Thruster-Specific Force Estimation and Trending of Cassini Hydrazine Thrusters at Saturn

Joan Stupik
Thomas A. Burk

Cassini Spacecraft Operations Office
Jet Propulsion Laboratory
California Institute of Technology

January 8, 2016
Cassini Spacecraft

- General spacecraft information
  - Main engine: 445 N (2)
  - Launch total mass: 5,574 kg
  - Propellant launch mass: 3000 kg
    - Additional 132 kg hydrazine
  - Thrusters: 1 N at launch (16)
    - Prime set (8)
    - Back-up set (8)
  - Reaction wheels (4)
    - 3 active, 1 back-up

From NASA/JPL Cassini website
Mission Phases of Cassini


Prime Tour (2004 – 2008)

As the spacecraft ages, monitoring hardware health becomes increasingly important
GNC Subsystem

- Calibrations at least once per year for IRUs, gimbals, SRU
- Currently using some back-up hardware:
  - Reaction wheel 4 (RWA4) replaced RWA3 as prime in 2003
  - Thruster branch B (B-branch) replaced A-branch in 2009, due to degradation

From NASA/JPL
Cassini RCS Thruster Branch

- Eight 1-N (0.225 lb) thrusters
- Y-thrusters fire in pairs – no ΔV produced (nominally)
- A-branch and B-branch are almost identical

<table>
<thead>
<tr>
<th>Torque Axis Needed</th>
<th>+X</th>
<th>-X</th>
<th>+Y</th>
<th>-Y</th>
<th>+Z</th>
<th>-Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrusters to Fire</td>
<td>Z3,Z4</td>
<td>Z1,Z2</td>
<td>Z1,Z4</td>
<td>Z2,Z3</td>
<td>Y2,Y4</td>
<td>Y1,Y3</td>
</tr>
</tbody>
</table>
Thruster Activities

- Cruise phase attitude control
- Orbit trim maneuvers (OTMs)
- Reaction wheel momentum biasing (changing from one momentum state to another)
- Reaction wheel friction characterization tests (not done since 2010)
- Low-altitude Titan or Enceladus flybys to counteract atmospheric torque (rare)
- Special observations when a science team needs to turn quickly (rare)
- Safe mode (rare...hopefully)
Thrust Magnitude Estimation

- There is no direct measure of the thrust produced from each individual thruster

**Doppler**
- Navigation team is able to determine the average thrust for events whose $\Delta V$ is along the Earth line
- Theoretically could fire thrusters individually for thrust magnitude estimation, but never done for Cassini

**Thrust Calibration Slews**
- Slews done using RCS thrusters for the sole purpose of backing out the thrust values
- Costly in terms of hydrazine

**Use Existing Thrust Activities**
- Specifically, RWA momentum biases
- Biases are the most frequent thrusting event
- Can back-calculate the individual thrust for each Z-facing thruster
RWA Momentum Biases

- Change reaction wheels from an initial rate to a desired final rate
- Thrusters fire to counteract torque, holds the S/C at a fixed attitude
**RWA Momentum Y-Biases**

- **Purpose:** distribute thruster usage more evenly between Y-branch and Z-branch
- **Goal:** momentum bias the RWAs using only Y-thrusters
- **Turn the spacecraft to align the predetermined, desired ΔH vector with the spacecraft Z-axis**
Thrust Estimation Algorithm

\[ I_s/c \dot{\vec{\omega}} + \dot{\vec{H}}_{RW_A} + \vec{\omega} \times (I_s/c \vec{\omega} + \vec{H}_{RW_A}) = \vec{r}_{net} \]

\[ \int_{t_1}^{t_2} I_s/c \Delta \vec{\omega} + \Delta \vec{H}_{RW_A} + \int_{t_1}^{t_2} \vec{\omega} \times (I_s/c \vec{\omega} + \vec{H}_{RW_A}) dt = \int_{t_1}^{t_2} \vec{r}_{net} dt \]

- Euler’s rigid body dynamics equation (in spacecraft body frame)

- Assumptions
  - Only significant external torque comes from thrusters
  - Mechanical misalignments are negligible
  - Products of inertia, center of mass and thrust magnitude do not change over a small thruster event
  - Products of inertia, center of mass and thrust magnitude do not change between two small thruster events close in time
Thrust Estimation Algorithm

\[ I_{s/c} \Delta \vec{w} + \Delta \vec{H}_{RW A} + \int_{t_1}^{t_2} \vec{w} \times \left( I_{s/c} \vec{w} + \vec{H}_{RW A} \right) dt = \int_{t_1}^{t_2} \vec{t}_{net} dt \]

Reaction wheel momentum

\[ b \vec{H}_{RW A} = B C^W \cdot W J \cdot W \vec{\Omega} \]

Reaction wheel rates (rad/s)

\[
\begin{bmatrix}
0 & -1/\sqrt{2} & 1/\sqrt{2} \\
\sqrt{2}/3 & -1/\sqrt{6} & -1/\sqrt{6} \\
1/\sqrt{3} & 1/\sqrt{3} & 1/\sqrt{3}
\end{bmatrix}
\]

Equality holds only when \( \vec{H} \) is constant – for most biases, it is a piecewise linear function

\[ \dot{\vec{H}}_{RW A} \rightarrow \Delta \vec{H}_{RW A} \neq \vec{H}_{end} - \vec{H}_{start} \]
Thrust Estimation Algorithm

- Each RWA changes at the same constant rate, but the desired Δrpm is different for each wheel – so they reach the final speed at different times (called phases)
- Note that Y-axis spacecraft momentum rate of change switches signs at the end of phase 2
- SOLUTION: disregard phase 3
Thrust Estimation Algorithm

\[ I_{s/c} \Delta \vec{\omega} + \Delta \vec{H}_{RWA} + \int_{t_1}^{t_2} \vec{\omega} \times (I_{s/c} \vec{\omega} + \vec{H}_{RWA}) \, dt = \int_{t_1}^{t_2} \vec{t}_{\text{net}} \, dt \]

Applied external torque:
- Solar pressure
- Gravity
- Atmosphere
- Other negligible sources
- Thrusters

Sum of each thruster’s thrust vector

\[ \vec{t}_{\text{net}} = \sum_{i=0}^{8} \vec{t}_i \]

Cross product moment arm and force vector

\[ \sum_{i=0}^{8} \{\vec{r}_i \times \vec{u}_i \} \int_{t_1}^{t_2} \vec{F}_i \, dt \]
Thrust Estimation Algorithm

\[ \int_{t_1}^{t_2} F_i \, dt = N_i \int_{\text{pulse}} F_i \, dt = N_i F_i \left[ \delta + (t_T - t_R)(1 - e^{-\frac{t_\delta}{t_R}}) \right] = F_i \Delta s_i \]

- Tail-off time updated four times
- Rise time assumed constant throughout the mission
Thrust Estimation Algorithm

\[ I_{s/c} \Delta \vec{\omega} + \Delta \vec{H}_{RW A} + \int_{t_1}^{t_2} \vec{\omega} \times (I_{s/c} \vec{\omega} + \vec{H}_{RW A}) dt = \int_{t_1}^{t_2} \vec{r}_{net} dt \]

\[
\begin{bmatrix}
\Delta H_{total,x} \\
\Delta H_{total,y}
\end{bmatrix} =
\begin{bmatrix}
Q_{xy,(2x4)}
\end{bmatrix}
\]

\[
\begin{bmatrix}
\Delta H_{total,z}
\end{bmatrix} =
\begin{bmatrix}
Q_{z,(1x2)}
\end{bmatrix}
\]

Q contains moment arm and on-time information

Note the size of the Q’s!
More unknowns than equations

Previous solution – solve equation many times during a bias, solve system using pseudoinverse

Current solution – pair two adjacent events to obtain a fully determined system
Thrust Estimation Algorithm

\[
\begin{bmatrix}
(\Delta H_{\text{total},z})|_\alpha \\
(\Delta H_{\text{total},z})|_\beta
\end{bmatrix} =
\begin{bmatrix}
(Q_{z,(1x2)})|_\alpha \\
(Q_{z,(1x2)})|_\beta
\end{bmatrix}
\begin{bmatrix}
F_{Y1/3} \\
F_{Y2/4}
\end{bmatrix}
\]

\[
\begin{bmatrix}
(\Delta H_{\text{total},x})|_\alpha \\
(\Delta H_{\text{total},y})|_\alpha \\
(\Delta H_{\text{total},x})|_\beta \\
(\Delta H_{\text{total},y})|_\beta
\end{bmatrix} =
\begin{bmatrix}
(Q_{xy,(2x4)})|_\alpha \\
(Q_{xy,(2x4)})|_\beta
\end{bmatrix}
\begin{bmatrix}
F_{Z1} \\
F_{Z2} \\
F_{Z3} \\
F_{Z4}
\end{bmatrix}
\]

Spacecraft Telemetry
- S/C body rates (rad/s)
- RWA rates (rpm)
- Individual thruster on-time

"Known" Parameters
- Products of inertia
- Rise, tail-off times

Algorithm

Individual Thrust Magnitude Estimates
Results: Verification

- For any biasing event in which only one of the Y-thruster pairs is used, that equation becomes fully determined.
- Calculate both independently and paired for comparison.
Results: Y-Thrusters

- Thrust is a function of tank pressure, so there is a certain amount of expected degradation
- Hardware degradation would result in a departure from the expected thrust level
- Y-thruster results for A-branch follow the expected trend, but show a constant offset from the predicted thrust
  - Algorithm is sensitive to rise and tail-off time, and a discrepancy between the used and true values would manifest as a constant offset
Results: Z-Thrusters

A-Branch

$Z_1$ Thrust [N]

07-Jan 07-Jul 08-Jan 08-Jul 09-Jan

Time [year-month]

B-Branch

$Z_1$ Thrust [N]

10-Jan 12-Jan 14-Jan

Time [year-month]

$Z_2$ Thrust [N]

07-Jan 07-Jul 08-Jan 08-Jul 09-Jan

Time [year-month]

$Z_2$ Thrust [N]

10-Jan 12-Jan 14-Jan

Time [year-month]

$Z_3$ Thrust [N]

07-Jan 07-Jul 08-Jan 08-Jul 09-Jan

Time [year-month]

$Z_3$ Thrust [N]

10-Jan 12-Jan 14-Jan

Time [year-month]

$Z_4$ Thrust [N]

07-Jan 07-Jul 08-Jan 08-Jul 09-Jan

Time [year-month]

$Z_4$ Thrust [N]

10-Jan 12-Jan 14-Jan

Time [year-month]
Conclusions

• Noise in the thrust estimates results from noise in the telemetry
• Algorithm produces accurate thrust estimates for trending analysis
• Y-thrusters on both A-branch and B-branch are in good health
• A-branch Z3 and Z4 thrusters are significantly degraded
• B-branch Z-thrusters are in good health
  – Z4 has been consistently on the low end of the expected thrust envelope, but has been following the expected trend
• This trending analysis, when coupled with other independent detection methods, should identify performance problems early enough for mitigation strategies to be explored