Spacecraft Trajectory Design Near Asteroid 4769 Castalia

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Introduction

- Asteroids and comets are of significant interest
  - Science - Insight into early solar system formation
  - Mining - vast quantities of useful materials
  - Impact - high risk from hazardous Near-Earth asteroids
- Near-Earth asteroids (NEAs) are especially interesting
  - Orbit close to the Earth and are easily accessible
  - Many asteroids hold vast quantities of useful materials
  - Asteroid mining: Precious metals, propulsion fuels, semiconductors
  - Commercialization is feasible with huge amounts of possible profit
- High probability of future asteroid impacts

Technical Challenges

- Low-thrust propulsion systems offer innovative options
  - Electric propulsion offers much greater efficiency
  - Allows for greater velocity change with a reduced mass cost
  - Key component for long duration missions with frequent thrusting
  - Requires new methods of design
- Optimal trajectory design is complicated
  - Highly nonlinear and chaotic dynamics requires intuition by designer
  - Using low-thrust propulsion adds additional difficulties in accurately capturing the small perturbations
- Astrodynamics trajectory design typically uses direct optimal control
  - Large nonlinear programming problem inherently approximates the true optimal solution
  - High dimensionality of the solution makes it extremely computationally intensive

Gravitational Modeling

- Asteroids are extended bodies - not point masses
  - Gravity is the key force in orbital mechanics
  - An accurate representation of gravity is critical to accurate and realistic analysis
- Spherical Harmonic approach is popular but not ideal
  - Model is only valid outside of circumscribing sphere
  - Composed of an infinite series - always results in an approximation
  - Model will diverge when close to the surface and is not ideal for landing missions
- Polyhedron Gravitational model used to represent the asteroid
  - Gravity is a function of the shape model
  - Globally valid and closed-form analytical solution for gravity
  - Exact potential assumes a constant density assumption
  - Accuracy is only dependent on the shape

Dynamics about the asteroid 4769 Castalia

- Dynamics are very similar to the famous three-body problem
  \[ \frac{d}{dt} \begin{bmatrix} \dot{r} \\ \dot{v} \end{bmatrix} = \begin{bmatrix} g(r) + h(v) + u \\ 0 \end{bmatrix} \]
- Huge history of analytical tools allow for great insight into the dynamics
- Analytical insight is critical to understanding the free motion around an asteroid
  - We require an accurate understanding of the motion under the influence of gravity alone
  - Efficient use of the limited onboard fuel is dependent on exploiting the natural dynamics of the asteroid environment
- Jacobi Integral - single constant of motion which bounds the feasible regions in terms of “energy”
  \[ J(r, v) = \frac{1}{2} r^2 (x^2 + y^2) + U(r) - \frac{1}{2} (x^2 + y^2 + z^2) \]

Simulation Results

- Transfer between two periodic orbits of 4769 Castalia
  - Thruster represents a current electric propulsion \( \approx 400 \, \text{mN} \)
  - Combining multiple iterations of the reachability computation allows for general transfers
  - Combining four iterations of the reachability set
    - Each iteration of the reachability set enlarges the achievable states
    - We choose a direction on the reachability set which lies closest to the target
    - This iterative approach avoids the difficulty in choosing accurate initial guesses for optimization

Reachability on the Poincaré section

- Reachability on the Poincaré section
  - Reachability set on a Poincaré section

Conclusions

- Demonstrate a transfer around an asteroid using multiple reachability sets
  - Each reachability set moves the spacecraft towards the target
  - Alleviates the need for selecting accurate initial guesses
  - Automatically gain insight into the feasible region of motion for the spacecraft
- Future work will extend this principle to landing trajectories on asteroids
  - Irregular shape of asteroids requires innovative techniques for controlling both position and orientation
  - Nonlinear control allows for the exploitation of the coupled dynamics
  - Complex dynamics requires accurate integration schemes - Variational Integrators
- Successful extension of previous work in the circular restricted three-body problem