Thrust Direction Optimization: Satisfying Dawn’s Attitude Agility Constraints

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- The long arrays create a large moment of inertial
- Spacecraft attitude is determined by “Power Steering”
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  - Spacecraft is rotated around the thrust direction
  - Solar arrays are rotated
The Problem with Power Steering

- There are two “poles” that can require very rapid 180° attitude flips
- The flip involves the highest moment of inertial (solar arrays)
- The two poles are the Sun and Anti-Sun directions
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Dawn’s Attitude Control System

- Dawn’s attitude was controlled using thrust vectoring in two axes perpendicular to thrust and reaction wheels parallel to thrust
- Thrust vectoring was achieved with gimbals on the ion thrusters
- Max excursion was $< 5^\circ$
- Thrust $\sim 50$ [mN]
- Spacecraft $\sim 1200$ [kg]

Weak Control: Low Agility
Maneuvers required at Vesta had to be very complex.

- Strong/complex gravity
- Tangential gravity > thrust
- Transfer safety
- Science orbits targeting

An example of an executed maneuver at Vesta, November 2011. Yellow vectors are thrust directions.
Maneuver Design At Vesta

- Software: “Mystic” uses Static Dynamic Optimal Control
- Based on Bellman’s Principal of Optimality and Dynamic Programming (not NLP or calculus of variations)
- Very-high fidelity trajectory design tool used to design all maneuvers (High order gravity harmonics, multi-body gravity, radiation pressure, nonlinear thruster model, desat ΔV, etc.)
- Many operational constraints
- Original objective functions: Minimum Propellant or Minimum Time.
Attitude Agility Constraints

• Must constrain thrust direction time evolution
• Attitude agility constraints are:
  – Not analytic
  – Not predictable (unknown spacecraft momentum)
  – Monte-Carlo analysis necessary to evaluate fly-ability

• General rules exist to improve chances of fly-ability
  – Thrust “further” from Sun and Anti-Sun directions
  – Make attitude rates (accelerations) lower
  – Keep thrust direction movement continuous!
Attitude Agility Constraints

- Cone angle exclusion constraints do not work
  - Result in high accelerations
  - Discontinuous thrust directions
  - Does not address high rates or accelerations
Mystic Optimal Control Formulation

Objective Function:

$$J(v, w) = \int_{t_0=w_1}^{t_f=f(w)} F(x(t), v(t), w, t)dt + \sum_{i=1}^{M} H_i(x(t_i), v(t_i), w, t_i) + G(x(t_f), v(t_f), w, t_f)$$

State Equation:

$$\frac{dx(t)}{dt} = T(x(t), v(t), w, t)$$

Initial Condition Function:

$$x(t_0) = \Gamma(w)$$

STATE: \( x(t) = \) s/c position, velocity, mass
CONTROL: \( v(t) = \) thrust vector
CONTROL: \( w = \) initial time, flight time, initial state
**Mystic Optimal Control Formulation**

**Objective Function:**

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\]

**State Equation:**

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\frac{dx(t)}{dt} = T(x(t), v(t), w, t)
\]

**Initial Condition Function:**

\[
x(t_0) = \Gamma(w)
\]

So Called “3 DOF” model

**STATE:**

\(x(t) = \text{s/c position, velocity, mass}\)

**CONTROL:**

\(v(t) = \text{thrust vector}\)

**CONTROL:**

\(w = \text{initial time, flight time, initial state}\)
6 Degree of Freedom Model

- Include 3 attitude angles as part of the state vector

- Natural formulation for constraining attitude rate, accel.
- Account for attitude even when not thrusting
- Complexity of formulation makes initial guesses difficult
- Many more local minima from spacecraft revolution
- Power steering algorithm will also create local minima
- Essentially need to know the answer before starting!
Thrust Direction Optimization

- Sought a new formulation with the advantages of 3 DOF
  - Fewer local minima
  - Simple initial guesses
- Provide ability to manipulate thrust directions and attitude rates
- Solutions must exhibit thrust direction continuity and smoothness

1. Select direction(s) in some frame
2. Find a thrust profile minimally or maximally far away
3. Still achieve all other constraints and state targets
Thrust Direction Optimization

**Direction Attractor**

\[
\min_{v, w} \int_{t \in \tau} \left[ 1 - \hat{v}(t) \cdot \hat{D}(x(t), v(t), w, t) \right]^2 dt
\]

Thrust
Direction Objective

**Pole Repulsor**

\[
\min_{v, w} \int_{t \in \tau} \left[ 1 - (\hat{v}(t) \times \hat{S}(x(t), v(t), w, t)) \cdot (\hat{v}(t) \times \hat{S}(x(t), v(t), w, t)) \right] dt
\]

Attitude Pole to Avoid
Direction Optimization Example

R = 640 to 580 [km] transfer, 7 revolutions around Vesta, Time of flight = 2 days, Vesta Operations 11/2011
Pole Repulsor Example

Mystic: EMO 2000 UNIT SPHERE THRUST DIRECTION

- Mass Optimal
- Direction Optimal

- Thrust Direction
- Sun Direction
- Anti-Sun Direction
Rotating with S/C radius vector:

\( \hat{R} \): radial direction

\( \hat{T} \): Transverse direction = local horizontal nearest velocity direction

\( \hat{N} \): orbit normal = \( \hat{R} \times \hat{T} \)
Mystic: Vesta RTN UNIT SPHERE THRUST DIRECTION

MASS OPTIMAL
RTN DIRECTION OPTIMAL

N
Mystic: Vesta RTN UNIT SPHERE THRUST DIRECTION

START
Mystic: Vesta RTN UNIT SPHERE THRUST DIRECTION

RTN DIRECTION OPTIMAL
Mystic: Vesta RTN UNIT SPHERE THRUST DIRECTION

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RTN DIRECTION OPTIMAL
Conclusions

• Direction Optimization was essential to Dawn’s success at Vesta
• Allowed for timely creation of fly-able maneuvers
• Solutions tended to exhibit direction continuity and smoothness
• Most effective formulation: Direction Attractor in RTN frame. Distant second: inertial frame pole repulsor.
• Generally best to choose frame in which thrust pattern is compact.
• There are many interesting, non-intuitive behaviors of direction optimal solutions