Short Abstract of paper to be presented as in the AAS Astrodynamics Specialist Conference,
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Analysis of Thrust Vectoring Capabilities for the Jupiter Icy Moons Orbiter[1]

Marco B. Quadrelli[2], Konstantin Gromov[3], Emmanuell Murray[4]

A strategy to mitigate the impact of the trajectory design of the Jupiter Icy Moons Orbiter (JIMO) on the attitude control design is described in this paper. This paper shows how the thrust vectoring control torques, i.e. the torques required to steer the vehicle, depend on various parameters (thrust magnitude, thrust pod articulation angles, and thrust moment arms). Rather than using the entire reaction control system (RCS) system to steer the spacecraft, we investigate the potential utilization of only thrust vectoring of the main ion engines for the required attitude control to follow the representative trajectory. This study has identified some segments of the representative trajectory where the required control torque may exceed the designed ion engine capability, and how the proposed mitigation strategy succeeds in reducing the attitude control torques to within the existing capability.

[1] This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautic and Space Administration.

[2] Senior Engineer, Mail Stop 198-326, Guidance and Control Analysis Group, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109-8099, U.S.A.

[3] Staff Engineer, Mail Stop 198-326, Guidance and Control Analysis Group, JPL
[4] Staff Engineer, Mail Stop 198-326, Guidance and Control Analysis Group, JPL

Extended Abstract of paper to be presented as in the AAS Astrodynamics Specialist Conference, Lake Tahoe, NV, August 2005

Analysis of Thrust Vectoring Capabilities for the Jupiter Icy Moons Orbiter[5]

Marco B. Quadrelli[6], Konstantin Gromov[7], Emmanuell Murray[8]

NASA is developing plans for an ambitious mission to orbit three planet sized moons of Jupiter - Callisto, Ganymede and Europa - which may harbor vast liquid oceans beneath their icy surfaces, the Jupiter Icy Moons Orbiter (JIMO). The objective of the JIMO mission study is to design a spacecraft to explore the three icy moons and investigate their makeup, their history and their potential for sustaining life. To do so, NASA is looking at how a nuclear reactor could enable long-duration deep space exploration. A nuclear fission reactor could produce unprecedented amounts of electrical energy to significantly improve scientific measurements, mission design options, and telecommunications capabilities. The JIMO mission will incorporate a form of electric propulsion called ion propulsion, which will be powered using a nuclear fission reactor and a system for converting the reactor's heat to electricity. The two ion engines banks are articulated and provide the means for thrust vector control (TVC). At JPL, the lead center for the JIMO government studies, we have been investigating ways to change the attitude of the spacecraft by changing the direction of the thrust vector, which in turn is required by the trajectory design to follow the mission profile.

The preliminary performance assessment of the thrust vector control capability currently proposed for the JIMO Attitude and Articulation System reveals a significant conceptual problem in that the thrust vectoring capability needed for trajectory guidance is intimately coupled with the torque vectoring capability needed for attitude control. This problem arises because the electric thrusters for attitude control are placed on the same articulated pods where the propulsion ion engines are also located. Therefore, any maneuver intended to implement an attitude correction will significantly affect the trajectory, and viceversa, on account of the attitude-translation coupling. For the JIMO mission, attitude and orbital dynamics interactions are intimately coupled due to the low-thrust trajectory design, and the implementation of this

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[6] Senior Engineer, Mail Stop 198-326, Guidance and Control Analysis Group, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109-8099, U.S.A.

[7] Staff Engineer, Mail Stop 198-326, Guidance and Control Analysis Group, JPL

[8] Staff Engineer, Mail Stop 198-326, Guidance and Control Analysis Group, JPL

interaction through the articulated electric propulsion engines poses a significant challenge to the dynamics and controls analyst.

A strategy to mitigate the impact of the trajectory design of the Jupiter Icy Moons Orbiter (JIMO) on the attitude control design is described in this paper. This paper shows how the thrust vectoring control torques, i.e. the torques required to steer the vehicle, depend on various parameters (thrust magnitude, thrust pod articulation angles, and thrust moment arms). We investigate the potential utilization of only thrust vectoring of the main ion engines for the required attitude control to follow the representative trajectory, rather than using the entire reaction control system (RCS) system. This study has identified some segments of the representative trajectory where the required control torque may exceed the designed ion engine capability. We also discuss the derivation of the required attitude control torques for a JIMO representative trajectory. Emphasis is given to the assumptions to derive these control torques, because the mission profile contains only trajectory (point mass) information which by itself is insufficient to define the attitude of the spacecraft. By means of introducing variable time segments in approaching and departing from adjacent thrust levels, which reflect realistic time lags associated with realistic ion engine performance, we can significantly reduce the torques that the ion engine gimbals need to apply to track the prescribed trajectory.

Assuming that the orbiting frame and the vehicle's body frame are the same, thrust vectoring forces and torques are computed in the body frame of the spacecraft. Figure 1 shows the resultant roll, pitch and yaw torques in the body frame and Figure 2 shows the resultant induced forces acting on the JIMO spacecraft along the body frame axes when the ion pods are gimbaled in the elevation degree of freedom β.

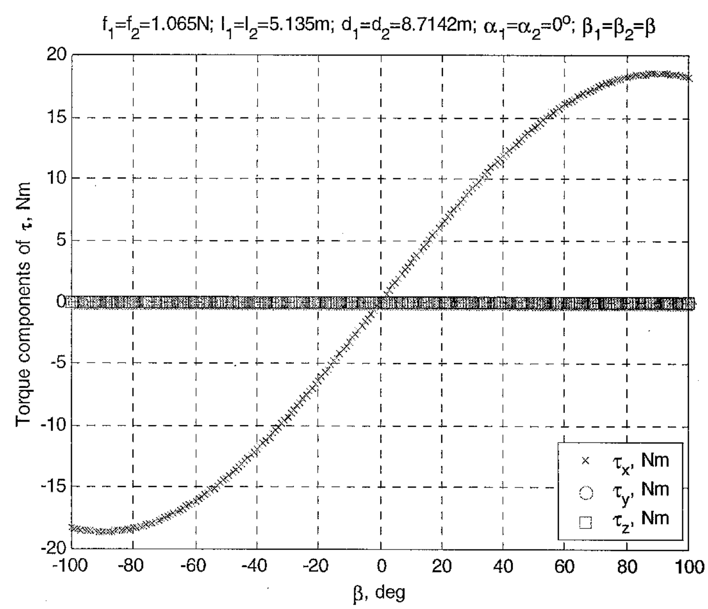

Figure 1. Pitch Control Example Torques

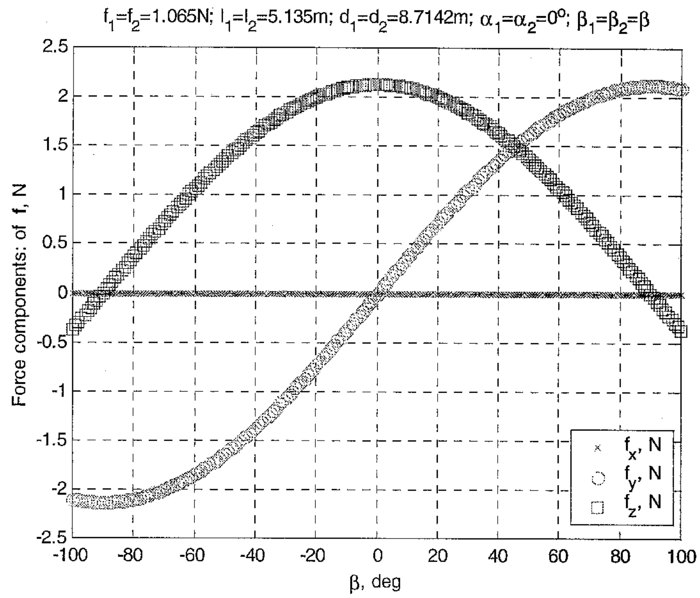

Figure 2: Pitch Control Example Forces

Table 1 shows that although it is possible to generate a pure pitch torque (τ_x) that is uncoupled from other torques, it would still be coupled with a thrust force along the $\mathbf{O}_z$ and $\mathbf{O}_y$ directions, resulting in spurious lateral accelerations of the vehicle which ultimately affect the trajectory.

Table 1: Pitch Control Forces and Torques

β, deg	τx, Nm	τy, Nm	τz, Nm	Fx, N	Fy, N	Fz, N	Fx/Fmax	Fy/Fmax	Fz/Fmax
-40	-11.9309	0	0	0	-1.3691	1.6317	0	-0.6428	0.766
-20	-6.3483	0	0	0	-0.7285	2.0015	0	-0.342	0.9397
-10	-3.2231	0	0	0	-0.3699	2.0976	0	-0.1736	0.9848
-5	-1.6177	0	0	0	-0.1856	2.1219	0	-0.0872	0.9962
-2	-0.6478	0	0	0	-0.0743	2.1287	0	-0.0349	0.9994
-1	-0.3239	0	0	0	-0.0372	2.1297	0	-0.0175	0.9998
0	0	0	0	0	0	2.13	0	0	1
1	0.3239	0	0	0	0.0372	2.1297	0	0.0175	0.9998
2	0.6478	0	0	0	0.0743	2.1287	0	0.0349	0.9994
5	1.6177	0	0	0	0.1856	2.1219	0	0.0872	0.9962
10	3.2231	0	0	0	0.3699	2.0976	0	0.1736	0.9848
20	6.3483	0	0	0	0.7285	2.0015	0	0.342	0.9397
40	11.9309	0	0	0	1.3691	1.6317	0	0.6428	0.766

The JIMO mission design team in collaboration with trajectory analysis and design team produced a representative spacecraft trajectory in order to better understand the complexities of the mission. The JIMO AACS team was provided with this trajectory for the purpose of deriving JIMO attitude control requirements. The design of the representative trajectory assumes that the spacecraft is a point mass with a thrust vector applied to it. The task for the AACS team was to interpret this data, make assumptions on the attitude of the spacecraft, and then derive the required control torques to follow this trajectory.

Once the entire trajectory had been designed, the trajectory geometry and thrust profile as a function of time was made available for data analysis and reduction. This trajectory was broken up into separate mission phases that represented different maneuvers JIMO had to perform (i.e. coasts between planets, spirals, and plane changes). Also, the trajectory geometry data was available with a finer time resolution than the thrust profile data.

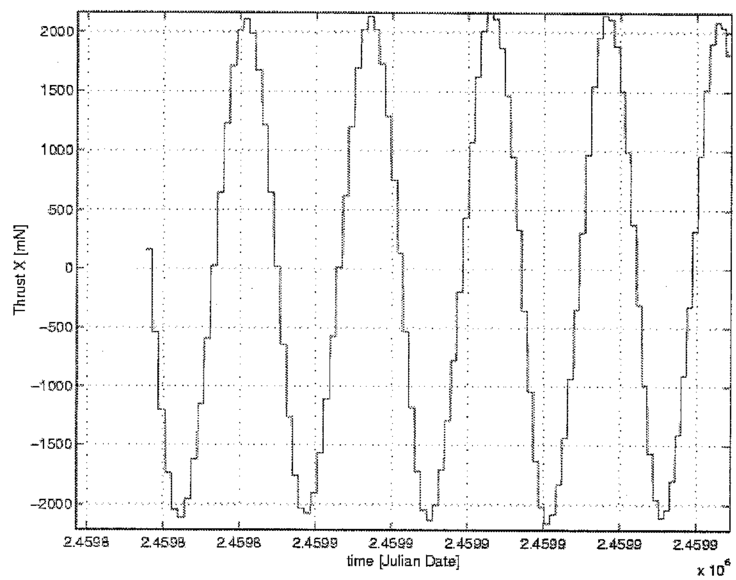

Figure 3: Representation of thrust profile as given by trajectory design

Figure 3 is a graphical representation of the thrust profile along the inertial X direction. The actual thrust is a three-dimensional vector, but to simplify the graphical representation it is convenient to represent the thrust as a scalar value vs. time. What Figure 3 points out is that the thrust profile is discontinuous in time. This time discontinuity is at the origin of the large torques that the vehicle would experience if numerical differentiation of the trajectory data was applied by a brute force approach. Rather, a new technique was developed to reduce the impact of the jumps in thrust, hence in resulting torque, at the beginning and end of the thrust intervals, by advancing and retarding the instants of thrust application. The practical aspect of this approach is that the time delays to produce the thrust can be directly linked to realistic ion engine performance delays. The changes to the thrust profile to accommodate the changes in the thrust vector caused by these time delays is shown in Figure 4.

Using this approach, we succeeded in reducing the torque levels that the vehicle would need to apply to a much more manageable level. Figure 5 depicts roll and yaw torque profiles resulting from this approach, where the discontinuities are more benign. The implication for design of the gimbal articulations is that the gimbals are now required to produce a smoother and lower level of torque to steer the vehicle.

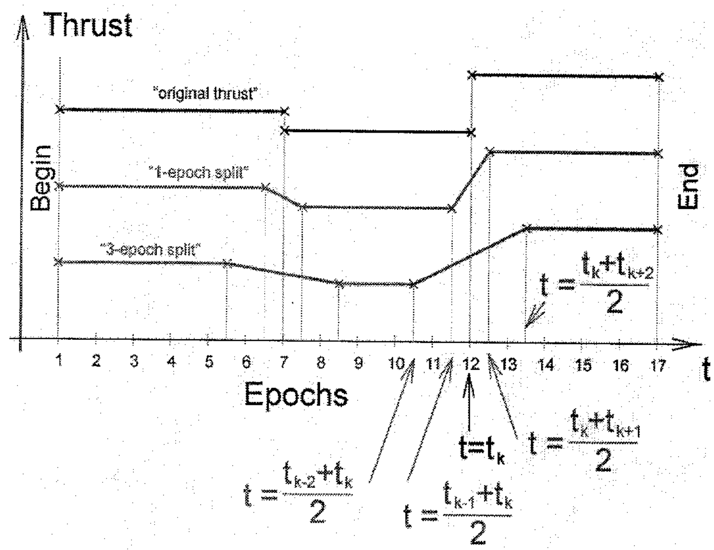

Figure 4: Changes to thrust profile to accommodate change of thrust vector

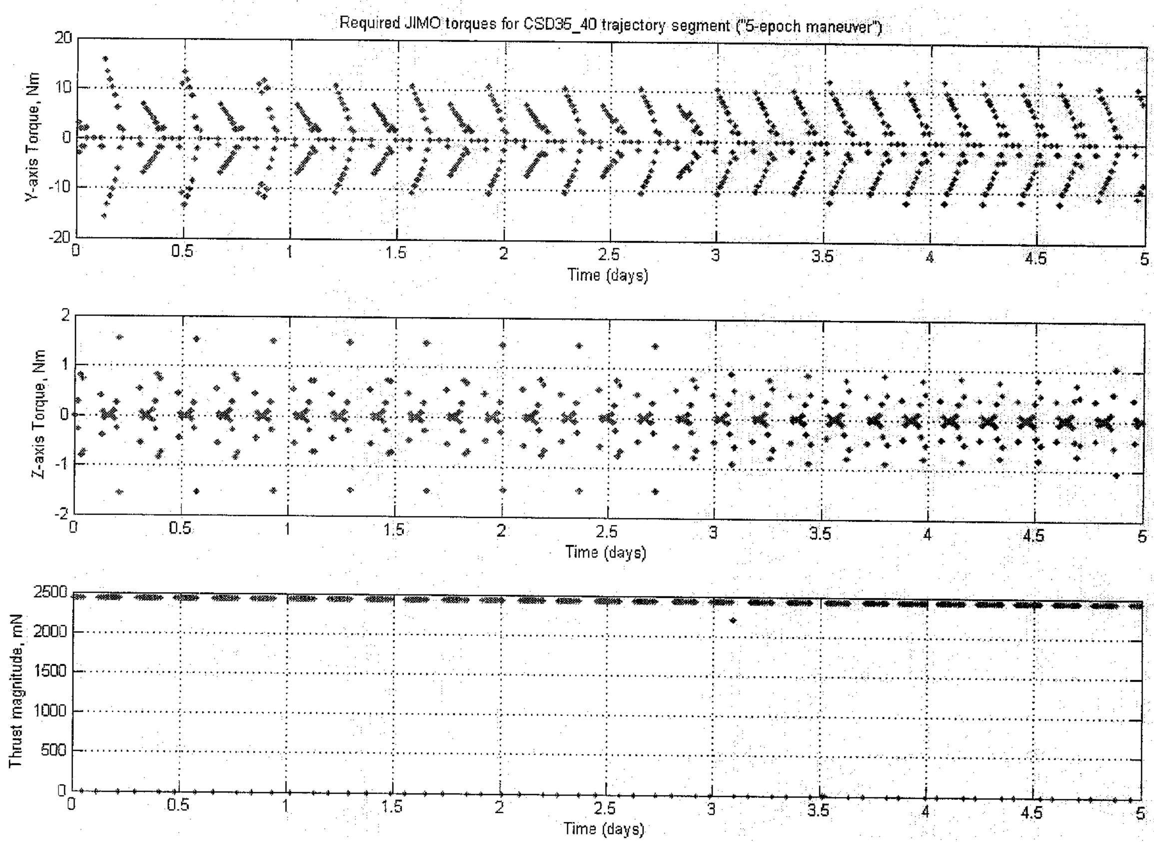

Figure 5: Y- and Z-axis torques and thrust magnitudes for 5-epoch ramp