Autonomous Navigation for Deep Space Missions

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Agenda

• Why Autonomy?
• Autonomous Optical vs. Radio Navigation
• Overview of Autonomous Optical Navigation
• Image Processing
• Orbit Determination
• Reduced State Encounter Navigation (RSEN)
• AutoNav Interfaces with Spacecraft
• Mission Results
Ground-based Navigation

- Ground-based navigation uses 3 main data types
  - Radiometric data types (two-way range and Doppler) to get spacecraft line-of-sight range and range-rate information from Deep Space Network tracking station
  - Delta Differential One-way Range (DDOR) to get plane-of-sky angular position of s/c relative to known quasar
  - Optical data from onboard camera to get target relative angular measurements, used on approach to target (primarily planetary satellites and small bodies)

- Tracking data obtained using 3 Deep Space Network complexes
- All data processed on ground to compute orbit solution
- Ground-based maneuvers computed and uplinked to spacecraft
- Limited by light-time, turnaround time to compute and validate solutions and maneuvers
- Used successfully on missions to all planets (except Pluto), several small bodies, for many mission types (orbiters, landers, etc.)
Why Autonomy?

• Reduce mission cost
  – Tracking data involves use of Deep Space Network antennas
    • Limited resource
    • Cost directly related to amount of tracking time
  – Operations personnel
    • The more people needed for ground operations, the higher the cost

• Increased science return
  – Round-trip light time to interplanetary spacecraft can be tens of minutes to several hours
    • Decisions about sequencing of observations therefore cannot rely on real-time data about spacecraft attitude and location
  – Build in conservatism so that observations cover all possible cases, resulting in data which has no science information
  – Use of onboard information can greatly improve ability to optimize science observations
Why Not Autonomy?

• Limited computer resources onboard spacecraft
• Maturity of onboard navigation systems still low
  – Break-even point for cost vs. benefit not yet achieved
  – Limited decision making capability -- cannot react to parameters beyond the design
• Inherent reluctance to relinquish control to onboard computer
A Brief History of Autonomous Navigation used in Deep Space …

- Deep Space 1
  - 1st demonstration of fully autonomous onboard navigation
  - Cruise autonav used operationally until failure of onboard star tracker
  - Flyby autotracking used successfully at encounter of comet Borrelly
- STARDUST
  - Encounter target tracking
  - Successful demo during flyby of asteroid Annefrank
- Deep Impact
  - Autonav successfully used by Impactor spacecraft to hit lit area of comet as well as Flyby spacecraft to image impact site
Autonomous Navigation Overview

• Place certain computational elements of navigation onboard a spacecraft so it can compute its own orbit and maneuvers to achieve desired target conditions

• Current version of autonav is based solely on optical data
  – Optical data is inherently easier to schedule and process
  – Unlike radio data, does not require the use of DSN antennas
  – Does not depend on Earth-based parameters which need to be updated
    • Media calibrations
    • Earth orientation parameters
  – Easier to detect anomalies

• Addition of camera hardware to spacecraft, if not already needed, difficult to justify

• Future versions will incorporate additional data types
Autonomous Navigation Overview

• Key elements of autonomous navigation system
  – Image Processing
    • Point source center-finding
      – Center of brightness
      – Multiple cross-correlation
    • Extended Body center-finding
      – Center of brightness
      – “Blobber” (largest contiguous object) identifier
  – Trajectory Numerical Integration
    • RK-7/8 N-body numerical integrator
    • Point-source gravity models
    • Solar pressure
  – Orbit Determination
    • Iterating batch-sequential least-squares filter
    • Optical-only observables
    • Estimates s/c position, velocity, bias acceleration, solar pressure, s/c attitude errors and rates
  – Maneuver computations
Interplanetary Cruise - Optical Triangulation

- Two lines-of-sight vectors to two beacon asteroids provides instantaneous position fix
- Stars in camera FOV provide inertial pointing direction of camera boresight -- at least 2 stars needed for accurate determination of camera twist
- In reality, two beacons will rarely ever be in the same FOV, and in any case, need better geometry than provided with two images in narrow angle camera
- Individual LOS sightings incorporated into orbit determination filter
Optical Triangulation

- Accuracy of triangulation method dependent on several factors:
  - Ability to determine exact centers of stars and object in FOV ("centerfinding")
  - Camera resolution
  - Distance from s/c to beacon object
  - Ephemeris knowledge of beacon object
- With given camera and centerfinding ability, angular accuracy of LOS fix is proportional to distance of beacons from s/c and knowledge of beacons ephemeris
- Asteroids make better beacon targets due to their proximity and number
- As target becomes nearer, it becomes sole beacon
Flyby and/or Impact Navigation

- Target body becomes “extended” -- size greater than a pixel element
- Series of angular measurements of target computed by finding center-of-brightness or other region on target body
- Measurements combined in filter with a priori estimate of target relative position and velocity used to update target relative state to high accuracy
- Due to large difference in brightness between stars and target, image processing done in starless mode
  - Inertial camera pointing taken directly from IMU data, which is not as good as using the stars
  - IMU bias and drift must be accounted for in filter to avoid aliasing attitude effects with translational motion
Example Raw Image from DS1 Cruise

date: 01–FEB–1999 15:51:19.9726, id: 2000001
pointing: RA = 54.9562, DEC = 19.5061, TW = 283.6640

exposure: 111.600 sec
sun cone angle: 109.76 deg, aft
Example Processed Image from DS1 Cruise

date: 01-FEB-1999 15:51:19.9726, id: 2000001
pointing: RA = 54.8562, DEC = 19.5061, TW = 283.6640

exposure: 111.600 sec
sun cone angle: 109.76 deg, aft
Orbit Determination

• Individual LOS fixes incorporated into filter to estimate complete s/c state
  – Position and velocity
  – Other parameters (solar radiation pressure, thruster mismodelling accelerations, gas leaks, etc)

• OD filter
  – Linearization of dynamical equations of motion around reference trajectory
  – Partial derivatives of observables (pixel/line centers of beacon in FOV) with respect to state parameters used to form information matrix
  – Residual vector obtained from difference of observed beacon locations and predicts from reference trajectory
  – Solution at epoch obtained using batch least-squares formulation to solve normal equations

• Dynamical equations of motion
  – Central body gravitation and 3rd body perturbations from planets
  – Solar radiation pressure and thruster accelerations
  – Integrated using Runge-Kutta 7-8 order integrator
Maneuver Computation

- Based on OD results, map filtered solution to desired target conditions
- Determine miss distance from projected to desired target
- At predetermined times, compute velocity adjustment needed to achieve desired target
- Reconstruct achieved maneuver after execution using OD process
- OR...continuous control of thrust pointing vector for ion propulsion system (e.g. DS1)
DS1 Example - Comparison with Ground Radio OD During Interplanetary Cruise
Autonomous Target Tracking

- During flyby, pace of events happening is much faster than during cruise
- Quick turnaround OD solutions are needed to use late images of target to update pointing control
- Ground-based navigation solution not possible due to round-trip light times
- Reduced State Encounter Navigation (RSEN)
  - Uses simplified, linear model of s/c flyby past comet.
  - Uses optical images as sole data type, with images starting about E-30 minutes at a rate of about 1 image every 30 seconds.
  - Initialized using final ground or onboard estimate of spacecraft state relative to comet.
  - Observations accumulated for many minutes; 1st state update at about E-10 minutes. Subsequent state updates performed after every image acquisition.
  - Controls camera pointing only - no maneuvers performed to correct trajectory
Autonav Interfaces with Spacecraft

- Autonav system needs to talk to rest of spacecraft
  - Point camera to take images, either by turning entire spacecraft in case of fixed camera, or camera subsystem alone
  - Implement and execute maneuvers
  - Disseminate orbit information to Attitude Control System
  - Receive attitude, thruster information from ACS

- Optimal to break out interface into real-time and non real-time sections
  - Real-time interface for high data rate information, such as ephemeris server, thrust history data
  - Slower interface used for basic image processing, OD, maneuver computation, and mini-sequence generation
AutoNav Heritage Architecture

ACS

RCS

S/C Side

AutoNav Side

Sequencing Subsystem (Main Sequence)

Onboard-built MicroSequence

Fault-Protect Subsystem

AutoNav Executive

Nav Real-Time

Data-Update Management

Ephemeris Server

Non-Grav History Maintenance

Nav Main

Orbit Determination

Maneuver, SEP Control

Encounter Operations

Picture Planning and Processing

Imaging Subsystem

Gimbal Subsystem

DS1 Heritage

DI Heritage
Deep Space 1

• Background
  – DS1 was the first mission in NASA’s New Millennium Program - a series of missions whose primary purpose is technology validation.
  – 12 new technologies validated during DS1’s prime mission. These included:
    • Ion propulsion system
    • Autonomous optical navigation
    • Miniature Integrated Camera and Spectrometer (MICAS)
    • High power solar concentrator arrays (SCARLET)

• Mission timeline
  – Launched on October 24, 1998
  – Encounter with asteroid Braille on July 29, 1999 (completed primary technology validation mission).
    • Demonstrated cruise autonav
    • Failed to track Braille during flyby.
      – Due to grossly low signal from the APS camera channel (cause: inadequate camera calibration and extremely inopportune presentation geometry).
    • Led to lessons learned for future flybys
Deep Space 1

- Extended science mission to rendezvous with short period comets Wilson-Harrington and Borrelly approved.
- Sole onboard star tracker failed on November, 1999.
  - Spacecraft placed on extended safe-hold while new software developed and tested to use MICAS camera as replacement for star tracker.
  - Loss of thrust time resulted in inability to reach both targets, so Wilson-Harrington encounter was cancelled.
  - Cruise autonav system relied on star tracker, so remainder of cruise used standard ground-based navigation
  - RSEN successfully tracked Borrelly for 2 hours through closest approach
Deep Space 1

- Encounter on September 22, 2001
- Flyby velocity of 16.6 km/s, distance at closest approach of 2100 km
- RSEN initiated at E-32 minutes, based on ground-based navigation information from E-12 hours
  - A priori position uncertainties of 350 km in Radial (or equivalently, 21 seconds in time to encounter), 20 km in Transverse and Normal
  - A priori gyro bias uncertainty of 0.1 deg, drift of 0.3 deg/hour
- Total of 52 images taken
  - 45 had Borrelly in camera FOV
  - Closest image taken at E-2 min, 46 seconds, at distance of 3514 km and resolution of 46 m/pixel
RSEN Image Sequence at Borrelly

E-30 m

E-22 m

E-9 m

E-8 m

E-5.6 m

E-3.2 m
Closest Image

- Image shuttered at E-2min, 13 sec.
- Distance of 3514 km.
- Resolution of 40 m/pixel.
STARDUST

- NASAs fourth Discovery Mission, following Mars Pathfinder, NEAR, Lunar Prospector
- Mission events:
  - Launch in February 7, 1998
  - Asteroid Annefrank flyby on November 2, 2003
    - Dress rehearsal for actual encounter
    - Successfully tested RSEN tracking of asteroid
    - Flyby at comet relative velocity of 6.1 km/s
      - Successful tracking of comet during flyby
  - Earth return on January 15, 2006 with sample return capsule landing in Utah
- Primary science goal was to collect 500 particles of cometary dust greater than 15 micron size and return them to Earth
- Secondary science goal is to image the comet nucleus at a resolution of better than 40 m
STARDUST

• Encounter on January 2, 2004
• Flyby velocity of 6.12 km/s, closest approach at 237 km
• RSEN initiated at E-30 minutes based on ground-based information at E-48 hours
  – Opnav information from E-14 hours available, but state errors considered to be of insufficient size to warrant additional command upload
  – A priori RTN position uncertainties of 1100x20x20 km (time-to-encounter equivalent of 9 minutes)
  – A priori gyro bias uncertainty of 0.1 deg
• 114 total images taken
  – All 114 images containing the comet in the FOV (72 total images stored for downlink)
  – Closest image taken at E-4 seconds at distance of 239 km and resolution of 14 m/pixel
• Image taken at E - 8 sec
• Distance of 3148 km
• Resolution = 190 m
Deep Impact

• NASA Discovery Mission
• Mission timeline
  – Launch on January 10, 2005
  – Comet impact on July 4, 2005
    • Full autonav successfully used by Impactor to hit lit area on comet and Flyby spacecraft to image impact site
• Engineering Objectives
  – Impact comet Tempel 1 in an illuminated area
  – Track the impact site for 800 sec using the Flyby s/c imaging instruments
• Science Objectives
  - Expose the nucleus interior material and study the composition
  - Understand the properties of the comet Tempel 1 nucleus via observation of the ejecta plume expansion dynamics and crater formation characteristics
Deep Impact

ADCS aligns ITS Control frame with Relative velocity E-5 min

ITM-3 E-12.5 min
ITM-2 E-35 min
ITM-1 E-90 min

AutoNav/ADCS Control E-2 hr

Impactor Release E-24 hours

Tempel 1 Nucleus

Shield Attitude Entry

Science and AutoNav Imaging to Impact + 800 sec

Shield Attitude through Inner Coma ADCS aligns shield with relative velocity

500 km

2-way S-band Crosslink

64 kbps

ϑ = 0.6 mrad

Impact!

Flyby S/C Science Data Playback to 70-meter DSS

Look-back Imaging E+45 min

Flyby Science Real-Time Data

Impactor Release + 12 min (101 m/s)

Flyby S/C Deflection Maneuver

TCM-5 at E-30 hours

AutoNav/ADCS Control

E-2 hr

ITM-1

E-90 min

ITM-2

E-35 min

ITM-3

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ADCS aligns ITS Control frame with Relative velocity E-5 min
Deep Impact

QuickTime™ and a Sorenson Video 3 decompressor are needed to see this picture.
Deep Impact - Impactor

- Impact on July 4, 2005 with impact velocity of 10.1 km/s
- Full-up autonav system used
- Autonav initiated at E-2 hr
  - Acquire images of the comet nucleus every 15 sec
  - Perform trajectory determination updates (OD) every minute starting 110 minutes before the expected time of impact
- Perform 3 primary Impactor targeting maneuvers
  - ITM-1 @ E-90 min, ITM-2 @ E-35 min, and ITM-3 @ E-12.5 min
- Acquire 3 images for Scene Analysis (SA) based offset @ E-16.5 min
- Use SA offset for computation of final targeting maneuver
- Align the ITS boresight with the AutoNav estimated comet-relative velocity vector starting @ E-5 min
  - Capture and transmit high-resolution images of the nucleus surface surrounding predicted impact site
Deep Impact - Flyby

- Flyby velocity of 10.1 km/s at radius of 500 km
- Autonav initiated at E-2 hours
  - Acquire MRI images of the comet nucleus every 15 sec
  - Perform trajectory determination updates every minute starting 110 minutes before the expected time of impact
  - Produce and hold deltaTOI and deltaTOFI time updates with every OD
- Acquire 3 images for Scene Analysis (SA) based offset, relative to CB @ E-4 min
- Used SA offset to correct HRI control frame pointing
- Align edge of Solar Array with the AutoNav-estimated comet-relative velocity vector at shield mode entry
  - Shield mode defined to be when the estimated range is 700 km)
Future Enhancements

• Small-body orbit case
  – Requires pre-determined shape model to correlate observed features with known features
  – Features can be limb/terminator or craters

• Planetary approach and capture
  – Use satellites of planets as beacons (e.g., Phobos and Deimos for Mars)

• Entry, descent, and landing
  – Use correlation of surface features, combined with ranging from Lidar