surface gravity field be known. This will enable the S/C to design surface movements which will not result in the S/C jumping off' of the surface or becoming subject to steep slopes. The surface gravity will be irregular and weak enough so that careful planning and control must be made for surface operations. The prime mode] for surface gravity is the polyhedron model, which provides the exact constant density gravitational field for an arbitrary polyhedron ([14]). This field is non-singular at the surface of the body and can be easily modified to account for any local density inhomogeneities which arc believed to exist.

4.5 Return to Orbit

Given a successful soft landing on an asteroid, the design and implementation of a return trajectory is much simpler. A typical sequence would consist of at least three burns which could be pre-programmed with sufficient accuracy, These consist of an initial burn to lift the S/C from the asteroid surface to some altitude, followed by a burn that turns the current altitude in the orbit periapsis and moves the orbit apoapsis a safe distance from the surface, followed by a third burn at orbit apoapsis which raises periapsis to a high, safe altitude.

5 Conclusion

The unique requirements of missions to small asteroids stem from two factor-s: (i) orbital dynamics that are intrinsically complex and depend strongly on the target's physical properties, and (ii) ignorance prior to encounter of those properties, especially three dimensional shape, spin state, mass and gravity field. Clearly, the time line of any close-encounter mission would be speeded up if a reliable pre-encounter model were available, Physical models constructed] from ground-based radar imagery could dramatically reduce the complexity, cost and risk of such missions.

This paper discusses the different types of asteroid landing trajectories and some particulars of their implementation. If such a nrission is planned to an asteroid, it may be the case that time be of the essence. In such a situation the entire time line from encounter to landing would be greatly speeded if a pre-existing shape and rotation state model of tire asteroid exists, estimated from range-dopl)ler measurements of the target asteroid,

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