Trajectory Design Considerations for Small Body Touch-and-Go

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2/14/2011
Introduction

• What is TAG?
  – Descent to the surface
  – Brief contact
  – Ascends to a safe distance

• Why TAG?
  – Sample acquisition, demonstration of landing technology, etc
  – May be preferable to landing
    • Avoid additional hardware
    • Mitigates concerns about topography

• Outline
  – Trajectory Description
  – Design Drivers:
    • Dynamics
    • Environment
    • Spacecraft and Ground System Capabilities
    • Mission Objectives
  – Design Choices
  – Historical Precedents
  – Case Studies
**TAG Trajectory Description**

**Trajectory Design Considerations for Small Body Touch-and-Go**

- **Staging**
  - Before the commitment is made to go to the surface
  - Flybys, orbits, active stationkeeping

- **Descent**
  - Between staging and contact.
  - Contains most of the maneuvers

- **Contact**
  - On the surface
  - Spacecraft/surface interactions

- **Ascent**
  - From contact to some safe distance
  - Typically initiated with a single burn.
Drivers: Dynamics

Trajectory Design Considerations for Small Body Touch-and-Go

- Very complex due to:
  - Non-spherical gravity
  - High SRP relative to gravity
  - Effect of tides
  - Which is dominant varies with position

- Contain atypical effects
  - Coriolis and centrifugal effects
  - Outgassing
  - Secondaries
Dynamical Uncertainty

- Dynamics of the small body environment have large uncertainties
  - Limited observations from Earth
  - Available data should be used to bound uncertainty
- Design must be robust to these uncertainties
Drivers: Environment

- Orbiting debris and dust
  - TAG event itself can raise significant quantities of dust which may interfere with spacecraft functionality
  - Cometary outgassing can lift dust and rocks (10s of cm) which can cause damage upon impact

- Landing site availability and topography
  - Almost always entirely unknown/unknowable pre-rendezvous
  - Spacecraft may require smooth, obstacle-free sites for successful TAG.
  - Delivery errors should be minimized to increase likelihood that a suitable site can be found.
Drivers: Spacecraft and Ground

Trajectory Design Considerations for Small Body Touch-and-Go

• Navigation and maneuver capabilities
  – Light time constraints
  – Approach can limit number of maneuvers
  – Optical navigation

• Power and Communications
  – Over-constrained geometries
  – Battery depth-of-discharge

• Thrust available
  – Allowable time/distance during contact
  – Moments by surface

• Fault protection
  – Ascent-on-fault
  – Can potentially constrain attitude during descent
Drivers: Mission Objectives

Trajectory Design Considerations for Small Body Touch-and-Go

- Landing site location and contact site accuracy
  - Surface topography typically unknown during mission planning
    - Range of landing sites
    - Ability to adapt
  - Contact state variations may be constrained
    - Samples may be desired from some specific site
    - End-effector works best in a small range
    - Etc.

- Contamination
  - Sample science may require unaltered samples
  - Can constrain maneuvers such as to minimize plume impingement on the surface
  - Can constrain campaign to ability to reach multiple sites
  - Could require special approaches to ascent
Design Choices (1)

Trajectory Design Considerations for Small Body Touch-and-Go

• Staging
  – Gateway between TAG and the rest of the mission
  – Should ensure that the spacecraft remains on a safe trajectory until descent is willfully initiated.
  – Options:
    • Stable orbit
    • Unstable orbits with stationkeeping
    • Ping-pongs
    • Hovering in a fixed position

• Descent
  – Begins and ends motion toward the surface.
  – Includes all the maneuvers to reach the contact state and time
    • Driven by navigation approach
    • Must meet requirements (e.g. contamination)
    • Execution errors
  – Passive abort vs. direct descent
Design Choices (2)

Trajectory Design Considerations for Small Body Touch-and-Go

• Contact
  – Lasts a few seconds
  – Complex 6-DOF dynamics due to surface interaction
  – Drivers:
    • Purpose of TAG
    • Contact velocity
    • Spacecraft design
      – Thruster size
      – Allowable stroke
      – Attitude control system

• Ascent
  – “Ascent burn” triggered at contact or shortly thereafter
    • Sized to ensure re-contact doesn’t occur
    • Must account for attitude and rate disturbances during contact
  – Single burn or series of smaller burns
    • Contamination
    • Propulsion system type
## Precedents and Case Studies

### Trajectory Design Considerations for Small Body Touch-and-Go

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<tr>
<td>NEAR-Shoemaker Landing on Eros</td>
<td>Large small body (33 km), weak SRP</td>
<td>Retrograde equatorial orbit</td>
<td>No passive abort with horizontal velocity biasing</td>
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<tr>
<td>Hayabusa TAG on Itokawa</td>
<td>Very small body (0.5 km), strong SRP</td>
<td>Earth-line vertical hovering</td>
<td>No passive abort with autonomous cross-track control</td>
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<tr>
<td>Deimos</td>
<td>Medium size body (15 km), dominated by Mars tides</td>
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<tr>
<td>Comet Tempel 1</td>
<td>Active Jupiter-family comet with known shape (6 km)</td>
<td>Hyperbolic flyby</td>
<td>Passive abort, fully autonomous descent with sensitivity to contamination</td>
<td>Escape</td>
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<tr>
<td>1996 FG3</td>
<td>Small body (1.8 km), fast rotator, small moon</td>
<td>Horizontal sun-line hover</td>
<td>Passive abort with periodic Coriolis cancellation during fully autonomous descent and sensitivity to contamination</td>
<td>To staging</td>
</tr>
</tbody>
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Historical Precedents: NEAR

Trajectory Design Considerations for Small Body Touch-and-Go

- **Not TAG**
  - Objective: As much low-altitude imaging as possible.
  - Spacecraft survival not a requirement
  - No ascent planned

- **Staging:**
  - 35 km radius retrograde orbit
    - Eros: 34 x 11 x 11 km in extent
    - Hovering rejected due to fuel requirements

- **Navigation:**
  - Ground-based optical navigation
  - Autonomy considered and rejected due to need to alter flight code.

- **Descent included 5 “end of mission maneuvers,” or EMMs**
  - EMM-1: alter inclination and place s/c on impact trajectory
  - EMM-2 zeroed horizontal velocity at 12.2 km radius, 3.75 hrs after EMM-1
  - EMM-3 and 4: “Bouncing” braking maneuvers
  - EMM-5: Minimize landing velocity and bias horizontal velocity to keep s/c upright

- **Maneuver control:**
  - Timing update after EMM-1 to target EMM-2
  - Absent the update, EMM-3 and 4 would place s/c on escape trajectory
Historical Precedents: Hayabusa

Trajectory Design Considerations for Small Body Touch-and-Go

- **Itokawa**
  - 12 hour “day”
  - 535 x 294 x 209 meters in extent

- **Staging:**
  - Earth-line hover
    - Motion directly observable in Doppler
    - Ground-commanded station-keeping
  - Orbits unstable due to SRP

- **Descent:**
  - Extension of hovering control box to include surface.
    - Manual control of real-time residuals to control velocity and timing of contact
    - Constrained sites to be through the Earth line
  - Plane-of-sky control via autonomous tracking of artificial landmark
  - Anomalous contact

- **Ascent** was reversal of descent.
Case Study: Deimos

Trajectory Design Considerations for Small Body Touch-and-Go

• Deimos:
  – Smaller and further of Martian moons
  – 15 x 12.2 x 10.4 km in extent
  – Imaged by Viking and others

• Staging:
  – 20 x 24 km equatorial DRO
  – Altitude chosen to allow sufficient time for ground-based NEAR-like navigation
  – Type was most stable option

• Descent:
  – 500 meter “flyby” at 5 m/s
  – Two-part drop burn with autonomous correction
  – Two braking burns

• Contact:
  – DRO-based design and passive abort requirement constrained sites to be sub-Mars or antipode

• Ascent:
  – Escape to Deimos-leading Mars orbit
Case Study: Comet Tempel 1

Trajectory Design Considerations for Small Body Touch-and-Go

- **Tempel 1**
  - Active Jupiter-family comet
  - Target of Deep Impact and Stardust NExT
  - 7.4 x 6.2 x 5.4 km in extent
  - Significant uncertainty in mass

- **Staging**
  - 3 m/s hyperbolic flyby
  - 120 km radius to 500 meter alt
  - One cleanup and AutoNav enabled

- **Descent**
  - “Drop burn” to send to surface
  - Two autonomous braking burns
  - Must occur while on battery power only
  - Contamination concerns

- **Contact:**
  - Local morning to avoid outgassing

- **Ascent**
  - Single burn
  - Separate cold-gas system was too expensive
Case Study: 1996 FG3 (1)

Trajectory Design Considerations for Small Body Touch-and-Go

- **Unknown size/shape**
  - Lightcurve data available and processed by astronomers
  - “Normalizing distance” of 720 meters
    - Primary: 756 x 684 x 504 (radii)
      - Spin: 3.6 hrs
    - Secondary: 231 x 166 x 166 (radii)
      - Orbit Radius 2.09 km
      - Period: 16.2 hrs
  - Periods well known, but $2^{1/2}$ uncertainty in distances and $2^{3/2}$ uncertainty in mass

- **Unknown topography**
  - Used uniform boulder distribution from Itokawa to simulate likelihood of finding landing sites
    - 19 sites with landing ellipse diameter of 6 meters
    - 0 sites with landing ellipse diameter of 10 meters
    - Admittedly conservative because it neglects sorting mechanisms
  - Concluded that the landing location dispersions needed to be as small as possible.
Case Study: 1996 FG3 (2)

Trajectory Design Considerations for Small Body Touch-and-Go

• Staging
  – “Horizontal hover” at 5 km radius, ±45 deg off sun-line
  – Simplified phasing to keep Secondary on far side of Primary during TAG and meet lighting requirements at contact

• Descent
  – Two “corridor correction” maneuvers to counter strong Coriolis effect
  – Two “push down” maneuvers to bias trajectory for contamination

• Contact
  – Context imaging required mid afternoon or morning contact
  – Mid morning selected to keep entire trajectory over sun-lit surface

• Ascent
  – Single burn to return to 5 km altitude within 5 hours including contact disturbances
  – On escape trajectory
Any Questions?