IAA-PDC13-04-27

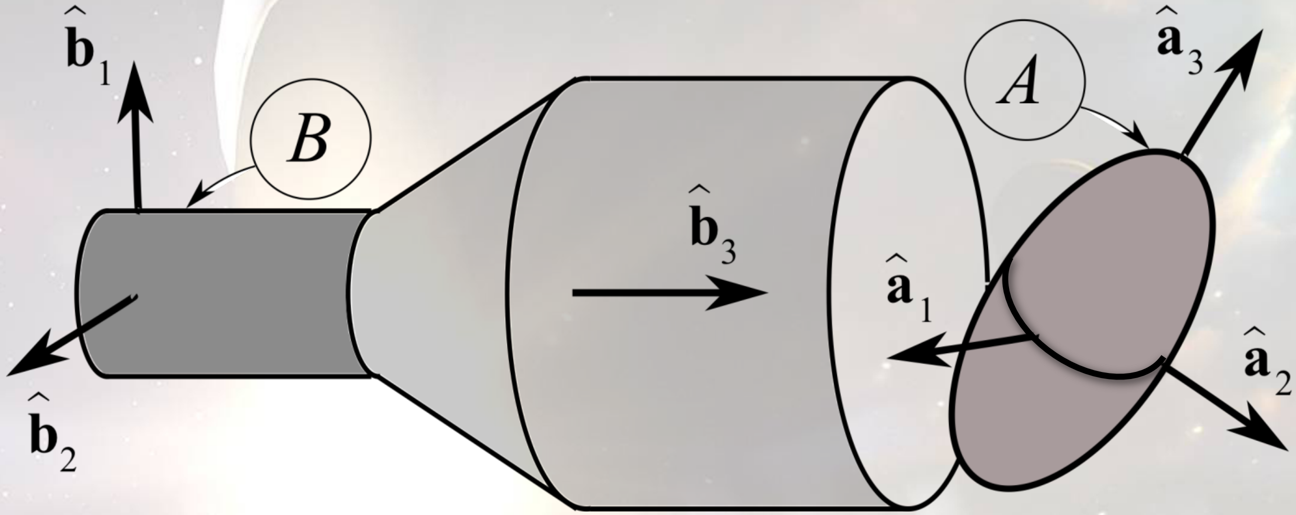
Catching a Rolling Stone: Dynamics and Control of a Spacecraft and an Asteroid

Carlos Roithmayr[1], Haijun Shen[2],
Mark Jesick[2], and David Cornelius[2]

[1] NASA Langley Research Center, Hampton, Virginia
[2] Analytical Mechanics Associates, Inc., Hampton, Virginia

2013 IAA Planetary Defense Conference
April 15 – 19, 2013
Flagstaff, Arizona

Introduction



- NASA is considering the mission proposed by John Brophy et al. in "Asteroid Retrieval Feasibility Study," April 2, 2012
- Spacecraft *B* (18×10^3 kg) collects small asteroid *A*, ~7 m dia. (~500×10^3 kg), or small boulder from a larger asteroid
- Spacecraft transports *A* to orbit in Earth-Moon system
- **Requires solutions to same engineering problems as asteroid deflection**

Dynamics and Control of :

1. **Initial Approach**

   From a nearby stationary position, spacecraft approaches and begins hover

2. **Hover**

   Spacecraft *B* moves such that it is fixed in reference frame (rigid body) *A*

3. **Removal of Relative Angular Velocity**

   Orientation of *B* is changed so that the opening of the container is facing *A*

   Angular velocity of *B* relative to *A* is eliminated

4. **Descent (Ascent)**

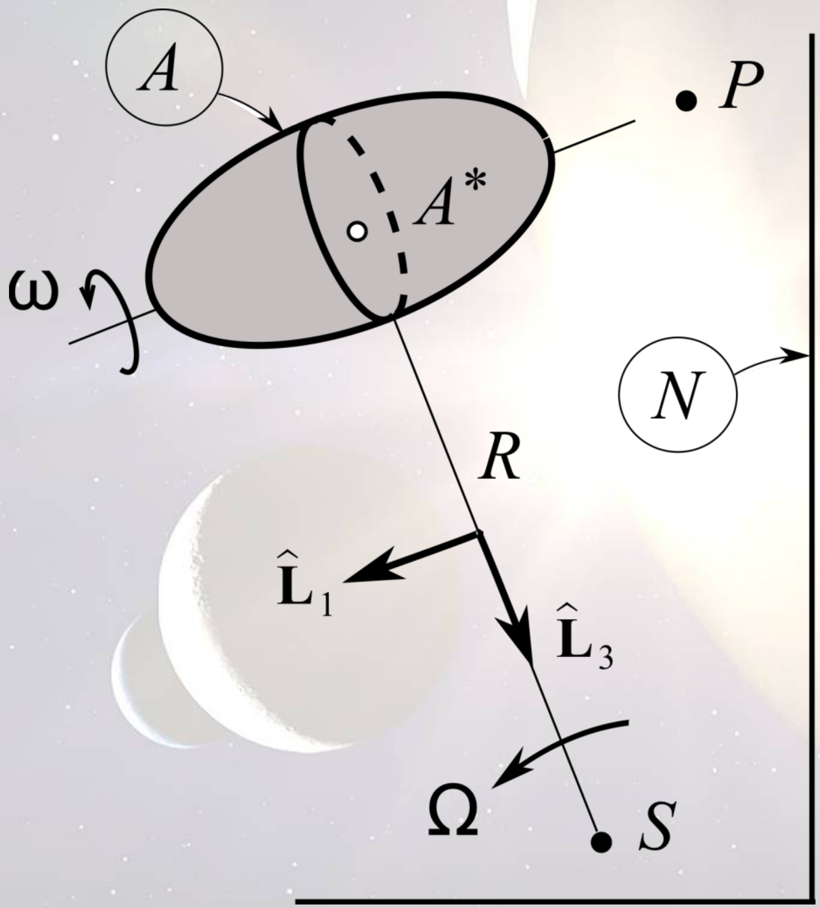
   Spacecraft descends to collect *A* into container

   If asteroid is large, spacecraft ascends after collecting small boulder

5. **Removal of Inertial Angular Velocity**

   Inertial angular velocity of spacecraft and payload (rigidly connected) is eliminated so that thrust and solar arrays can be aimed properly

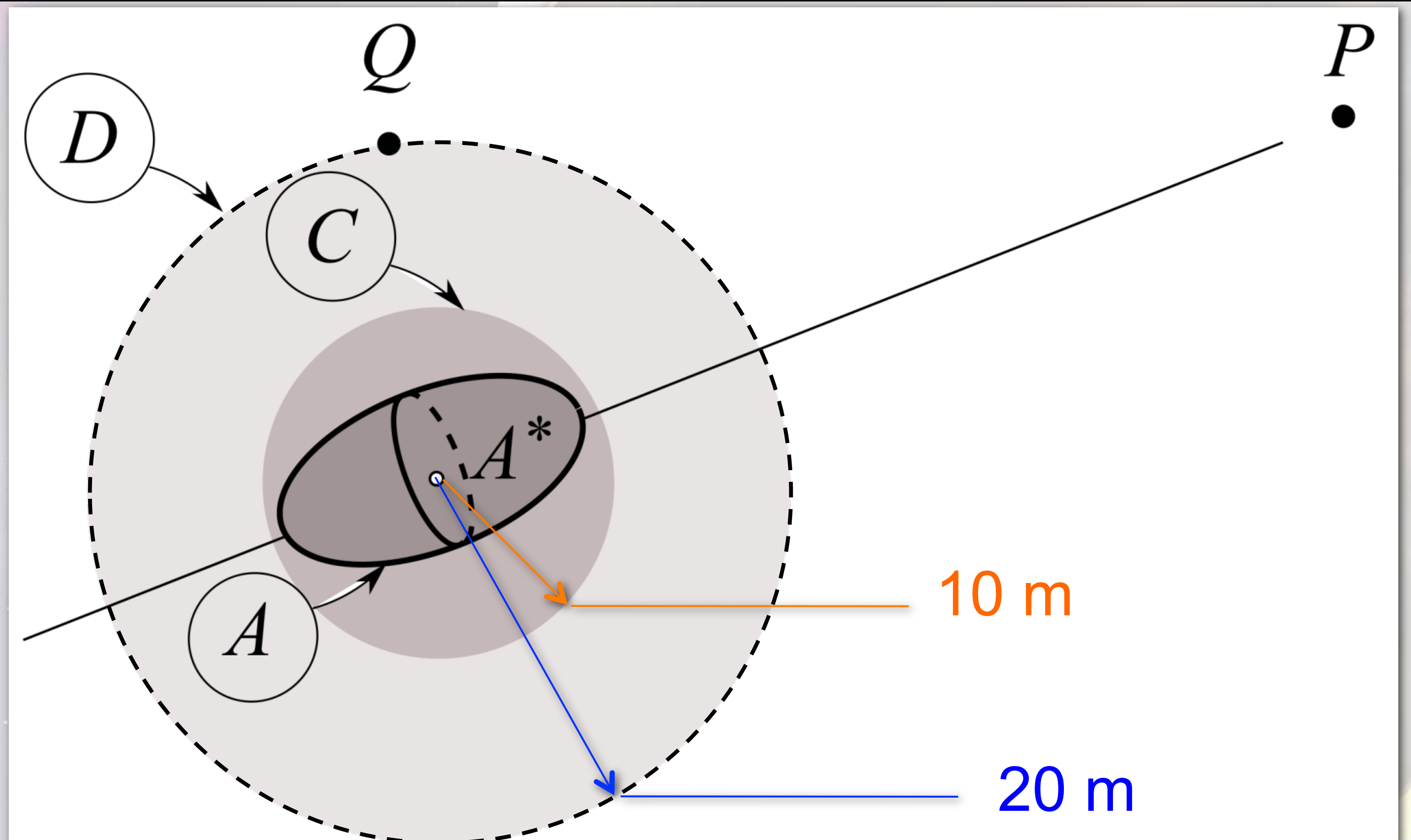
Asteroid Motion



- Assumed asteroid motion for : Approach, Hover, Descent, Ascent

- Heliocentric circular orbit, R = 0.9 AU
- Asteroid spin rates ω = 0.5, 1, 5, 10, 60 rev/hr

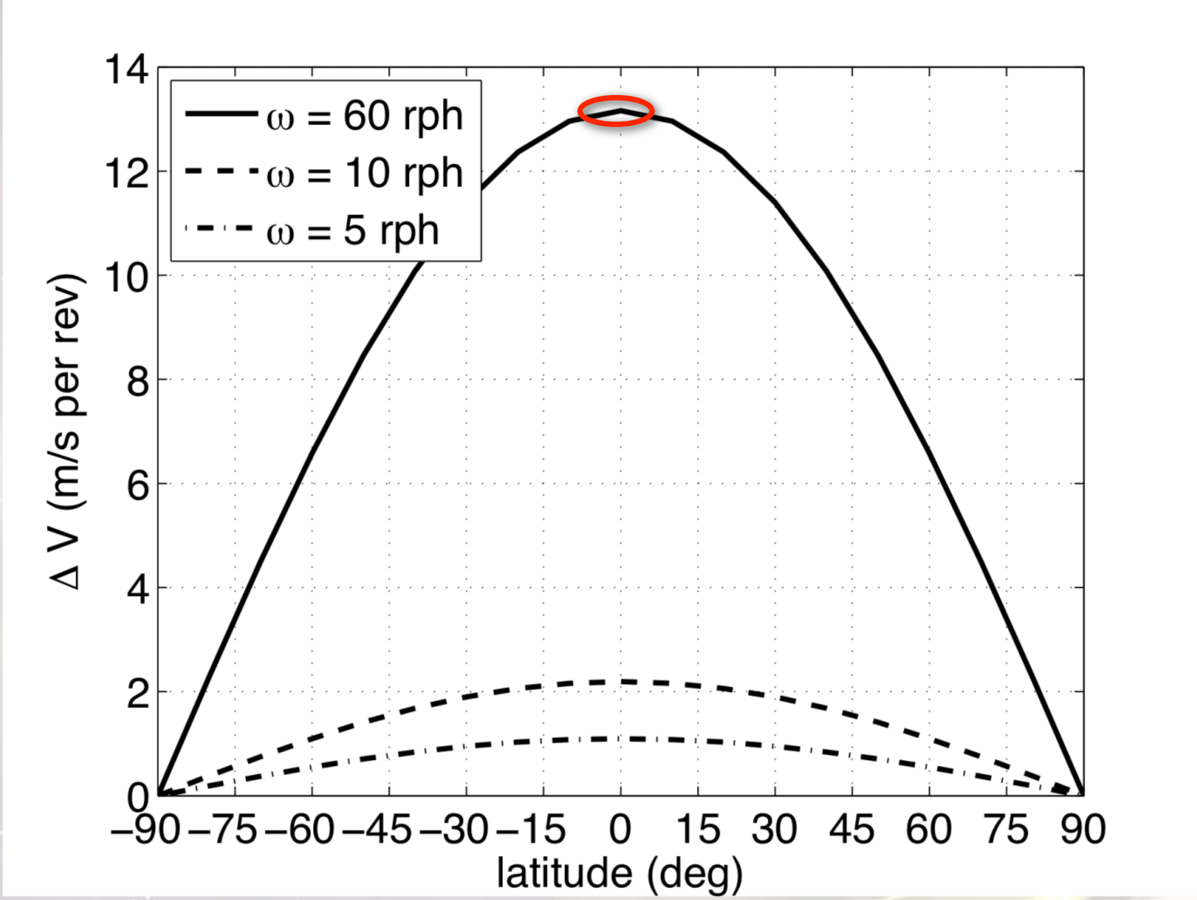
Initial Approach



Depart from *P*, stationary relative to *A**.

- Minimum ΔV, multi-impulse, trajectories to stations on *D*
- Keep-out sphere *C* for collision avoidance
- Relatively inexpensive. ΔV = 2.1 m/s and Δm = 14 kg for I_{sp} = 287 s, ω = 60 rev/hr, time of flight = 2600 s

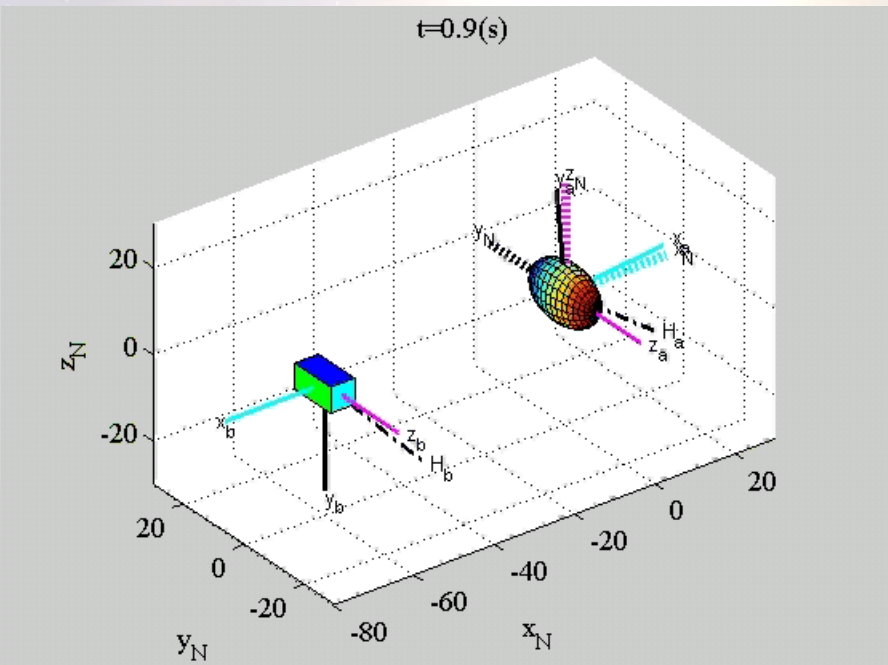
Hover



- Hovering can be prohibitively expensive. ΔV = 13 m/s per minute for ω = 60 rev/hr; Δm = 84 kg after 1 minute

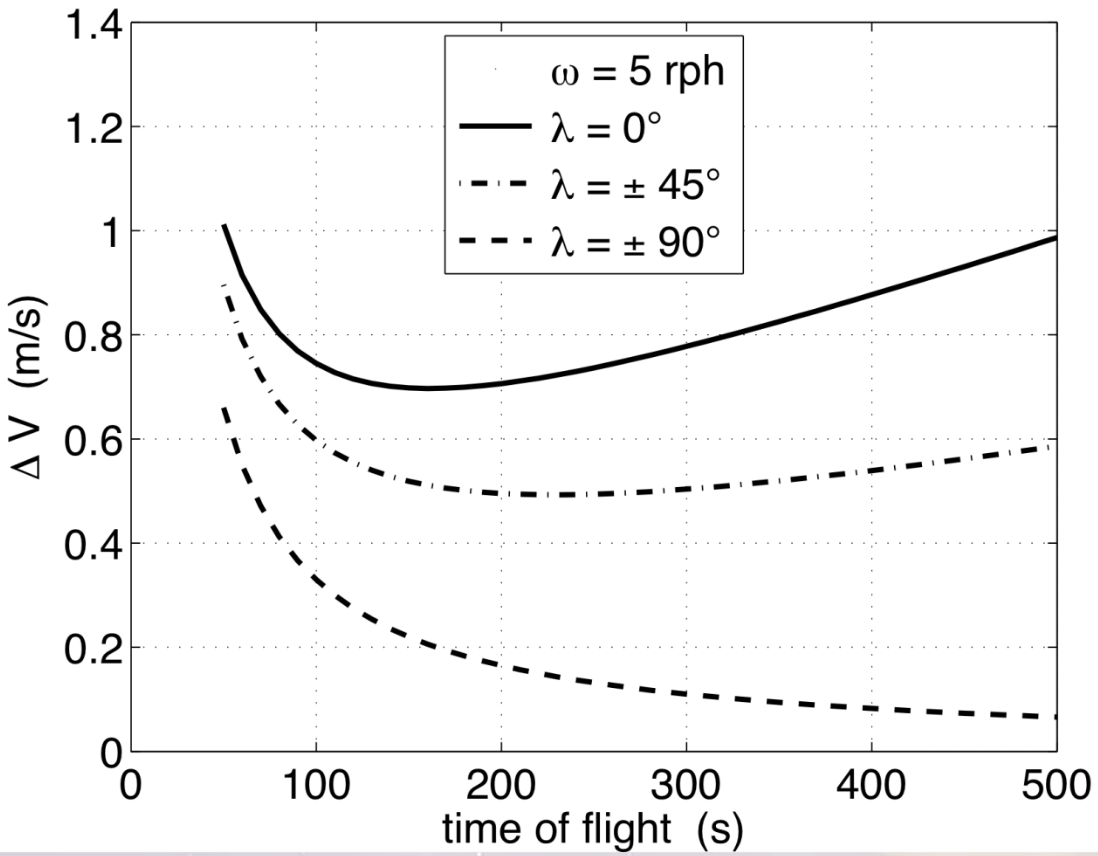
Removal of Relative Angular Velocity (Spin-up)

- Attitude control algorithm developed to
  - Keep S/C axis of symmetry parallel to a line fixed in *A*
  - Drive relative angular velocity $^A\boldsymbol{\omega}^B = {^N\boldsymbol{\omega}^B} - {^N\boldsymbol{\omega}^A}$ to **0**
    - Assume no particular relative orientation is required about the symmetry axis, between *A* and *B*



- Example with tumbling asteroid
  - *A* is unsymmetric:
    - $J_1 = 2.5 \times 10^6$ kg-m^2
    - $J_2 = 4.1 \times 10^6$ kg-m^2
    - $J_3 = 3.4 \times 10^6$ kg-m^2
  - At $t = 0$, $^N\boldsymbol{\omega}^A = [0.6\ \ 0.6\ \ 6.0]$ deg/s

Descent



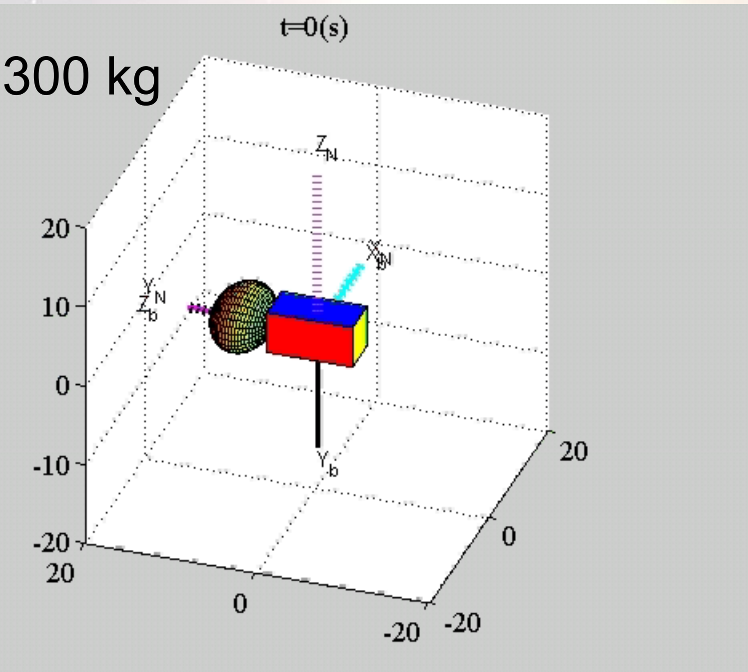
- ΔV is a function of ω, λ, and time of flight
- Descending too quickly or too slowly can be expensive

- Curves for ascent have similar character; large payload mass significantly increases propellant mass compared to descent

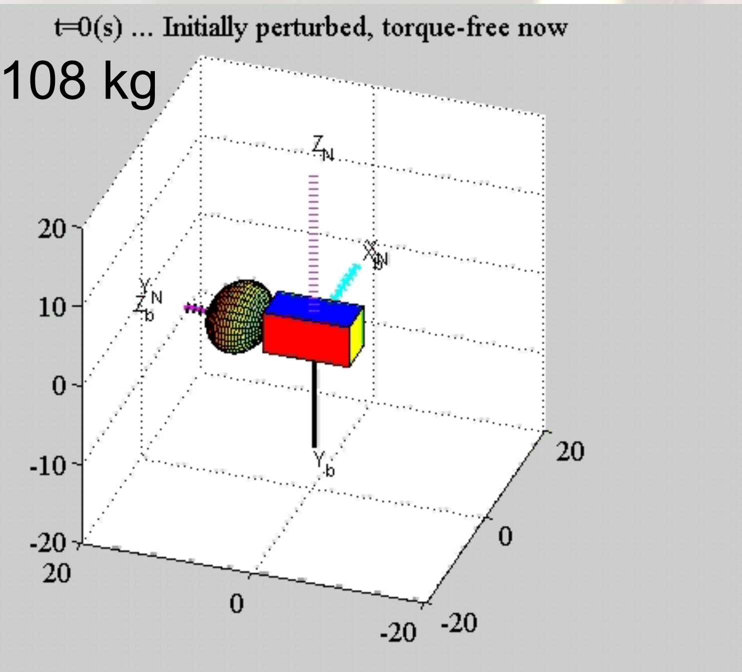
Removal of Inertial Angular Velocity (Despin)

- Asymptotically stable attitude control algorithm developed
  - Dissipates rotational kinetic energy; drives ${}^{N}\boldsymbol{\omega}^{B}$ to **0** without constraining final attitude
  - Use of control energy can be adjusted
- Example, unsymmetric rigid body formed by *B* and *A*

Δm = 300 kg



Δm = 108 kg



Conclusions

1. **Initial Approach** to a NEA is not expensive
2. **Hover** can be prohibitively expensive
3. **Removal of Relative Angular Velocity**
   - A feedback controller is developed
   - Spin-up is moderately expensive
4. **Descent (Ascent)**
   - Descent along a line fixed in the asteroid can be moderately expensive
   - Ascending with a massive payload can also be expensive
5. **Removal of Inertial Angular Velocity**
   - An asymptotically stable feedback controller is developed
   - Inducing tumbling in an unsymmetric body can save much propellant

Retrieving a Boulder from Itokawa

- Total Δm = 18 kg, of which 17 are used for ascent and despin
- Boulder mass = 250 × 10^3 kg. For planetary defense, contemplate delivering a propulsion system with mass = 250 × 10^3 kg