Science Benefits of Onboard Spacecraft Navigation

Primitive bodies (asteroids and comets), which have remained relatively unaltered since their formation, are important targets for scientific missions that seek to understand the evolution of the solar system. Often the first step is to fly by these bodies with robotic spacecraft. The key to maximizing data returns from these flybys is to determine the spacecraft trajectory relative to the target body—in short, navigate the spacecraft—with sufficient accuracy so that the target is guaranteed to be in the instruments' field of view. The most powerful navigation data in these scenarios are images taken by the spacecraft of the target against a known star field (onboard astrometry).

Traditionally, the relative trajectory of the spacecraft must be estimated hours to days in advance using images collected by the spacecraft. This is because of (1) the long round-trip light times between the spacecraft and the Earth and (2) the time needed to downlink and process navigation data on the ground, make decisions based on the result, and build and uplink instrument pointing sequences from the results. The light time and processing time compromise navigation accuracy considerably, because there is not enough time to use more accurate data collected closer to the target—such

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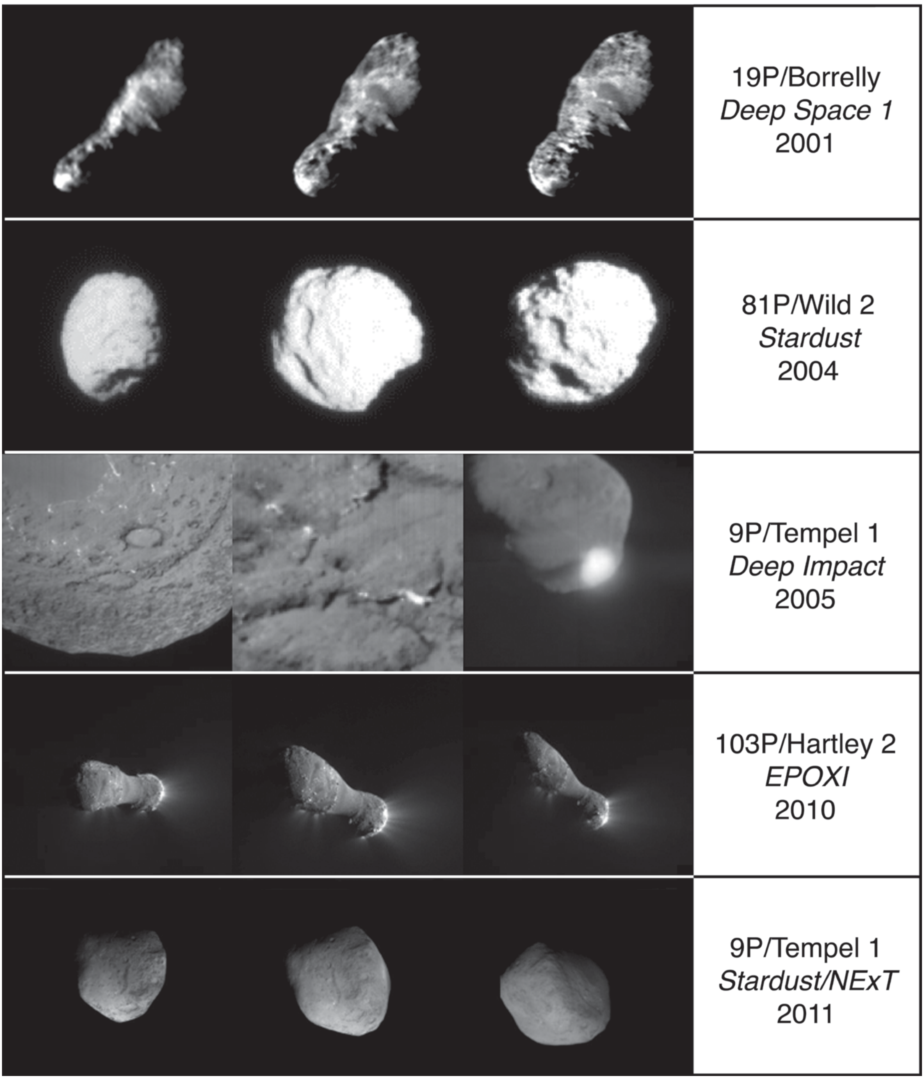

Fig. 1. AutoNav technology enabled the comet flyby imagery depicted in this mosaic. (top to bottom) Deep Space 1 flew within 2200 kilometers of Borrelly in September 2001. Stardust flew within 240 kilometers of Wild 2 in January 2004. In July 2005 the Deep Impact (DI) spacecraft encountered Tempel 1 and released a nucleus impactor subspacecraft before executing a divert maneuver that resulted in a 500-kilometer flyby of the nucleus, where it then observed the impact. The DI spacecraft, renamed EPOXI, flew within 700 kilometers of Hartley 2 in November 2010. The Stardust spacecraft, renamed Stardust-NExT, flew within 180 kilometers of Tempel 1 in February 2011 and observed the crater left by the DI impactor. The different views in this figure exhibit showcase imagery that would not have been possible without AutoNav.

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data are more accurate because the angular capability of the onboard astrometry is essentially constant as the distance to the target decreases, resulting in better "plane-of-sky" knowledge of the target.

Excellent examples of these timing limitations are high-speed comet encounters. Comets are difficult to observe up close; their orbits often limit scientists to brief, rapid flybys, and their coma further restricts viewers from seeing the nucleus in any detail, unless they can view the nucleus at close range. Comet nuclei details are typically discernable for much shorter durations than the round-trip light time to Earth, so robotic spacecraft must be able to perform onboard navigation.

This onboard navigation can be accomplished through a self-contained system that by eliminating light time restrictions dramatically improves the relative trajectory knowledge and control and subsequently increases the amount of quality data collected. Flybys are one-time events, so the system's underlying algorithms and software must be extremely robust. The autonomous software must also be able to cope with the unknown size, shape, and orientation of the previously unseen comet nucleus. Furthermore, algorithms must be reliable in the presence of imperfections and/or damage to onboard cameras accrued after many years of deep-space operations.

The AutoNav operational flight software packages, developed by scientists at the Jet Propulsion Laboratory (JPL) under contract with NASA, meet all these requirements. They have been directly responsible for the successful encounters on all of NASA's close-up comet-imaging missions (see Figure 1). AutoNav is the only system to date that has autonomously tracked comet nuclei during encounters and performed autonomous interplanetary navigation. AutoNav has enabled five cometary flyby missions (Table 1) residing on four NASA spacecraft provided by three different spacecraft builders. Using this software, missions were able to process a combined total of nearly 1000 images previously unseen by humans.

By eliminating the need to navigate spacecraft from Earth, the accuracy gained by AutoNav during flybys compared to ground-based navigation is about 1 order of magnitude in targeting and 2 orders of magnitude in time of flight. These benefits ensure that pointing errors do not compromise data gathered during flybys. In addition, these benefits can be applied to flybys of other solar system objects, flybys at much slower relative velocities, mosaic imaging campaigns, and other proximity activities (e.g., orbiting, hovering, and descent/ascent).

Table 1. AutoNav Usage on Cometary Flyby Missions

Mission	Comet Target	Flyby Year	Spacecraft	Spacecraft Provider
Deep Space 1	Borrelly	2001	Deep Space 1	Spectrum Astro
Stardust	Wild 2	2004	Stardust	Lockheed Martin
Deep Impact (DI)	Tempel 1	2005	DI impactor	Ball Aerospace
			DI flyby	Ball Aerospace
EPOXI	Hartley 2	2010	DI flyby	Ball Aerospace
Stardust-NExT	Tempel 1	2011	Stardust	Lockheed Martin

Capabilities

AutoNav technology exists in multiple versions, driven by mission-specific needs. Common baseline features include image processing and orbit determination. For image processing, stars and target bodies in the spacecraft cameras' field of view are detected and identified. Orbit determination estimates the trajectory of the target body using least squares filtering to minimize the differences between observed and predicted target positions. The updated parameters capture the improved target-relative trajectory knowledge of the spacecraft, which is key to performing the functions described in the following paragraphs.

For the Deep Space 1 mission's flyby of comet Borrelly and Deep Impact's encounter with comet Tempel 1, AutoNav was augmented to include maneuver computation. This allowed the software to compare the spacecraft's computed trajectory with the desired one and to compute and execute required spacecraft trajectory course corrections [*Riedel et al.,* 2000].

AutoNav was utilized most fully on the Deep Impact mission [*Kubitschek et al.,* 2006], in which part of the spacecraft (the impactor) struck comet Tempel 1 in July 2005, while the remaining part still in orbit (the flyby spacecraft) took pictures of the collision (see Figure 1, middle row). Both impactor and flyby spacecraft used AutoNav—the former to target the comet and the latter to target and time the flyby imaging.

Four main innovations stemmed from the use of AutoNav on Deep Impact. The first involved scene analysis, in which the impact site was selected from actual images taken by AutoNav. This enabled AutoNav to meet the objective of ensuring that the impactor portion of the spacecraft crashed into an illuminated area on the comet within the hemisphere visible to the flyby spacecraft. Both impactor and flyby spacecraft used this algorithm to process their respective images; each selected essentially the same site on the comet surface.

The second innovation provided updates on the forecasted time of impact. This allowed AutoNav to control when the imaging sequence started, which in turn allowed the flyby spacecraft to collect images at a high rate during the impact. As a result, cameras on board the flyby spacecraft were able to detect the exact moment of collision (the impact flash) at the highest possible temporal resolution allowable by the mission. Furthermore, given the geometric observational advantages of the flyby spacecraft trajectory, time-of-impact updates computed on board that spacecraft were transmitted to the impactor spacecraft. Such coordination was the result of the third innovation: spacecraft synchronization.

Finally, AutoNav on Deep Impact allowed for internal image simulation, in which actual images were modified with simulated target body images before they were passed on to the other AutoNav algorithms. This capability provided a means of testing the targeting system on the spacecraft in flight, with all components in the loop, prior to the actual flyby event.

All of AutoNav's capabilities for each mission were bundled into a function core set managed by a higher-level software package, dubbed the "AutoNav Software Executive." This ensemble required approximately 13,000 lines of code, all running on the flight system's central processing unit. A fully integrated AutoNav requires only a few interfaces with the flight system.

Future Applications

AutoNav's general framework can be customized for other scenarios, such as outer planet satellite tours and aerobraking (the use of atmospheric drag to modify the spacecraft's orbit at Mars, Titan, etc.). Furthermore, a new version of AutoNav includes the processing of landmarks on bodies, enabling precise landings on previously identified surface locations. For small body scenarios where the spacecraft is not to land but to perform a surface "touch-and-go" maneuver, the control logic handles both (1) spacecraft orientation control in the presence of perturbing torques from the spacecraft-surface interaction and (2) the ascent maneuver. The adaptation with this additional guidance, navigation, and control functionality has been renamed "AutoGNC" [*Bayard et al.,* 2010].

With its simple interfaces and flight validation pedigree, AutoNav and AutoGNC technology should be thought of as the first powerful "navigation apps" for solar system exploration. With this app paradigm, it is easy to plan and implement enhancements that enable other deep-space-mission science. Therefore, AutoNav and AutoGNC will continue to be a central technology needed to carry out NASA's goals related to solar system exploration.

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Author Information

—Al Cangahuala, Shyam Bhaskaran, and Bill Owen, Jet Propulsion Laboratory, California Institute of Technology, Pasadena; E-mail: albe@jpl.nasa.gov