AN ANALYTICAL SOLUTION FOR YAW MANEUVER OPTIMIZATION ON THE INTERNATIONAL SPACE STATION AND OTHER ORBITING SPACE VEHICLES

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The goal of maneuver optimization

To find a maneuver trajectory with minimal torques acting on the vehicle during the maneuver.

- Minimal thruster firings necessary to perform the maneuver.
  - Saves propellant
  - Decreases structural loads
  - Decreases contamination of the vehicle critical elements
  - Saves the service life of the thrusters and the vehicle itself

Large maneuvers could be performed either using Control Moment Gyroscopes (CMG), or with significantly reduced thruster firings.

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International Space Station (ISS) operations

ISS rotations about its center of mass are the standard operations of the space station.

- Visiting vehicle docking and undocking events
- Orbit correction and debris avoidance maneuvers
- Extravehicular Activities (EVA)
- Various experiments

For the ISS, yaw maneuvers are used most often.

Background

- First 180 degree yaw “Zero Propellant Maneuver” (ZPM) of the ISS was created by Draper Laboratory (USA) and performed in 2006.
- Each ZPM was unique, and can only be calculated on the ground since significant computer resources are needed for calculations.
- Complicated operation (~ 100-200 commands have to be sent onboard).
- Similar to ZPMs are Optimal Propellant Maneuvers (OPM). First OPM executed in 2012.
- Maneuver duration for OPMs is less than for ZPMs, but OPMs cannot be performed without thruster firings. Propellant consumption for OPMs is low.

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Simplified maneuver optimization solution

- The goal - to find a simplified maneuver optimization solution which, in contrast to the Draper Laboratory method, does not require a lot of computer resources.
- An approximate analytical solution was obtained. The results match the existing computational results.
- The analytical solution can be implemented using onboard software.
- The maneuver execution can be automatic, thus simplifying operations - one of the major benefits of the proposed solution.
- The maneuver can be performed with no communication with the ground.

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Model

- ISS is a rigid body
- The aerodynamic torques are not taken into account.

ISS equation of rotation

- The ISS equation of rotation around its center of mass are described in yaw, pitch, and roll Euler angle sequence.
- For the pure yaw maneuver the roll and pitch angles are zero.
- For yaw maneuver optimization we will look for the cases when the roll and pitch angles are small.

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Formulating the problem

- The task is to perform the 180 degree yaw rotation minimizing the magnitudes of control torques.

- Assuming the initial conditions: $\alpha = 0,\ \beta = 0,\ \gamma = 0,\ \ \dot{\alpha} = 0,\ \dot{\beta} = 0,\ \dot{\gamma} = 0.$
  The required final conditions: $\alpha = 180,\ \beta = 0,\ \gamma = 0,\ \ \dot{\alpha} = 0,\ \dot{\beta} = 0,\ \dot{\gamma} = 0.$

  Where $\alpha - \text{yaw angle},\ \beta - \text{pitch angle},\ \gamma - \text{roll angle}.$

- The goal is to find $\alpha(t),\ \beta(t),$ and $\gamma(t)$ which will bring the ISS from the initial to the final position with the minimized control torques (minimized thruster firings or minimized increase of CMG momentum).

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Yaw rate profile selection

- For a yaw maneuver on CMGs the yaw rate and acceleration should be low enough so that the yaw torque is as low as the CMGs are able to control.
- For a maneuver on CMGs, the optimal yaw rate profile should also help to avoid high accelerations spikes since the CMGs cannot handle high torques.
- To satisfy the requirements, a bell profile, which is close to a triangle, was selected.
- The maximum acceleration is the smallest for such a profile. The profile should also provide zero rate and acceleration at the start and the end of the maneuver.

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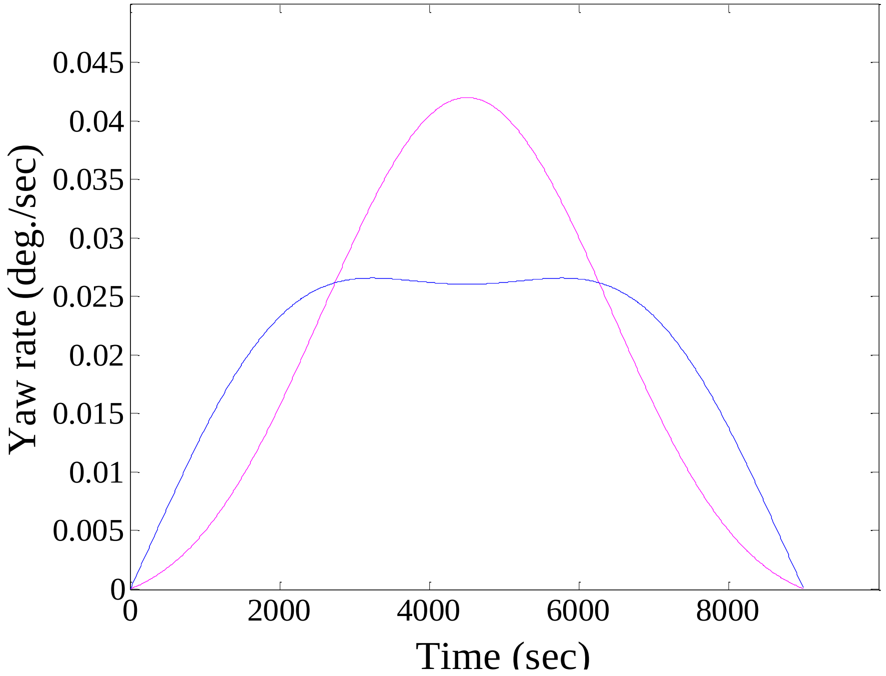
Yaw rate profiles



Yaw rate profiles

$$\dot{\alpha}\,(t) = K(1-\tau)^2\tau^2\ , \qquad \text{where}\ \tau = \frac{t}{T}$$

Coefficient K depends on the duration of the maneuver and the maneuver angle-to-go.

T – maneuver duration

Legend:

Red – yaw rate profile described by above equation

Blue – yaw rate profile modification example.

Yaw maneuver torques

- Consider 180 degree pure yaw maneuver, where roll and pitch angles remain zero. This maneuver is performed using thrusters.

- For such a maneuver the torques in roll (T_x) and pitch (T_y) can be written as:

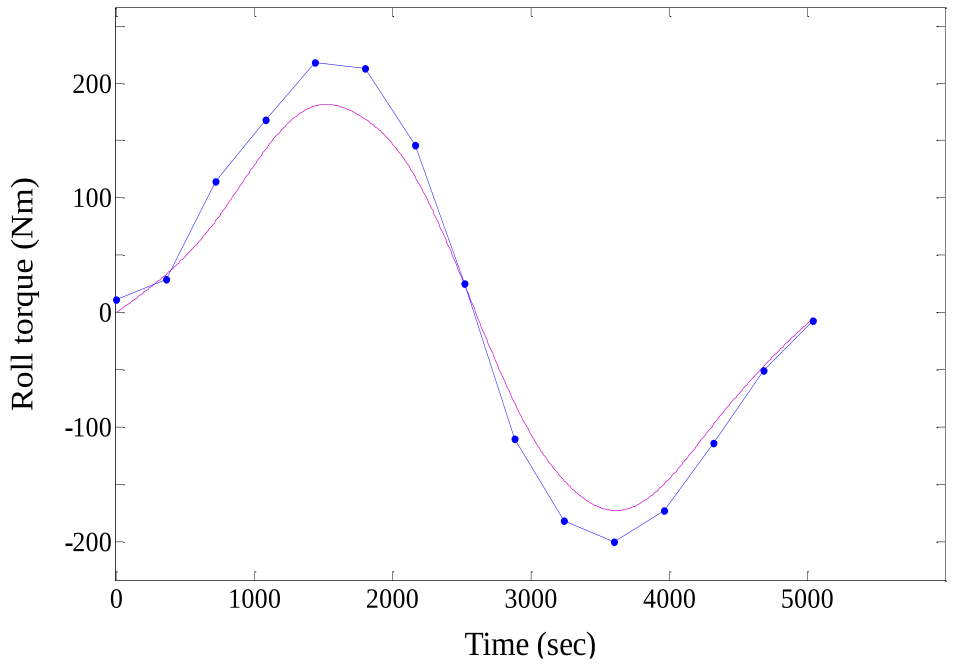
$$T_x = -(C - B + A)n\dot{\alpha}cos\alpha$$
$$T_y = (C + B - A)n\dot{\alpha}sin\alpha$$

where: A, B, C - are the ISS principal moments of inertia, n - orbital rate.

- For the ISS mass properties and common maneuver durations (about 5400 sec.) these torques are large with respect to the CMG capabilities.

Yaw maneuver torques

Comparing flight roll torque telemetry (blue line) and calculated roll torque (red line)



Roll torque during a 180 deg. pure yaw maneuver.

- Torque is rather large - much more than the ISS CMGs can handle without desaturation.
- Goal of a maneuver optimization is to reduce these torques.
- Gravity torques can be used to solve the problem by compensating for these torques.
- This compensation is the essence of the suggested method.

Maneuver optimization limitations

- The proposed maneuver optimization is not possible for all ranges of mass properties of any given space vehicle.

- The gravity torques have to be big enough to compensate for the pure yaw maneuver torques. The gravity torques in case of a small angle approximation:

$$T_{gravity_x} = 3n^2\,(C - B)\gamma, \qquad T_{gravity_y} = 3n^2(C - A)\beta, \qquad T_{gravity_z} = 0$$

  In the extreme case when $C = A$, or $C = B$ the proposed optimization is impossible.

- The optimization is more effective with larger gravity gradients in pitch and roll, and lower maneuver rate.

- Simple computations can determine if the suggested maneuver optimization method is applicable for each specific vehicle. It is applicable for the ISS.

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First approximation solution

- In case of large gravity gradients in pitch and roll, and small pitch and roll angles, rates, and accelerations, the following simplified solution can be suggested as a first approximation for roll and pitch profiles:

$$\gamma_0 = \lambda\dot{\alpha}\, cos\alpha$$
$$\beta_0 = \mu\dot{\alpha}\, sin\alpha$$

Where $\lambda = -\frac{(C-B+A)}{4n(C-B)}$, $\mu = \frac{(C-A+B)}{4n(C-A)}$

- For the possible range of the ISS mass properties and for the commonly used range of the ISS maneuver rates, this solution significantly reduces the roll and pitch torques.

Second approximation solution

$\gamma = \lambda\dot{\alpha}\, cos\alpha\; + \lambda_1\ddot{\alpha}\dot{\alpha}\, sin\alpha + \lambda_2\, \ddot{\alpha}\, cos\alpha$

$\beta\; = \mu\dot{\alpha}\, sin\alpha + \mu_1\ddot{\alpha}\dot{\alpha}\, cos\alpha + \mu_2\, \ddot{\alpha}\, sin\alpha,$ where

$$\lambda = \; -\frac{(C-B+A)}{4n(C-B)}\;,\;\; \mu = \; \frac{(C-A+B)}{4n(C-A)}$$

$$\lambda_1 = \; \frac{-3A\,\lambda - A\mu + (\,C-B-A)\mu}{4n^2\,(C-B)},\;\; \mu_1 = \; \frac{-3A\,\lambda - A\mu + (\,C-B-A)\mu}{4n^2\,(C-A)}$$

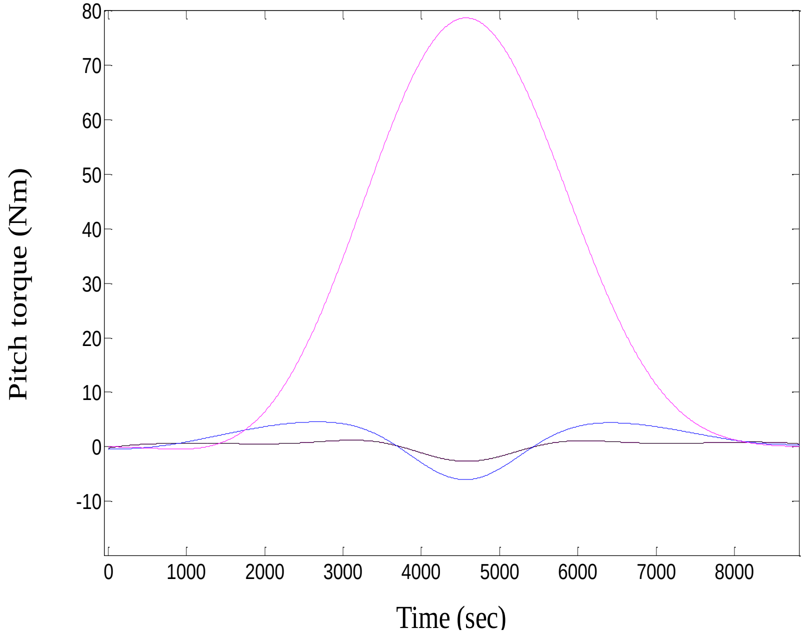
$\lambda_2 = \;\varepsilon_1\, \frac{A\,\lambda}{4n^2\,(C-B)},\;\; \mu_2 = \;\varepsilon_2\, \frac{B\,\mu}{4n^2\,(C-A)}$ ($\varepsilon_1\; = 0.1$, $\varepsilon_2\; = 0.6$ for ISS) .

- Calculations necessary to obtain the ε_1 and ε_2 values are not complicated .

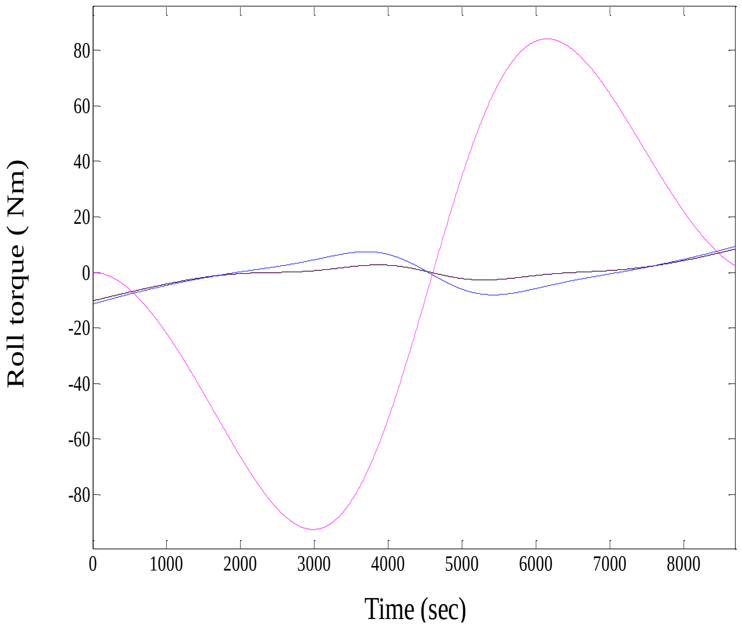
- This solution can be used for the whole possible range of the ISS mass properties.

Torque reduction for 9000 sec. 180 deg. maneuver

Legend: Red line – non-optimized pure yaw maneuver
Blue line – first approximation solution
Black line – second approximation solution



Pitch torque reduction for optimized 9000 sec. yaw maneuver.



Roll torque reduction for optimized 9000 sec. yaw maneuver.

- Either solution can be used to reduce the torques to the level that CMGs can handle.
- These maneuvers may be performed without thruster firings (ZPMs).

Optimized ISS yaw maneuvers with thruster support

- ISS 180 degree yaw maneuvers with a duration of about 5400 sec. or less cannot be performed without thruster support.
- Even if these maneuvers are optimized, torques cannot be reduced to the level at which CMGs can control them.
- However, the propellant required for the optimized maneuver (OPM) is significantly reduced.
- For faster maneuvers the effect of using different approximations is more significant.

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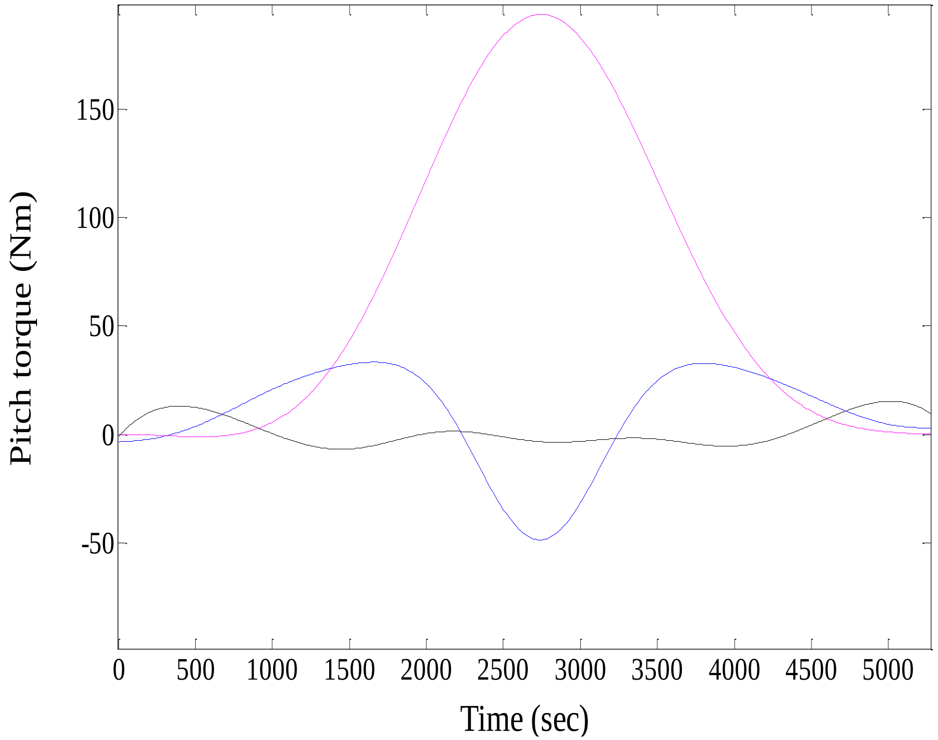
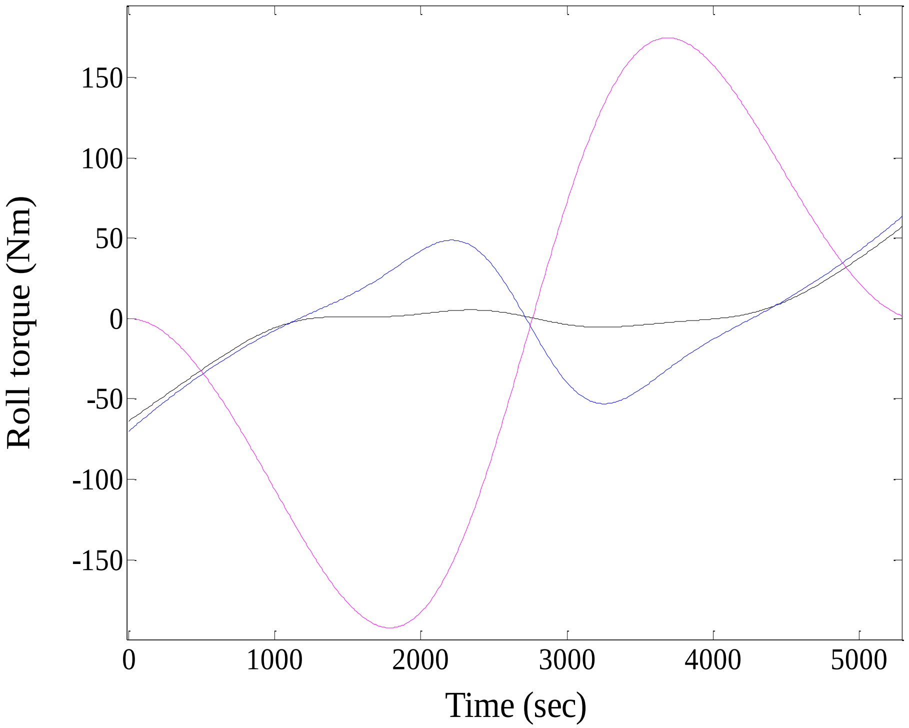
Torque reduction for 5400 sec. 180 deg. yaw maneuver

Legend: Red line –non optimized pure yaw maneuver
Blue line – first approximation solution
Black line – second approximation solution.



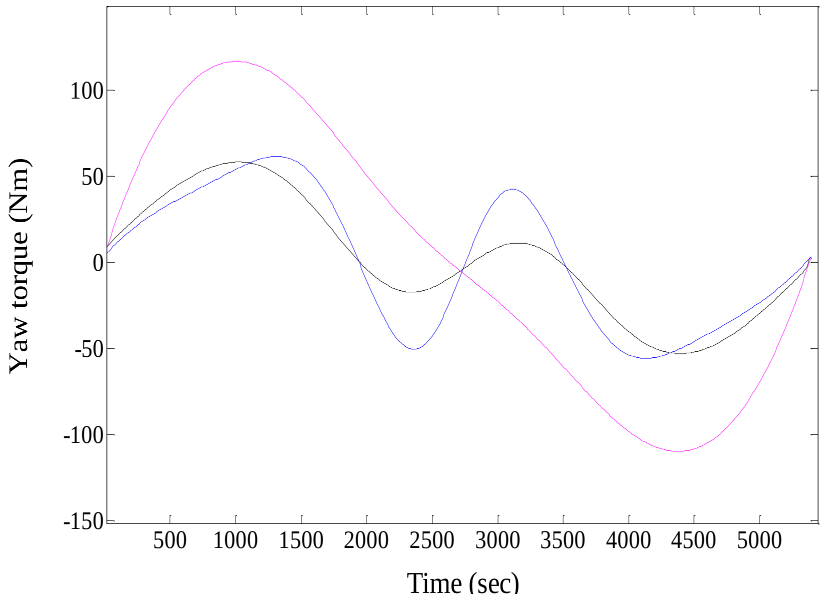
Pitch torque reduction for optimized 5400 second yaw maneuver.



Roll torque reduction for optimized 5400 second yaw maneuver.

Torque reduction for 5400 sec. 180 deg. yaw maneuver

Legend: Red line –non optimized pure yaw maneuver
Blue line – first approximation solution
Black line – second approximation solution.



Yaw torque reduction for optimized 5400 second yaw maneuver.

- Second approximation solution significantly reduces all the torques, and is noticeably better than the first approximation for the 5400 sec. maneuver.
- Simulations showed that the proposed solution provides the maneuver performance similar to the existing computational solution.

Comparison of maneuver optimization solutions

- Calculations using the suggested method were done for a number of yaw maneuvers at different time periods starting from year 2006 to 2014.
- The results were compared to the existing cases of Draper Laboratory calculations.
- The roll and pitch profiles and the torque reductions related to these profiles were compared.

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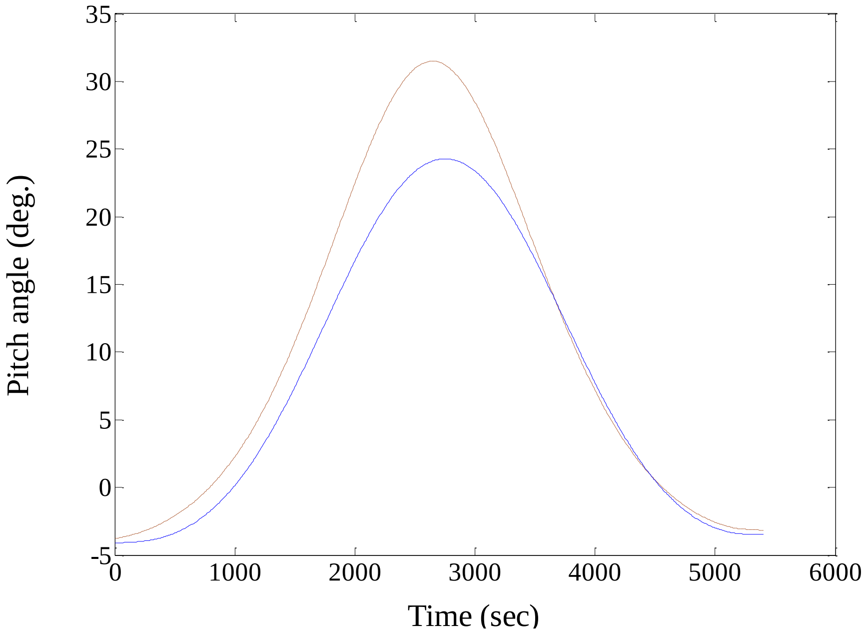
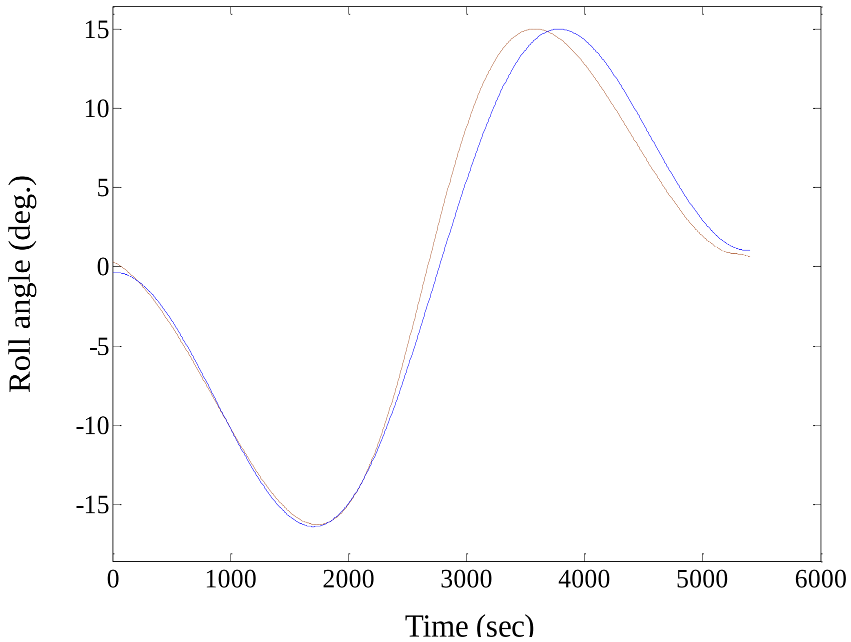
Pitch and roll profile comparison

Maneuver duration 5400 seconds.

Legend:
Blue line – analytical solution
Brown line – Draper Laboratory computational solution



Pitch profile for optimized yaw maneuver.

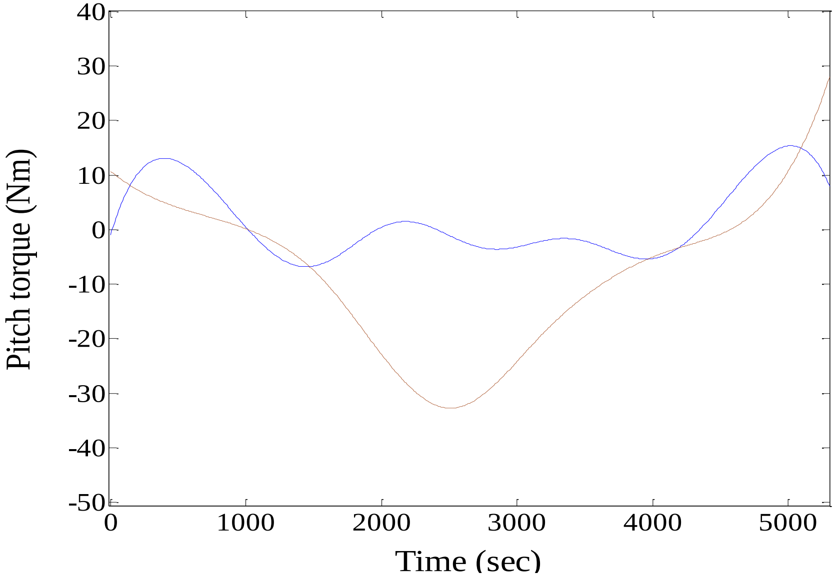


Roll profile for optimized yaw maneuver.

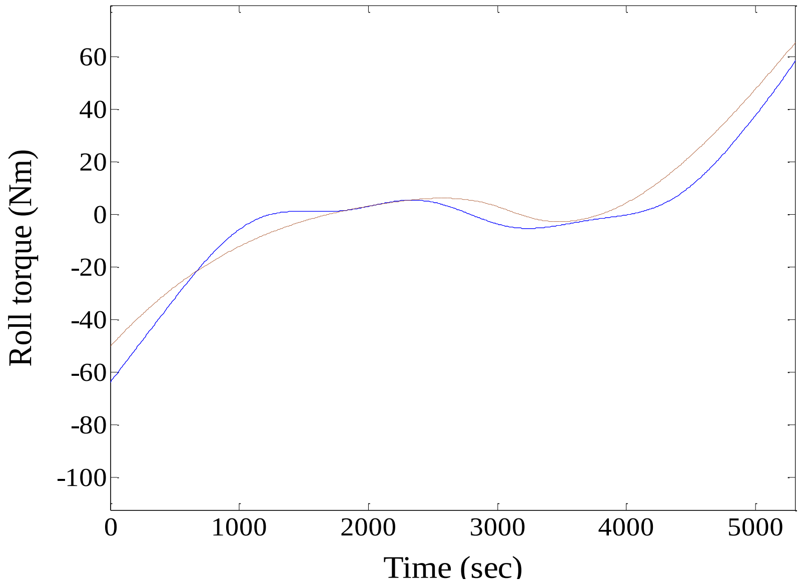
Torque reduction comparison

Legend:
Blue line – analytical solution
Brown line – Draper Laboratory computational solution

Maneuver duration = 5400 seconds.



Pitch torque comparison for the 5400 sec. yaw maneuver.

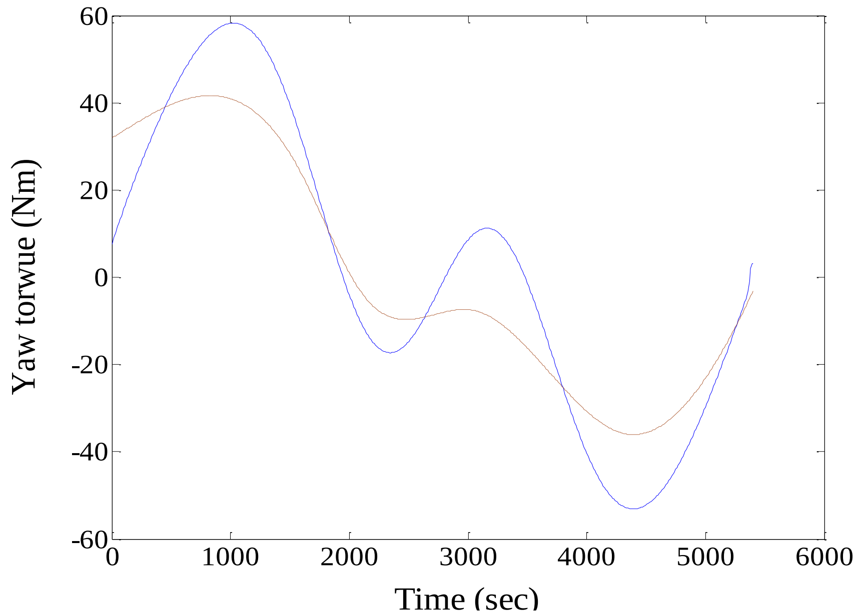


Roll torque comparison for the 5400 sec. yaw maneuver.

Torque reduction comparison

Legend:
Blue line – analytical solution
Brown line – Draper Laboratory computational solution

Maneuver duration = 5400 seconds



Yaw torque comparison for the 5400 sec. yaw maneuver.

- Simulations using the ISS flight software were performed to confirm the validity and accuracy of the proposed analytical solution.
- The simulation results showed similar propellant consumption for both analytical and computational methods.

Conclusions

- An analytical solution for optimizing the ISS yaw attitude maneuvers was suggested.

- While approximate, the suggested solution provides optimization results that agree with the existing computational solution obtained by Draper Laboratory.

- The suggested analytical solution provides a new method for space vehicle maneuver optimization, which is automatic and less complicated.

- The suggested maneuver optimization method can be used not only for the ISS, but for other space vehicles as well.

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