Autonomous Navigation and Mobility

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Small Body Exploration Trends

• Recent trends in planetary exploration are placing increased emphasis on small body exploration
  – Asteroids, comets, NEOs, etc.

• Examples of NASA small body encounters
  – DS1, Star Dust, Deep Impact, Dawn, NEAR
  – AutoNAV used for all JPL Autonomous Navigation functions

• RAISING THE BAR: New challenges associated with small body surface sampling and especially sample return

• Existing capabilities
  – JAXA’s Hayabusa (asteroid surface sampling)
  – ESA’s Rosetta (comet surface sampling)
Example Small Body Sample Return Scenario

Staging Altitude (10 km)

Descent

Pre-Contact Altitude (50 m)

Contact Altitude (4 m)

Touch&Go Sampling

Ascent
Needed Capabilities

• Autonomy for near-surface operations
  – Ground commanding is not possible (two-way light times ~1 hr)
  – Proximity operations performed at several meters above surface
  – Potential outgassing and non-grav forces

• On-Board Landmark-Based-Navigation
  – Determination of target-relative position and velocity from camera images
  – Shape modeling, rendering, on-board maps

• Real-time image-based feedback control

• 6DOF control of touch-and-go (TAG) sampling event
  – Descend along guided path
  – Achieve prescribed guidance condition for sampling (position/orientation, velocity, contact force profile)
  – Recover from sampling disturbances and induced attitude rates
  – Ascend from surface to safe altitude
Benefits from GN&C Autonomy

• Without Autonomous GN&C, small body landing error approx 100-200 m in diameter on surface with 1-2 m/s velocity dispersions
  – Example: NEAR landing on Eros had 500 m error ellipse with 1.8 m/s touchdown velocity

• Drives the need to find wide hazard-free regions for landing sites (> 200 m)

• On-board autonomous GN&C can reduce errors to approx 5-10 m in diameter with 3-5 cm/s velocity error
  – Enables much larger class of small body missions
Recent JPL Developments

AutoGNC

- AutoGNC product developed as extension of AutoNAV product to handle full 6DOF (rotation and translation), with VML autonomy engine, and capability for near-surface operations, contact, and sample-return
- Product of JPL internal R&TD funding and other project investments (New Millennium DS1, Deep Impact, etc.)
- Level-of-readiness currently at TRL 5

Goal

- Provide “off-the-shelf” on-board autonomous GN&C capability that can be systematically integrated into emerging comet and asteroid missions
An AutoGNC Flight Integration Strategy

**AutoGNC (integrated C-monolith)**

- **AutoNav**
  - Calc TCM
  - Orbit Determination
  - Nav and OpNav Gofers

- **Guidance and Control**
  - NonLinear Path Planner?
  - Docking Controller?
  - Attitude Estimator
  - Attitude Profiler
  - Attitude Controller
  - Thrust Allocator

- **External flight element**
  - Flight Director
  - Picture Manager
  - OD Manager
  - Maneuver Manager
  - Attitude Manager
  - Trajectory Manager
  - Fault Protection & Monitors

- **OBIRON**
  - Landmark Tracking
  - Altimeter Model

**Requests for S/C action**
- Thruster commands
- Thrust directives
- Fault Status Flags

**“Raw” data inputs**
- Radio Metric Data
- Command Directives
- Star Tracker Handler
- IMU Handler
- Ranger Handler
- Contact Sensor Handler
- Camera Handler

**VML Language Constructs**
- Altimeter Model
- CMD
- TLM
- Clock
- Messaging

**C-Code flight Elements**
- Resident RTOS or OLVM-Derived Elements

**Onboard AutoGNC Function**
- Onboard AutoGNC Function (speculative)

**Currently (4/09) non-C code elements hosted in DSENDS**
- Resident FDIR

**Requests for S/C action**
- Thruster commands
- Thrust directives
- Fault Status Flags
Simulated Scenario: Descent, TAG and Ascent

- **Safe Flyby** Trajectory ~1km range
- Altimeter lock-up
- Commit Maneuver
- Surface Intersecting Trajectory
- Target-Site relative rate nulling maneuver

- 40 km Range in Station-keep “Start Zone”
- GN&C statistical trajectory correction opportunities
- “Safe Flyby” Trajectory
- ~70m range
- Passive TAG-abort Trajectory
- Earth Radiates “Okay to Commit to TAG”
- Target-Site relative rate nulling maneuver
- Two vertical correction opportunities with dominant deterministic “thrust-down” components to reduce exhaust contamination of surface.
- Terrain-relative Nav (Optical Nav)
- Post-TAG departure ~70m range
- ZOOM

TAG Target Site OpNav Pictures
Example Image from Op-nav camera
AutoGNC Performance
Spacecraft Descent, Touch&Go Sampling and Ascent

Magnitude of Position Difference (Inertial)

Position errors at contact below 6 meters with less than 3 cm/sec velocity error
Navigation Images Used for Landmark Tracking

On-Board feature recognition using 3-D features and stored image maps
On-Board Optical Navigation Issues

- Landmark tracking function has to deal with 4 order-of-magnitude changes in image scale (e.g., 10 km to 1 m)
- The smoothest and safest regions for landing are often the least informative for camera-based navigation
- Typically >100 landmarks are available per image for processing
- Given typical CPU constraints of allowing 10% of a RAD 750, landmark-based navigation can process approximately 1 image every 15 seconds
  - Assumes processing is limited to 10 landmarks per image
- Just adequate to perform autonomous navigation to support small body landing errors at the 5-10 m landing error level
- Higher imaging rates and more landmarks-per-image are desired to mitigate risk (false matches, low lighting, sparsity of features, scale changes, viewing angle changes, and map errors)
  - Alternative Architectures:
    - Dedicated processor for GN&C computations
    - Dedicated hardware for image processing/correlation
    - Faster spacecraft CPU
Control Challenges for TAG Sampling

- Achieve prescribed guidance condition for sampling (position/orientation, velocity)

- Achieve prescribed sampling force profile on end-effector

- 6DOF control to implement ascent burn while recovering from sampling disturbances and induced attitude rates

- Minimize control interactions with flexible solar panels

- Avoid surface contact with any part of spacecraft

- Tolerate over 4 orders of magnitude uncertainty in strength/stiffness of surface material

- Avoid thruster plume contamination of sampling area
CONCLUSIONS

• New GN&C challenges are associated with small body surface proximity operations, contact, and sampling

• Autonomous GN&C capability with landmark-based navigation drives landing errors down from 100-200 m (without) to 5-10 meters (with)
  – Enables much larger class of small body missions
  – Will become essential as mission goals become more ambitious

• Very few Autonomous GN&C systems in existence
  – Hayabusa (JAXA) – experimental - not exercised for mission purposes
  – Rosetta (ESA) – to be exercised at comet 67P/Churyumov-Gerasimenko in 2014

• JPL’s AutoGNC technology product developed from internal R&TD funding and other project investments
  – Level-of-readiness currently at TRL 5 (AutoNav capability at TRL 9)
  – Continued development for infusion into emerging small body missions
APPENDIX
Integrated 6DOF GN&C Solution

• Near-surface operations and autonomous sampling couple spacecraft attitude and translation

• An integrated 6DOF GN&C capability simultaneously optimizes over attitude and translation degrees-of-freedom
  – Thrust allocation (use of same thrusters)
  – Close-range maneuvering (geometric constraints, camera/antenna pointing, avoiding surface-S/C contact)
  – Rejection of sampling-induced reaction force & torque disturbances (a 6-DOF control problem)
  – Flex-solar-panel interactions with control system
  – Response to active environmental disturbances (e.g., active vents, dust, outgassing)
  – A fully integrated 6DOF GN&C architecture is currently nonstandard for exploration spacecraft