Autonomous Nucleus Tracking for Comet/Asteroid Encounters: The STARDUST Example

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STARDUST, the fourth mission in NASA's Discovery program, is a mission to be launched in early 1998, flyby the comet Wild-2 in early 2004, and return to Earth in 2006. Its primary science goal is to collect 1000 particles of cometary dust during the flyby and return them to Earth in a sample return capsule which will parachute into an uninhabited region of Utah. As secondary science goals, the spacecraft will also collect interstellar dust particles and obtain Wild-2 coma and nucleus images during encounter. To meet its primary science goal, the current plan is to flyby the comet at a radius of about 120-150 km at a relative velocity of a little over 6 km/s. The spacecraft is protected from the hypervelocity impacts of coma particles by a forward facing dust shield, (termed the "Whipple" shield) and will collect dust using a unique substance known as aerogel, developed at JPL. The imaging science will be performed using a 3.5 degree field-of-view (FOV) camera with a 200 mm focal length and four color filters to image the coma. The camera will also double as a navigation instrument for encounter using a clear filter for maximum light transmission. Although the camera remains fixed, the FOV can be swept through a 180 degree range in a single plane using a mirror which articulates about one axis. In addition, a periscope is used to see in the direction of motion through the Whipple shield. This periscope/mirror combination enables the comet nucleus to be tracked in the period prior to, during, and after the encounter.

In order to target the final flyby aimpoint, four trajectory correction maneuvers (TCMs) are scheduled at Encounter (E) - 30 days, E - 10 days, E - 2 days, and E - 6 hours (numbered TCMs 10 -13). Navigation data taken to support these maneuvers include standard radio (Doppler and ranging) data, as well as comet images from the camera. At the time of the final ground uplink for the final maneuver (about E-7 hours) however, the navigation uncertainties in the in-plane and out-of-plane directions are too large to allow for ground sequencing of the spacecraft attitude and mirror angles to keep the comet in the camera FOV during encounter. This information is only available from processing nucleus image data in the several minutes prior to encounter. Due to the large (~40 minute) round-trip light time, sending images to the ground, processing it, and uplinking updates is clearly infeasible. The only solution therefore, was to perform the nucleus tracking task autonomously onboard the spacecraft.

The algorithm to perform nucleus tracking has to be simple, reliable, and fast. It incorporates a linear model of the spacecraft trajectory with nominal values of the comet relative position and velocity initialized using ground-based navigation information. A least-squares filter is used to update the position employing information from images of the nucleus, taken at the rate of one every 10 seconds, starting at E-20 minutes. The image is processed to determine the center of brightness and then corrected for phase variations to obtain an estimate of the center of figure. This information is then converted into a line-of-sight vector, which can then be compared against a predicted line-of-sight to form a residual. Partial derivatives of the observation with respect to the various components of the state are also computed to form the information matrix and, together with the observation residuals, are used in a least squares computation to correct the initial state.

In addition to the navigation uncertainties, other error sources affecting the solution are spacecraft attitude errors and comet centerfinding errors. During cruise, the spacecraft obtains attitude knowledge from two star cameras. During encounter, however, it is assumed that stars will not be visible through the coma, so the spacecraft will switch to using gyros to determine attitude. The gyros are not as accurate as the star trackers and have a bias and drift associated with them. Current estimates for the bias and drift are 0.1 degrees and 0.0033 degrees/hour (1-sigma). In addition, there will be random walk and random noise components of drift of assumed to be about 0.025 degrees/hour$^{0.5}$ and 2 x 10^{-4} degrees, respectively. Analysis has shown that of these error sources, the bias has the largest effect on nucleus tracking accuracy and must be accounted for. Thus, in addition to solving for the spacecraft position, three components of spacecraft attitude are also estimated in the filter.

Centerfinding errors are due to lack of knowledge of the comet nucleus shape, albedo, and surrounding environment. Ideally, the image acquired by the camera should be processed to determine the line-of-sight direction to the nucleus center-of-mass. Without a-priori knowledge of the nucleus shape and albedo, however, this is a difficult task and cannot be realistically done with the given resources. Thus, rough estimates are made of the correction from center-of-brightness to center-of-figure and applied to the raw center-of-brightness observable. Also, the brightness centroiding algorithm may be thrown off by gas jets emanating from the comet, or by spurious signals due to small particles impacting the periscope mirror. Due to uncertainties in comet modelling, it is difficult to quantify how all these error sources will affect the centroiding process. For simulation purposes, the centroiding error is modelled as a superposition of a bias and white noise, proportional to the radius of the nucleus. The same formula is used to weight the data, with the exception that the bias is also treated as white noise. In order to minimize the degrees of freedom of the filter, these error sources (the bias in particular) were not estimated.

Since the dynamics of the filter are known to be a subset of the true dynamics, the formal statistics from the filter do not accurately reflect its accuracy. Thus, Monte Carlo simulations were run with realistic error sources added, and statistics computed by differencing the "truth" values of the state from the estimated values from the filter. Examination of the results from 100 Monte Carlo runs showed that in all cases, the algorithm was successful in maintaining the comet nucles in the FOV of the camera. A comparison of results with and without estimating the spacecraft attitude excursions revealed that incorporating the latter into the filter increased the success rate from 75% to a 100%. Thus, the increased complexity and run time resulting from adding these parameters to the estimate list is necessary to ensure successful imaging of the nucleus during encounter.