Interactions Between Ground-Based and Autonomous Navigation for Precision Landing at Small Solar-System Bodies

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This article describes and discusses the navigation fundamentals needed for designing a precision-landing mission to a small solar-system body such as a comet or asteroid. The discussion focuses on the unique aspects of a small-body landing, the roles that ground-based operations and data types have, the roles that body-relative data types have, the constraints under which an autonomous system must operate, and the interaction and cooperation that must exist between all these aspects. Some specific examples of precision-landing capabilities are included for the Near Earth Asteroid Rendezvous (NEAR) spacecraft at the end of its prime mission and for the Champollion spacecraft.

I. Introduction

Small bodies, such as asteroids and comets, have been of increasing interest lately due to a desire to understand the primal constituents of the solar system, to further understand dynamical processes in the solar system, and to better understand those objects that occasionally impact with the Earth and other planets.

In response to this interest, there has been an increase in the number of proposed missions to these bodies. A common feature of many of these proposals is a phase of orbiting close to the body or a landing phase when in situ measurements can be made. This article addresses some of the basic questions that must be dealt with in these situations in terms of the navigation concerns that must be faced. It also includes some specific examples of precision-landing navigation deliveries for different combinations of ground and autonomous data types. Background on the problem of navigation about a small body is provided in [1–7].

II. The Small-Body Environment

The small-body environment is interesting from many different aspects. Scientifically, it represents a poorly understood element of the solar system that, in many ways, has played important roles at different stages of the solar system's development. From a navigation viewpoint, it is a challenging environment that brings issues of modeling, orbit determination, trajectory design, and control into one

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tightly correlated process. There are numerous other issues of interest as well, but this article will not develop those other lines of thought. In the following subsections, some of the essential elements of the navigation problem are identified and discussed.

A. Spacecraft Dynamics at a Small Body

Spacecraft dynamics about a small body such as a comet or asteroid are significantly different from their dynamics in heliocentric orbits or orbits about massive planets. The reasons for these differences can be attributed to several facts that combine to change the nature of orbits about small bodies.

First is the small mass of these bodies. This leads to relatively larger perturbations due to solar radiation pressure and the solar tide when in orbits that are fairly distant from the body (on the order of tens of radii). When orbiting closely to a small body, these perturbations become smaller and often can be ignored when considering orbits over shorter time spans.

The second difference is due to the irregular shapes that small bodies usually have. This leads to a gravity field with significant deviation from an oblate sphere, which is the usual case for a planet's gravity field. In terms of the dynamics of a spacecraft, the most important gravity field terms are those up through degree and order four. Due to interaction of a spacecraft with an irregular gravity field, it is common to find orbits that transition from initially circular to impacting or escaping orbits within a few days or hours in some cases. Proper design of the nominal spacecraft orbit often can minimize this effect, but in many situations a landing trajectory cannot be chosen under the appropriate design constraints and must deal with these large perturbations as the spacecraft flies toward its desired landing site.

The third difference is due to the rotation state of the body. The rotation periods of small bodies vary from a few hours to tens of days. Also, it is not uncommon to find comets and asteroids that are in nonprincipal axis rotation. The rotation state of the body will combine with its nonuniform gravity field to yield a large range of dynamical effects on a spacecraft orbit.

The final difference is found only at comets, where significant outgassing may act on a spacecraft and change its orbit significantly over a short time span. If the outgassing is strong enough, the spacecraft may be ejected from orbit about the body, while lower levels of outgassing may make it difficult to predict and control the spacecraft orbit over reasonable time spans.

B. Modeling the Small-Body Environment

The impact of the above differences makes it essential that the small body and its force environment be characterized properly upon initial rendezvous. All feasible orbital missions and the majority of feasible landing missions on a small body will require an initial period of a few weeks to months during which the body is characterized appropriately.

The mass of the body is measured early in the initial phase using Doppler tracking of the spacecraft. Other schemes that rely on a combination of optical data, calibration maneuvers, and accelerometer measurements also are possible, but they currently cannot approach the accuracy of the Doppler measurement.

To move from the mass determination to the gravity field determination first requires that the rotation state of the body be determined. This is best done using optical images of the body taken before strong interaction with its gravity field occurs. Doppler and range data are important because they allow the spacecraft orbit to be determined precisely, which allows for the body images to be registered properly to yield the body's true orientation in inertial space in each image. The accuracy of this determination is a function of the number of rotations over which the image data are collected. Thus, a slowly rotating body may require a longer time to generate an accurate rotation state. It may be feasible to perform this initial rotation analysis autonomously, but for the end result to be accurate requires that the spacecraft orbit relative to the body be accurately determined, which generally implies the use of radio metric data.

Once the state of the asteroid or comet rotation is determined, it is possible to begin accurate determination of the coefficients of the gravity field. Doppler data play an essential role here since they provide a direct measure of the acceleration acting on the spacecraft over short time spans. Optical data are valuable as well because they serve to pin the spacecraft position relative to the target. Range data are not as valuable in general; however, if precision range points of 1 to 5 meters can be acquired consistently, then they will aid in tying the optical and Doppler measurements together. In general, the process of improving the gravity field estimate occurs simultaneously with improving the body's rotation state estimate.

For a comet, the appropriate process for determination or characterization of the outgassing field is still an open issue, although some similarities will exist between this and the determination of the gravity field. Both Doppler and optical data again will be important measurements to determine the acceleration and position of the spacecraft relative to the comet.

C. Landing Goals and Their Impact

Finally, the specific landing goals of the spacecraft play an important role in deciding upon the necessary fidelity of the body model and the types of surface characterization that must be performed. If a high-speed impact with the body is desired, the need to model the body dynamics accurately may be reduced. Alternatively, if a precise, guided landing on the body is desired, it is necessary to develop accurate landmark maps of the surface in addition to a high-fidelity dynamic model of the body.

III. Ground-Based Involvement

The involvement of the ground (i.e., Earth-based mission components) in the operations at a small body leading up to and including the landing phase are pervasive and cannot be done away with in the near future. In the following subsections, the different activities in which the ground is involved and the prospects of moving these on board the spacecraft or of eventually eliminating them are discussed.

A. Ground-Based Data Types

The nominal data types associated with radio metric tracking are Doppler and ranging. Once orbit is achieved about the small body, the power of the ranging data type is somewhat diminished, although precision ranging techniques will supplement the Doppler data and allow for more precise orbit determination.

Clearly, however, Doppler data will be the baseline measurement associated with the ground data types. Starting with no a priori information, the spacecraft must be tracked for at least one orbit for a partial orbit determination to be performed; in general, the argument of the ascending node in the Earth's plane of sky will not be determined immediately. Thereafter, the changing geometry of the Earth and small body will allow for a complete orbit determination over multiple orbits. Given a priori knowledge of the orbit, Doppler tracking will allow for a continuing knowledge of the orbit in inertial space.

It is feasible for Doppler data to be processed on the spacecraft, essentially serving as an autonomous data type for onboard use. Such tracking schemes usually imply that the Doppler is one way, which in turn usually decreases the measurement accuracy (due to oscillator stability issues) and, hence, the utility of this measurement. But this is not always the greatest concern. Once the small-body model is well developed and the spacecraft is on a nominal path, autonomous processing of the Doppler data is feasible. However, during the initial stages of model development, human interaction often is needed to guide the linear process of model estimation in a nonlinear environment. In addition, there are advanced concepts being proposed that have two-way tracking, which may be extracted on board the spacecraft.

B. Target-Relative Data Types

Target-relative data types that often are processed on the ground include optical images and altimetry. Depending on the proposed use of the data, either can be processed on board, on the ground, or with some mix of the two. During the initial period of body characterization and landmark data base development, the optical data generally will be processed on the ground. Once a stable landmark data base is developed and the body is well characterized, it becomes possible to transition the processing function to occur on board the spacecraft.

Processing of the altimetry data depends on the specific use for the measurements. If they are needed only to sense altitude during the final phases of a landing, the altimetry data should be processed on board the spacecraft and used with an appropriately designed filter and control loop. If used to generate a global topography map of the body while in orbit, or if used in the orbit determination process, the altimetry data generally will be processed on the ground.

C. Ground-Based Operations

Ground-based navigation operations are, in general, limited by two factors. The first is the round-trip light-time between the station and the spacecraft; the second is the processing time, consisting of data conditioning, orbit determination, orbit maneuver design, and the process of taking these maneuvers and translating them into spacecraft commands. There is nothing that can be done about the round-trip light-time. However, the ground-processing turnaround time always is open to improvement. For many missions, the traditional ground-processing time delays are satisfactory and can be minimized when necessary at important events. For a spacecraft landing on the surface, however, this may not be the case because the necessary turnaround time between measurements and corrective actions will be very short. The exception to this is if the a priori uncertainties from the orbit determination, small body model estimate, and controllability of the spacecraft are accurate enough to meet the landing criterion.

Ground-based operations are essential, however, in building toward the final landing phase of the mission, especially if accurate delivery is needed. This is true currently because ground-based data types and processing techniques invariably will be more accurate than onboard measurements and processing techniques due to the greater control over measuring devices (i.e., DSN tracking stations and accurately calibrated models of optical and altimetry measurements) and to the human interaction in the estimation and maneuver design process. Thus, reliance on ground-based operations is important during the initial characterization, during the orbit maintenance period, and leading up to the landing trajectory, since the more accurately the nominal landing trajectory can be designed, the less burden is placed on the autonomous system.

IV. Onboard Autonomous Involvement

The exciting aspect of small-body landers is that the ground-based system often cannot accomplish the entire task; thus, it is necessary to incorporate some degree of autonomy in the navigation system. The level of autonomy needed is a complex function of the mission at hand, the capabilities of the ground system, and the degree of precision required in the landing. The following subsections identify the major components needed in an autonomous navigation system.

A. Target-Relative Data Types

Target-relative measurements that are usable from a navigation point of view generally include optical observations of the body and altimetry measurements. Additional "high-tech" combinations of such measurements include scanning laser altimeters and surface beacons that broadcast a known frequency and/or send out time-stamped signals.

Optical observations are useful when they are compared with a known map of the body, allowing for the observed image to be compared with a stored map containing limbs or landmarks whose positions in the body-fixed frame have been determined prior to use of the autonomous system. The offset between the predicted location of the map features and the actual locations is used to update the orbit estimate. The combination of several such measurements yields the position of the spacecraft in the body-fixed frame.

Autonomous altimetry measurements are useful mostly for determining the instantaneous range from the spacecraft to the body surface. The spacecraft attitude is an important component of the measurement and, in combination with the range measurement, gives the position vector of the spacecraft if the location of the measured point on the body is known. Note, however, that the attitude determination generally is performed without reference to the body frame, and thus systematic errors, which cannot be detected using this data type alone, easily are introduced. Comparing a time series of altitude measurements with a topography map of the body can be used to extract the path of the spacecraft over the asteroid surface; however, the processing of this type of measurement would be computationally intensive and relies on a long data arc in order to generate solutions. Due to these constraints, the best use of an altimeter for a landing trajectory may be as a simple altimeter from which altitude and altitude descent rate can be determined.

The use of beacons for autonomous navigation during an orbital or landing phase is quite attractive from a navigation point of view. Having several such beacons on the surface can provide Doppler and/or ranging information between the spacecraft and the beacons that easily can be turned into position and velocity estimates of the spacecraft in the body-fixed frame. For the beacons to be usable, however, it is required that there be some degree of stability in the beacon reference frequencies and clocks and that the location of the beacons on the body surface be well determined prior to their use. To perform this determination and calibration accurately probably will entail the use of ground tracking of the spacecraft and will require the spacecraft to retransmit the signals from the beacons to the Earth stations, where all the data could be combined to extract position and calibration estimates for the beacons.

The above measurements are by no means exhaustive in terms of the possible types of body-relative measurements. There may be a wide range of other sensor types and combinations that could yield valuable information that could be used during the spacecraft descent either to estimate the spacecraft's position and velocity in the body-fixed space or to measure some surface-relative quantities such as local horizontal speed and descent rate.

B. Spacecraft-Based Measurements

An essential component of any autonomous system are those measurements that can be made on board the spacecraft, namely, attitude estimates and acceleration measurements. The accuracy to which these quantities can be estimated and predicted relate to the ability of the spacecraft to deliver precise maneuvers and supply pointing information at the time other body-relative measurements are made. The attitude and acceleration measurements generally are estimated and known accurately in inertial space, so to transfer these quantities into the body-fixed space without significant degradations in accuracy requires that the body rotation state and attitude be known to a similar degree of precision. Significant inaccuracy in either the spacecraft-based measurements or the body attitude can severely corrupt the ability of an autonomous navigation scheme to deliver the spacecraft to the appropriate landing conditions.

V. Interactions Between Ground-Based and Onboard Autonomy

In situations when a ground-based approach alone cannot meet the necessary criterion, the different autonomous systems that must be used must be designed to interact with the system. This interaction can range from the autonomy supplying only a few tightly controlled enhancements to the system to the ground system being largely abandoned in favor of a totally autonomous approach. Regardless of the specific approach settled on, the fact that these two systems must interact can never be disregarded. In fact, designs incorporating both systems generally will result in a more satisfactory result. The following subsections discuss the specific roles that ground-based operations play in setting up the autonomous system and suggest different ways in which these roles could be shifted to autonomous operations.

A. Calibration and Modeling

To perform autonomous onboard navigation implies that the autonomous navigation system has some map from which to work. Here the concept of a map can vary greatly depending on the data measurements used—for optical measurements, the map will consist of the body limbs or of landmarks whose positions are registered in the body-fixed frame; for surface beacons, the map will consist of the locations of those beacons on the surface and relative to the target.

Another inherent assumption is that the measurement devices have been calibrated to the proper accuracy required to perform the autonomous navigation during landing. For optical images, the calibration would include the mounting accuracy of the imager, the distortion pattern in the image plane, the expected variation in the landmarks given different viewing conditions, and other such items. For a beacon system, the calibrations would include the drifts in the oscillator frequency, in the internal beacon clocks, and in the expected signal degradations encountered between the beacon and the spacecraft. For an altimetry system, the calibrations would include bias parameters in the ranging and the control and knowledge accuracy of the attitude control system (ACS). The list can be expanded to include other spacecraft-based measurements and body-relative observations.

It is not inconceivable for all this map making and calibration to be performed autonomously; schemes exist that would work on paper. However, the practicality of such schemes has not been realistically evaluated to date and, even if possible, the overall accuracy of this approach will be less than a ground-based approach, and the time necessary to accumulate sufficient data to perform this map making and calibration will, in general, be longer than a ground-based approach (due to the lower overall accuracy of the measurements).

Thus, ground-based measurements and processing have an invaluable role to play in this regard for the near future. Based on pre-mission analysis and post-rendezvous reanalysis, the accuracy in the body maps and the data calibration necessary to ensure a successful landing can be assessed and the ground data accumulated and processed until that level of accuracy is achieved. Then, before the landing is initiated, the maps and calibrations can be incorporated into the onboard software, and the spacecraft state can be initialized based on the best estimate of its location from the combination of ground and body-relative data.

It is important to note that, in some cases, the accuracy of the ground determination may be accurate enough so that the need for autonomy during descent to the surface can be eliminated or reduced to a simple measurement, such as altitude with a descent control loop built solely around the altitude and rate of descent of the spacecraft, all other target parameters being satisfied by the accuracy of the ground solutions.

One issue to consider when deciding the merit of performing map making and calibrations autonomously or with ground processing is the scientific interest in the results of these processes. Oftentimes the additional data and measurements that arise from the determination process have scientific merit and can be used to confirm or disprove various hypotheses.

B. Enabling Trades

If autonomy is required during the landing phase, the important question to ask is how the autonomy can be balanced against the ground-based measurements and processing. This is an important issue because the design and implementation of first-generation autonomous systems often are more expensive than reliance on ground-based measurements and operations, since these functions are standardized across many other missions, while autonomous systems must be designed specifically for the problem at hand.

The studies necessary to perform these trades must occur during the initial design of the spacecraft and the spacecraft mission and must, invariably, rely on reasonable assumptions about the body to be visited. This is not a simple task, as the small body's properties generally are unknown prior to rendezvous, although depending on the class of the body and the amount and quality of ground observations, some additional information may be available about the body. A conservative assessment of the body characteristics will drive a design toward reliance on manufactured components. As an example, if the target body is believed to be a poor candidate for locating and using optical landmarks, the design may favor the use of landed beacons, because they can be constructed to the necessary specifications prior to launch and only need to be calibrated and located after deployment on the surface in order to be useful for autonomous landing navigation. Conversely, if the target is an asteroid where there is good assurance of usable landmarks (i.e., craters), then the autonomous component of the system can be designed to use properties of the body itself, usually at a much lower development and mass cost.

In order to perform effective trades, meaningful metrics should be established so that relevant comparisons can be performed. The metrics of interest usually include the necessity of autonomous landing, the total time from rendezvous to spacecraft landing, the total development cost, and the cost of ground-based operations versus the cost of developing autonomy prior to launch plus the cost of calibration and map making prior to landing. General rules for applying these metrics cannot be established, as each mission invariably will weigh these considerations differently.

One final trade should be mentioned; this relates to the specifications of the landing target parameters. The constraints on the landing position and velocity accuracy may be a function of the spacecraft design or of the desired scientific return from the mission. Often, by relaxing these constraints, the need for autonomy can be removed or diminished, leading to a less complex and expensive design.

VI. Dynamics of the Landing Design

The specific landing trajectory for a mission often will have a large impact on the design of the navigation system. In the following subsections, a few different options for landing trajectories are discussed along with how they impact the level and degree of autonomy and ground interaction that must exist.

A. Ballistic Impact

In this type of landing, the spacecraft transitions from an orbit about the body into a ballistic trajectory that intersects with the surface. Generally, only one to three maneuvers would be used, the first to deorbit and the second and third to control the impact speed, if at all. A spacecraft that impacts directly from a hyperbolic approach orbit without transitioning into an orbit about the body also would be included in this class. This form of landing trajectory is the most amenable to minimizing the level of autonomy necessary, as a well-determined orbit and body model and an accurate spacecraft maneuver and attitude system can ensure that delivery occurs within reasonable accuracy specifications.

B. Controlled-Descent Trajectory

A more sophisticated approach would incorporate active orbit determination and trajectory control during the landing onto the body. The simplest implementation of such an approach would occur during the final landing phase, when altimetry measurements could be used to control the descent rate and ensure that the impact occurs with a controlled speed. Depending on the expected execution errors of the maneuver system, the modeling errors of the body, and the initial orbit determination errors, the active sensing phase may have to occur earlier to ensure that the lander trajectory is targeted to the proper location on the body surface. To be able to sense trajectory errors and retarget to the desired site implies that measurements are made that can tie the lander position and/or speed to the body-fixed frame, which in turn requires that the lander be navigated autonomously using a map of the body. The development of such an autonomous system is appreciably more complicated and requires significant operations support in order to generate and calibrate the maps and measurements used during this descent phase. Extreme care must be taken in evaluating all possible error sources into the system, as an overlooked systematic error easily could drive the trajectory from the desired target with a greater error than would be expected from an open-loop design.

C. Hovering

Finally, the most sophisticated descent trajectory would have the lander pause during descent, perhaps allowing for autonomous site selection or enhanced measurements during the descent phase. To execute these types of landing trajectories will require the maneuvering system to deliver constant values of thrust over longer periods of time. To realistically control the lander in such a trajectory will require measurements that sense body-relative velocity (or a component of it) directly, because position measurements may not provide sufficient information to close the control loop. Doppler altimeters can serve as sensors to control descent rate, but will not serve as well for lateral control of the trajectory. Full three-dimensional hovering control probably would be best effected by using a Doppler and range beacon system containing at least four beacons to measure time, position, and velocity.

VII. Applications

In this section, a high-level discussion is given that compares the necessary elements of the navigation design for two different landing concepts. The first is the Near Earth Asteroid Rendezvous (NEAR) spacecraft and its proposed landing on the surface of Eros at the close of its prime mission. The second is the Champollion lander and its main mission of landing on the surface of a comet.

A. NEAR Spacecraft Landing on Eros

The dynamics of the NEAR landing on Eros fall into the category of ballistic impact. This is driven by the lack of close-proximity navigation sensors on that spacecraft, which was designed for an orbital mission. While NEAR does contain a lidar, which conceivably could be used for descent control, it is not designed to operate at small distances.

The basic landing trajectory for NEAR starts with the spacecraft in a polar orbit. When over the north or south rotational pole of Eros, the spacecraft performs a deorbit maneuver that halts its lateral speed and gives it a small downward radial velocity (nonzero for control purposes). The gravity accelerates the spacecraft as it descends toward the asteroid, so a maneuver is planned and executed at a predetermined time to minimize the spacecraft's rate of fall, thus minimizing its impact speed. The navigation challenge here is to be able to execute the final maneuver as late as possible because this will minimize the impact speed. The measurements available to the spacecraft during this time are its a priori solution prior to the deorbit maneuver; the ACS, which maintains the spacecraft attitude during the entire trajectory; and the accelerometers, which are used to control the preplanned maneuvers. Additional error sources are the maneuver execution errors, the initial orbit determination errors, the Eros mass and gravity field, and the Eros rotational motion uncertainty.

One specific realization of such a landing trajectory has been analyzed, and the results are given below. The orbit starts in a 30-km $\times$ 30-km polar orbit. At the pole crossing, a 9-m/s maneuver is performed to send the spacecraft down toward the pole with an initial velocity of 7 m/s. After 36 minutes, the spacecraft is traveling downward at 12 m/s when a final maneuver of 4.5 m/s is performed (at a radius of 10 km), setting up an impact of 10 m/s on the pole (at a radius of 7 km) within 6 minutes.

This trajectory has been analyzed assuming maneuver execution errors of 0.1 percent in magnitude and 3 mrad in pointing. The error sources considered in the run are the a priori orbit determination uncertainty, the Eros mass uncertainty, the Eros second-degree and -order gravity-field uncertainty, and the rotation rate uncertainty (it is assumed that Eros is in principal axis rotation). The errors are measured in the local coordinate frame fixed to Eros and centered at the impact site with local normal being defined as the z axis. A tight a priori orbit determination uncertainty of 10 m in position and 1 mm/s in velocity is assumed 6 hours prior to the first maneuver. Table 1 spells out the computed and the consider covariances of this delivery.

Table 1. Computed and consider 1-σ covariances for the NEAR spacecraft landing on Eros.

Run description	Cross range, m	Vertical range, m	Cross speed, cm/s	Vertical speed, cm/s
Covariances				
Computed	70	100	4	9
Consider	252	423	14	35
Consider contributions				
Rotation uncertainty (0.001%)	183	301	10	25
Mass uncertainty (0.01%)	134	235	8	19
C_{20} and C_{22} uncertainty (>0.01%)	84	147	5	12

The computed value of μ for Eros is 0.001 km^3/s^2; its rotation period is 5.27 hours; and its nominal values of C_{20} and C_{22} are 35.1 km^2 and 17.55 km^2, respectively [8]. Because the landing will occur at the end of the mission, all of these parameters should be well established. Changing any of these uncertainties by an order of magnitude would make this particular landing too dangerous, because impact may occur prior to the final maneuver.

This is a good example of how an accurate small-body model, spacecraft orbit determination uncertainties, and spacecraft ACS can enable a landing without the use of additional navigation measurements prior to impact. The cost of not using additional navigation measurements is a relatively large impact speed of 10 m/s, probably fast enough to disable the spacecraft. Were a smaller impact speed desired, the final maneuver would have to be performed close to the surface of the body; an approximate relationship between final maneuver height and impact speed is

$$V_{\text{imp}}^2 = V^2 + V_{\text{esc}}^2 \left(1 - \frac{r_o}{r}\right) \tag{1}$$

For Eros, the escape speed on the pole is approximately 17 m/s. Thus, to impact with a speed less than 5 m/s requires a final maneuver at an altitude less than 670 m; an impact speed less than 1 m/s requires a final maneuver at less than 24 m. We already see that for a 5-m/s impact speed, the 3-σ uncertainty in altitude of approximately 1200 m is larger than the nominal maneuver height.

B. Champollion Spacecraft Landing on a Comet

The Champollion lander has considerably tighter requirements on its landing state than does the NEAR spacecraft, due to the fact that the Champollion primary mission consists of landing on a comet surface to obtain samples. The desired landing accuracy is a footprint of 50 m and velocity uncertainties of less than 12 cm/s, all 3 σ. An immediate comparison with the NEAR results cannot be made because the size, density, rotation rate, and gravity field of a comet will be different from those values for Eros. An additional complication is the large range of uncertainties in the comet model parameters, which leads to a large parameter space over which the nominal design must operate. In this article, we will use a specific example of a comet for the covariance runs in order to show the relative performance of an optical-based autonomous approach and a beacon-based autonomous approach.

The comet model has a 3.5-km mean radius with density of 1 g/cm^3. The shape of the body is ellipsoidal with size ratios of 1:0.6:0.5. The comet is in a uniform rotation state with a rotation period of 10 hours. The specific trajectory consists of three maneuvers; the deorbit maneuver occurs 2.6 hours prior to impact and is 2 m/s. The second maneuver occurs 222 seconds prior to impact and is 1.3 m/s in size. The final maneuver occurs at a 200-m altitude, and the impact speed is 1 m/s. One complication with this mission is that the maneuver execution errors currently are quite large, due to the use of a cold gas propulsion system for near-comet operations. The magnitude uncertainty is 2 percent, 1 σ, and the pointing accuracy is 10 mrad, 1 σ. These large errors place constraints on the trajectory design—the final maneuver must be made small enough that the proportional errors do not corrupt the final aim point. They also necessitate the use of autonomous navigation during the entire descent phase to recover from the errors introduced at each maneuver.

Two different autonomous approaches are presented; the first uses optical imaging during descent to image the surface and correlate the image with a landmark map created prior to the descent. Accumulation of these images gives the lander coordinates in the comet-fixed frame, which are combined in a filter to extract the trajectory and velocity estimate. The major systematic error accounted for in this analysis is the position uncertainty of the landmarks that comprise the map, as well as the usual comet rotation, mass, and gravity field errors. Since the landing takes place well after comet perihelion, the effect of outgassing on the lander is ignored. The accuracy of the optical system is assumed to be 0.4 mrad with a 22-deg field-of-view camera. It is assumed that three landmarks are processed per image, which are taken every 5 minutes. The results are given in Table 2.

Table 2. Computed and consider 1-σ covariances for optical autonomous landing on a comet.

Run description	Cross range, m	Vertical range, m	Cross speed, cm/s	Vertical speed, cm/s
Covariances				
Computed	5	13	1.6	2.3
Consider	15	38	6.0	5.7
Consider contributions,				
Landmark position uncertainty (5 m)	14	35	5.7	4.7
Rotation uncertainty (0.01%)	1	3	0.2	0.7
Mass uncertainty (0.1%)	2	5	0.4	1.4
C_{20} and C_{22} uncertainty (>0.1%)	2	5	0.5	1.6

The performance of the system is seen to be close to the desired accuracy. Note that, if the landmark position errors were reduced to the order of 1 m, then the performance of the optical autonomous approach would satisfy the constraints. In this case, to reduce the model errors to their small size, the gravity must be estimated to 0.1 percent of its nominal value, and the rotation must be estimated to 0.01 percent. An order of magnitude increase in any of these values would definitely rule out the current trajectory design. While these uncertainties are larger than those used for Eros, they still are sufficiently small to require the use of radio metric data for their estimation during the characterization phase.

The second approach uses beacons placed on the surface of the comet. Ideally, these beacons could provide Doppler and range data, although the system constraints on a Doppler beacon system for usable velocity measurement accuracy may be too high. These beacons are deployed after site selection in the vicinity of the target site, and their positions on the surface are estimated prior to descent during a period of joint spacecraft and beacon tracking (the beacon signals must be routed through the spacecraft and transmitted to Earth during periods of two-way tracking). Although this system will be more expensive and massive than the optical autonomy, conceivably it can have a greater accuracy and does not rely on the comet optical properties for its measurements. In this analysis, the systematic errors modeled are beacon position uncertainties as well as the comet model uncertainties mentioned above. Two runs are performed in this case, using range with and without Doppler. The range accuracy is assumed to be 10 m, while the Doppler accuracy is 1 cm/s, which will require the beacons to have stable oscillators and place constraints on the frequency of transmission they must use. Six beacons, placed within a few degrees of the target surface location, are assumed in these runs. The position errors of the beacons are assumed to be around 1 m. One measurement from each beacon is made every minute during the descent. In all the runs, measurements are not made after the final maneuver. These results are given in Tables 3 and 4.

Table 3. Computed and consider 1-σ covariances for a 10-m beacon ranging autonomous landing on a comet.

Run description	Cross range, m	Vertical range, m	Cross speed, cm/s	Vertical speed, cm/s
Covariances				
Computed	26	8	1.8	2.2
Consider	30	13	6.4	3.5
Consider Contributions				
Beacon position uncertainty (1 m)	14	3	0.8	0.6
Rotation uncertainty (0.01%)	0	1	0.3	0.2
Mass uncertainty (0.1%)	5	7	4.4	2.0
C_{20} and C_{22} uncertainty (>0.1%)	6	7	4.2	1.7

Table 4. Computed and consider 1-σ covariances for a 10-m beacon ranging and a 1-cm/s beacon Doppler autonomous landing on a comet.

Run description	Cross range, m	Vertical range, m	Cross speed, cm/s	Vertical speed, cm/s
Covariances				
Computed	15	5	1.7	2.2
Consider	22	17	8.5	7.2
Consider Contributions				
Beacon position uncertainty (1 m)	8	6	1.4	2.1
Rotation uncertainty (0.01%)	1	0	0.3	0.3
Mass uncertainty (0.1%)	15	11	5.7	4.7
C_{20} and C_{22} uncertainty (>0.1%)	13	11	5.9	4.5

There are several significant issues to note. First, since the computed velocity uncertainties between the range-only and range-plus-Doppler result are equal, this means that the lander maneuver execution errors are the limiting error source here, masking the true computed covariance of the range and Doppler measurements. The consider uncertainties, however, are quite different from each other and are uniformly too large at the level of accuracy assumed in the models. To enable successful delivery, the comet gravity should be estimated to 0.01 percent. The fact that the consider uncertainties are so large in this case implies that, using the beacon data, errors in the gravity field may be detectable at this level and, thus, once the beacons are deployed, their data can be used to refine the comet model estimate.

Overall, in this approach we see that the mass and gravity field of the small body and the locations of the beacon positions need to be determined to greater accuracy than in the optical approach.

VIII. Conclusions

This article discusses the navigation and operations of a spacecraft landing on a small body such as an asteroid or comet. The main purpose of the article is to acknowledge and highlight the necessary interactions that must occur between ground-based and onboard autonomous operations for these missions to succeed. It is intended to serve as an introduction to this problem and to define the various aspects of this problem that still require additional development. Some specific applications to the NEAR and Champollion missions are discussed to highlight how these interactions bear on each other.

Future research will attempt to characterize the ground and autonomous interactions analytically, provide estimates of model accuracy versus characterization and tracking time, and investigate the performance of autonomous navigation systems without ground-based support.

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