Reducing Pointing Errors During Cassini Reaction Control System Orbit Trim Maneuvers

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Abstract
The effect of altering a gain parameter in the Cassini reaction control system (RCS) delta-V controller on the maneuver execution errors during orbit trim maneuvers (OTMs) is explored. Cassini consists of two reaction control thruster branches (A & B) each with eight thrusters. Currently, the B-branch is operational while the A-branch serves as a back-up. The four Z-thrusters control the X and Y-axes, while the four Y-thrusters control the Z-axis. During an OTM, the Z-thrusters fire to maintain the X and Y-axes pointing within an attitude control dead-zone (-10 to 10 mrad). The errors do not remain at zero due to pointing error sources such as spacecraft center of mass offset from the geometric center of the Z-facing thrusters, and variability in the thruster forces due to the thruster hardware differences. The delta-V reaction control system (RCS) controller ensures that the attitude error remains within this dead-zone. Gain parameters within the RCS delta-V controller affect the maneuver execution errors. Different parameter values are used to explore effect on these errors. It is found that pointing error decreases and magnitude error increases rapidly for gain parameters 10 times greater than the current parameter values used in the flight software.

Nomenclature
\[ d \] = dead-zone pointing error
\[ f \] = disturbance torque
\[ \varepsilon_{mag} \] = magnitude error
\[ \varepsilon_{pointing} \] = pointing error
\[ \theta \] = pointing error time history
\[ \omega_0 \] = angular velocity
\[ t \] = time
\[ V_a \] = achieved velocity
\[ V_c \] = commanded velocity
\[ X \] = body-fixed frame X-axis
\[ Y \] = body-fixed frame Y-axis
\[ Z \] = body-fixed frame Z-axis

I. Introduction
The Cassini-Huygens mission is a joint National Aeronautics and Space Administration (NASA)/European Space Agency (ESA) effort whose primary purpose is to explore Saturn, its

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rings, and moons. The mission was launched in October 1997 and entered the Saturn orbit in July 2004 by performing two gravity assist-flybys of Venus (1998 and 1999), a flyby of Earth (1999) and Jupiter (2000). Cassini also successfully deployed the Huygens probe onto the surface of Titan in 2005. In order to keep Cassini on the planned trajectory, and enable targeted flybys of Saturn moons, several orbit trim maneuvers (OTMs) are performed on the spacecraft.

There are two types of OTMs, main engine (ME) and reaction control system (RCS) OTMs. The ME OTMs are needed for larger burns where delta-V requirement is above 300 mm/s. In all other cases, OTMs are performed using the RCS thruster system. Cassini has a set of two RCS thruster systems, A-branch and B-branch. Figure 1 depicts the Cassini spacecraft and location of the RCS thruster system.

![Figure 1: Cassini Spacecraft and Reaction Control Thruster System](image)

Each thruster branch consists of eight RCS thrusters. One set of thrusters is the prime, while the other is the back-up. The A-branch and B-branch RCS thrusters are ideally meant to represent the same system. Currently, Cassini uses the B-branch thrusters for RCS control activities. All four Z-axis aligned thrusters fire during the start of an OTM. The X and Y axes attitude control error is maintained within a dead-zone (-10 to 10 mrad) during the OTM burn. This attitude control error is maintained by off-pulsing the Z-thrusters. When either the X or Y dead-zone limit is reached, two of the four Z-thrusters turn off to impart a torque to correct the attitude error.

Maneuver execution error is the difference between the target delta-V vector and the achieved delta-V vector, and is a combination of a magnitude and a pointing (direction) error. Some sources of pointing error include spacecraft center of mass offset from the geometric center of the Z-facing thrusters, and variability in the thruster forces due to the thruster hardware
differences. The net effect of such sources on the pointing error ranges from -10 to 10 milliradians within the dead-zone during the RCS OTMs. This paper discusses how to modify the parameters of the RCS delta-V controller in order to reduce the pointing errors. The effect of changing the parameters on magnitude errors is also studied. Details of the RCS delta-V controller pulse adjuster in the flight software are presented. A software simulation is used to study the sensitivity of modifying the pulse adjuster parameters on the attitude control error.

II. RCS Delta-V Controller Pulse Adjuster

The average pointing error is dependent upon the thruster pulse size. This relationship is determined by idealizing the pulses as instantaneous rate reversals occurring at the pointing error dead-zone.

Figure 2: Pulse Size and Average Pointing Error

In Figure 2, $\theta, \theta_m, d, \omega_o$, and $D$ are the pointing error, peak pointing error, dead-zone pointing error, angular velocity, time and disturbance torque, respectively. The pointing error stays within this dead-zone when the spacecraft is quiescent during the OTM. When the pointing error reaches the dead-zone, the thrusters fire to push the pointing error downwards with an angular velocity of $\omega_o$. The disturbance torques produce an acceleration and cause the pointing error to reverse at time $t^*$. This counts as one thruster pulse, and the objective is to drive the average pointing error to zero. An optimal pulse size can drive the pointing error to zero. In order to attain this optimal pulse size, the RCS delta-V controller pulse adjuster shown in Figure 3 is used.
In Figure 3, the pointing error is low-pass filtered through the pa_filter block. There are two nonlinear functions within the pa_filter block. The first one is where the block does not allow the pointing error input to exceed the dead-zone (saturates at the dead-zone). In this feature, the pulse size is maintained in case the controller is responding to harsh transient effects. The second one in the pa_filter block zeros out the pointing error in case the rate is below a certain threshold. Here, the pulse adjuster is prevented from charging up due to negligible disturbance situations. The reset summer and torque polarity functions are used in case the imparted torque direction needs to be changed such that the pointing error remains within the dead-zone. This is required when the pointing error reaches the opposite side of the dead-zone (it was on the positive side before and then became negative). The pulse adjuster is triggered due to self-induced axes disturbances that arise from center-of-mass offsets, thruster misalignments and thruster-to-thruster performance variations. As stated earlier, the average pointing error can be driven to zero by choosing an optimal pulse size. The pulse size obtained from the reset summer is scaled by the pulse gain to obtain this optimal pulse size. The current pulse gain parameter values for the X, Y and Z spacecraft body-fixed axes are fixed at 0.5, 0.5 and 1, respectively. As the spacecraft parameters change such as mass properties, the ideal pulse gain to produce a zero average pointing error also alter. In this paper, a spacecraft simulation uses different pulse gain values to explore how the average pointing error is affected. This pointing error is related with the maneuver execution errors.

### III. Maneuver Execution Errors

During an OTM, the maneuver execution is measured in terms of the command delta-V, \( V_c \) and achieved delta-V, \( V_a \). There are two ways to quantify maneuver execution error: magnitude and pointing error. An illustration of both errors is shown next.
The $V_a$ is projected onto $V_c$, and the difference between this projection and $V_c$ constitutes the magnitude error, $\vec{e}_{mag}$:

$$\vec{e}_{mag} = \vec{V}_c - \{ \vec{V}_a \cdot \vec{V}_c \} \vec{V}_c$$  \hspace{1cm} (1)$$

For the pointing error, $\vec{e}_{pointing}$ is calculated by projecting $V_a$ onto $V_c$, and then taking the difference between this projection and $V_a$.

$$\vec{e}_{pointing} = \vec{V}_a - \{ \vec{V}_a \cdot \vec{V}_c \} \vec{V}_c$$  \hspace{1cm} (2)$$

The performance of the RCS delta-V controller during an OTM is evaluated using these two quantities. The plot shown next depicts the pointing and magnitude errors from several OTMs.
Figure 5: Pointing and Magnitude Error from RCS OTMs

From Figure 5, the general trend is that as the burn time for the OTM increases the errors also increase. This makes sense because a longer burn would contain larger sources of errors.

IV. Results

In order to explore the effect of the pulse adjuster gain on the maneuver execution errors, an OTM with decently large burn time is selected (~180 sec.). The OTM commands are processed in a spacecraft simulation called flight software development system (FSDS). This is a high fidelity Cassini spacecraft dynamics simulation. The pulse gain parameters are altered in this simulation and maneuver execution errors from the OTM are analyzed.
The gain parameters are altered from 1/50 to 50 times the current gain parameter values [0.5, 0.5, 1], and the maneuver execution error is evaluated. The pointing error decreases with increasing gain parameter value, while the magnitude error increases. From the log scale plot, it can be inferred that gain parameter values [5 5 10] (10 times current gain parameter values) marks a significant rise in the magnitude error and decrease in the pointing error. Next, a comparison of the pointing errors during current, current times 10, current times 50 and current times 1/50 parameter values is shown.
In Figure 7, the pointing control error during an OTM is shown. The RCS delta-V controller maintains the attitude within 10 mrad. The average pointing control error gets closer to zero as the gain parameter is increased.

V. Conclusion

In this paper, the reaction control system (RCS) delta-V controller gain parameters are varied and the effect on maneuver execution errors is investigated. The parameters are part of the flight software development system (FSDS) that is used to model spacecraft command activities during the orbit trim maneuver (OTM). In an OTM, the RCS delta-V controller maintains the errors within a dead-zone (-10 to 10 mrad). The errors emerge from sources such as center of mass offsets, thruster hardware variations. The correct gain parameters help reduce these errors. This type of study helps understand how the gain parameters can be modified to reduce the errors. The pointing error decreases and magnitude error increases as the gain parameters are increased from the current values.

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