

Autonomous Target Tracking of Small Bodies During Flybys

Shyam Bhaskaran, Corresponding Author

Shyam.Bhaskaran@jpl.nasa.gov

MS 264-380

Jet Propulsion Laboratory

4800 Oak Grove Dr.

Pasadena, CA 91109

Ph: (818)354-3152

FAX: (818)393-6388

Joseph E. Riedel

Joseph.E.Riedel@jpl.nasa.gov

MS T1722

Jet Propulsion Laboratory

4800 Oak Grove Dr.

Pasadena, CA 91109

Ph: (818)354-8724

FAX: (818)393-6520

Within the last decade, a number of deep space missions have flown by small solar system bodies (asteroids and comets). These encounters have either been opportunistic flybys, such as the Galileo spacecraft's encounters with asteroids Gaspra and Ida, or missions specifically targeted for observation of a small body, such as the Deep Space 1 encounter with comet Borrelly. In either case, an important component of the science return from these missions are images taken of the object during the flyby. Because the ephemeris of the small bodies are generally not well determined, however, a typical imaging sequence during the encounter involves shuttering frames which cover a two to three sigma area of the target's positional uncertainty as projected into the camera field-of-view to guarantee that the target will be in at least one of the frames. Although this process has worked well in the past, it necessarily results in image frames without the target and of no science value. However by using such an "open-loop" imaging technique, very close observations are impossible to obtain, due to time-of-flight errors, which are impossible to reduce from distant approach navigation images, mapping into the field of view.

It is obvious, however, that images taken during the approach to the target provides very good data to improve knowledge of the target's ephemeris beyond what is available from Earth-based or distant spacecraft observations, but the rapid pace of the flyby coupled with large (in the tens of minutes) round-trip light times preclude processing the observations on the ground to provide this information to the spacecraft. An autonomous onboard system though, can use this data to update its own knowledge of the target ephemeris and execute an imaging sequence taking advantage of this information to dramatically increase the number of image frames that include the target, thereby increasing the science return. Such a system has been developed for use, extensively tested on the ground using simulations, and proven in flight on two occasions -- the Deep Space 1 flyby of comet Borrelly and the Stardust flyby of asteroid Annefrank. This paper describes the algorithm used, as well as results from the ground testing and flight results.

A key consideration in the design of the autonomous tracking system was that it had to be simple, robust, and fast. Computing resources onboard spacecraft generally lag several years behind that available on the ground, and furthermore, many systems onboard that are required for spacecraft health and safety are competing for time on the same processor. This necessitates keeping the algorithm and associated code fairly simple, which also helps processing speed. The algorithm uses optical images of the target taken during the final 30 minutes or so of the encounter to solve for the 3 dimensional position of the spacecraft and two to three components of its attitude, using a standard least-squares filter. With this information, the spacecraft's attitude control system can point the camera to the appropriate inertial location to keep the target in the field-of-view during the final few minutes around encounter. As compared to other types of target tracking systems such as those used for missile interceptors, this approach is more robust because it is less susceptible to problems caused by lack of knowledge of the target characteristics and loss of images.

The flyby trajectory, which in the general case requires a multi-body numerical integration of the non-linear equations of motion, is simplified to a linear propagation of the initial position and velocity. This simplification is possible due to the fact that the gravitational attraction of the small body is very small, the flyby speeds are relatively high, and the time interval which the algorithm operates is fairly short. The initial target relative position and velocity is provided from standard ground navigation techniques. The spacecraft's attitude information is provided on a continuous basis to the algorithm from the onboard star tracker or gyroscopes. Because the accuracy of the ground-based position information and the onboard attitude is not sufficiently good to permit open-loop tracking of the target, both are estimated by the tracking system's filter loop. The spacecraft's velocity, however, is generally extremely good from the ground-based radio and optical orbit determination estimate, and need not be updated by the filter onboard.

The observations used by the tracking system are the optical images taken of the target body using a Charge-Couple-Device (CCD) camera. The observable is the "pixel" (horizontal) coordinate, and "line" (vertical) coordinate of the center-of-brightness (COB) of the target in the camera focal plane. Although in principle a simple moment-of-brightness algorithm could be used to compute the desired central location, it has been found in practice that this approach is very susceptible to noise in the images. In particular, high signals caused by cosmic rays can be very damaging to such algorithms. An alternative was therefore developed, which identifies regions of contiguous bright objects in the image frame; a post-processor then sorts through all the identified regions to find the one most probably containing the target. Within this region, then, a moment algorithm is applied to locate the COB.

The orbit determination filter used is a standard least-squares batch processor. The batch processor was chosen over the Kalman filter formulation because of its advantage in being able to do systematic data editing over the entire data set. In this methodology, a set of images is taken over some interval of time, and the observed pixel/line coordinates of the COB are differenced from the predicted ones based on the nominal trajectory to form a series of observation residuals. These residuals are compared three at a time to reject points which are obvious outliers. The residuals which pass this test are used in the least-squares formulation to update the spacecraft's position and attitude.

The overall procedure then, is fairly straightforward. At 20 to 30 minutes prior to the nominal encounter time, the tracking system starts taking images of the target body at a rate of one every 30-60 seconds. The images are processed and the observations are accumulated, but initially, the system is not allowed to close the control loop. At about 10 minutes to encounter, the orbit determination filter results are invoked, and the spacecraft state is updated. At this point, the attitude control system uses the new information to repoint the camera for upcoming images. At every subsequent image opportunity, the observation is used to continually update the state, with the associated repointing. This way, even should the filter fail, the spacecraft is using the latest available information to point the camera.

Numerous Monte Carlo simulations were performed on the tracking system incorporating realistic errors in the trajectory, images, and spacecraft attitude. The results showed that even under very demanding situations, the system was successful over 95% of the time. Furthermore, the system has been used twice in a real-world situation, once during the Deep Space 1 flyby of the comet Borrelly, and once during the Stardust flyby of comet Anefrank. In both cases, the system performed flawlessly, resulting in target images in almost all the frames taken during the flyby.