Solar Sail Attitude Control System for the NASA Near Earth Asteroid Scout Mission

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An Attitude Control System (ACS) has been developed for the NASA Near Earth Asteroid (NEA) Scout mission. The NEA Scout spacecraft is a 6U cubesat with an eighty-six square meter solar sail for primary propulsion that will launch as a secondary payload on the Space Launch System (SLS) Exploration Mission 1 (EM-1) and rendezvous with a target asteroid after a two year journey, and will conduct science imagery. The spacecraft ACS consists of three major actuating subsystems: a Reaction Wheel (RW) control system, a Reaction Control System (RCS), and an Active Mass Translator (AMT) system. The reaction wheels allow fine pointing and higher rates with low mass actuators to meet the science, communication, and trajectory guidance requirements. The Momentum Management System (MMS) keeps the speed of the wheels within their operating margins using a combination of solar torque and the RCS. The AMT is used to adjust the sign and magnitude of the solar torque to manage pitch and yaw momentum. The RCS is used for initial de-tumble, performing a Trajectory Correction Maneuver (TCM), and performing momentum management about the roll axis. The NEA Scout ACS is able to meet all mission requirements including attitude hold, slews, pointing for optical navigation and pointing for science with margin and including flexible body effects. Here we discuss the challenges and solutions of meeting NEA Scout mission requirements for the ACS design, and present a novel implementation of managing the spacecraft Center of Mass (CM) to trim the solar sail disturbance torque. The ACS we have developed has an applicability to a range of potential missions and does so in a much smaller volume than is traditional for deep space missions beyond Earth.

Key Words: Solar Sail, Attitude Control, Momentum Management

Nomenclature

ACS	:	Attitude Control System
SLS	:	Space Launch System

1. Introduction

A solar sail presents a unique challenge for deep space missions due to the relatively high solar disturbance torque and flexible body effects [ref]. The ACS designed for NEA Scout allows for a wide range of spacecraft attitude control capabilities, needed for the different phases of the NEA Scout mission. Early in the mission, and prior to solar sail deployment, primary control is performed by the RCS. The RCS provides the high torques needed for de-tumble shortly after deployment from the launch vehicle, and for attitude hold during the TCM, which is required to clean up navigational dispersions from the SLS-provided trajectory, which is performed using two axial thrusters. These thrusters are part of the RCS system, which use cold-gas propellant. The RW control system is the primary ACS for pitch, yaw, and roll control after the solar sail is deployed. Once the desired attitude is achieved using RW control, the AMT will autonomously move part of the spacecraft's mass, shifting the center of mass, to trim pitch and yaw solar sail torques.

For momentum management control, the AMT will be used to actively manage RW momentum buildup in the pitch and yaw axes by periodically shifting the CM of the spacecraft. RW momentum buildup due to the solar sail roll torque (along the sail normal axis) is managed separately using RCS pulsing. The roll axis momentum desaturation can be successfully managed with propellant because it is two to three orders of magnitude smaller than the pitch and yaw torque. Roll torque is on the order of nano-Nm while untrimmed pitch and yaw torques are on the order of micro-Nm. Throughout the duration of the mission, the RCS will serve as a secondary ACS that can be employed for attitude recovery maneuvers resulting from various off-nominal conditions, including a loss of RW control.

NEA Scout also has sensors for attitude determination, including three coarse sun sensors, a star tracker, and an IMU. The sun sensors are critical during recovery from the tumbling induced by deployment and the sun-pointing maneuver that immediately follows de-tumbling because the star tracker

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cannot sun-point due to a lack of accurate time reference onboard the spacecraft early in the mission. After these early critical operations, sun sensors are only used for backup and possibly for safing if the event causing safing is a sensor failure. The star tracker provides accurate attitude data at lower body rates, and is the primary sensor for both for the majority of the mission (after the sail is deployed, due to the higher inertia and mission requirements, rates are never nominally supposed to exceed 0.1 deg/sec). The IMU provides critical body rate measurements during the de-tumble event and sun-pointing slew and is weighted more heavily prior to sail deploy, when the inertia of the spacecraft is low and relatively high maneuver rates are possible. After sail deploy, the inertia increases and the IMU serves as a secondary source of rate data since it is relatively noisy compared to the star tracker at lower body rates.

2. Background

NEA Scout's primary science objective is to survey at least one Near Earth Asteroid within 2.5 years of launch and return high-fidelity images of the asteroid to Earth [ref]. Currently the asteroid that NEA Scout plans to image is VG 1991, although this may change due to launch delays or other changes to the primary SLS EM-1 mission.

During the approach to the asteroid, NEA Scout must perform a series of optical navigation measurements of the asteroid using the science camera to refine the ephemeris knowledge of the asteroid. The optical navigation pointing requirements must be met while accounting for flexible body effects and within the capabilities of the ACS actuators and sensors. The ACS must also support science pointing, but the optical navigation requirements are the most difficult to meet and envelopes the requirements for science pointing.

NEA Scout must also periodically slew to point at the Earth for communications when it is outside of a certain range of Earth and this requires a large slew to a high sun incidence angle. During some mission phases the solar arrays may be as much as 70 degrees away from direct sun-pointing during the Earth communication phase, and this drives a requirement to slew to Earth at the fastest rate feasible with margin to preserve power and extend the time that can be spent away from lower sun-pointing angles. During these long slews, the AMT must be active to continue to manage momentum.

The ACS must also point the sail for thrusting during the mission. However, as is typical of low-thrust trajectory guidance, the sail angles change relatively slowly (on the order of a degree or two a day) and the sail pointing for thrust guidance is the least challenging requirement the ACS must meet.

The momentum management system must meet a unique requirement of trimming a relatively large solar disturbance torque caused by sail optical properties and shape [ref]. Untrimmed, the solar disturbance torque in the pitch and yaw axes is on the order of micro-Nm, but the AMT can trim pitch and yaw to the order of tens of nano-Nm. The AMT is unable to trim the residual "windmill" torque about the roll axis, so roll momentum management is handled by the RCS. Residual roll torque is on the order of nano-Nm and requires thruster firings on the order of a day throughout the mission, but the propellant expenditure for each roll desaturation firing is small and the total propellant expended is within mission margins.

The RCS faces challenges from having a small volume to fit into as well as only having four thrusters available for attitude control. There are a total of six thrusters, but two are axial thrusters that are used for the TCM. The RCS must also be maintained at a minimum propellant temperature of 16 C. Since the RCS is mounted on the same side of the spacecraft, during most of the mission this is not a concern, but for the initial de-tumble, which is performed shortly after ejection from the SLS upper stage, the temperature of the RCS might be lower than required since NEA Scout as a secondary payload cannot control it's thermal state until it is powered up. Since battery power is a concern and the arrays cannot be pointed at the sun until after the spacecraft is de-tumbled, we must carry some contingency plans for spacecraft de-tumble in case the temperature of the RCS is too low.

3. Control System Design and Results

3.1. Reaction Wheel Control Allocation

The reaction wheel hardware is composed of four reaction wheels 0.015 Nms, provided by Blue Canyon, each arranged in pyramidal fashion with spin axis 60 degrees off the roll (sail normal) body axis, and a 45 degree clock from pitch/yaw body axis. This arrangement allows for redundancy in case one of the reaction wheel fails, and uses an allocation algorithm that distributes the commanded torque from the controller among to all the reaction wheels in a symmetrical fashion using a Moore–Penrose pseudo inverse. In case of a single reaction wheel failure, a new allocation matrix can be uploaded from the ground.

3.2. Control Feedback Loop Architecture

The reaction wheel control feedback control loop, Figure 1, is composed of a star tracker sensor for attitude and rate sensor, a low pass filter, an Attitude Kalman Filter, a Proportional Integral and Derivative (PID) control, and the spacecraft plant model. At low body rates, below 0.1 deg/sec, the star tracker provides less noise and no drift as compared with the IMU, and since for solar sail deployed conditions the maximum slew rates will be set 0.04 deg/sec, the star tracker becomes an ideal rate sensor. As a contingency, if the star tracker becomes unavailable, the IMU will serve as a backup sensor.

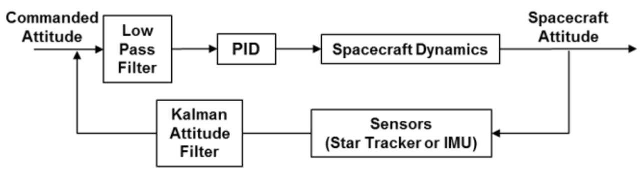


Figure. 1. Reaction wheel feedback control loop

3.3. Reaction Wheel Control Requirements

The RW control shall meet the control stability margins in frequency domain as well as the mission requirements, evaluated in time domain. Control stability requirements are 6dB gain margin and 30 deg. phase margin, including flex contributions from the sail and booms. Mission requirements include optical navigation requirements for asteroid detection and trajectory characterization, science requirements and communications requirements.

A communication pointing requirement of 1 deg. is needed once outside the earth-lunar phase of the mission. But this requirement is bounded by the science and optical navigation requirement of 0.5 degrees of attitude error. Besides pointing attitude error, a pointing stability requirements is needed for optical navigation and science, aimed at keeping the science camera steady during imaging periods. Therefore, the constraining mission requirements driving the reaction wheel control design are summarized below:

-Pointing attitude error of 0.5 deg.

-A maximum attitude error of 130 arcsec during a 60 sec. period

-A maximum attitude error of 13 arcsec during a 0.7 sec. period

Where error is defined as the difference between the desired commanded attitude and the true attitude.

3.4. Frequency Domain Control Stability

The PID control gains, proportional *Kp*, derivative *Kd* and integral *Ki,* and the low pass filter, order and cut-off frequency, are designed to meet control stability margins and mission requirements. The solar sail flexible dynamics posed a challenge since the natural frequencies of the sail and bus are low and close to the typical control bandwidth. The sail and bus free-free boundary condition have frequencies of: 0.67Hz for roll axis, 1.4Hz for pitch axis and 1.2Hz for yaw axis. However, a 0.7 uncertainty factor, α, is applied to the sail and bus natural frequencies that represents a 30% down shift to 0.47Hz in roll, 1.02Hz in pitch, and 0.85Hz in yaw. The uncertainty factor is applied since the frequencies are derived from analysis only, and validation using modal testing of the deployed sail would be impractical under earth gravity loads. Also, modal damping is assumed to be conservatively 0.1%. To remove the low flexible sail frequencies from the control bandwidth and attenuate sensor noise, a fourth order low pass filter, with cut-off frequency of 0.1 Hz, is used. The control open loop block diagram is shown in Figure 2 with parameters summarized in Table 1, shows the low pass posed a challenge since the natural frequencies of the sail and bus are low and close to the typical control bandwidth. The sail and bus free-free boundary condition have frequencies of: 0.67 Hz for roll axis, 1.4 Hz for pitch axis and 1.2 Hz for yaw axis. However, a 0.7 uncertainty factor, α, is applied to the sail and bus natural frequencies that represents a 30% down shift to 0.47 Hz in roll, 1.02 Hz in pitch, and 0.85 Hz in yaw.

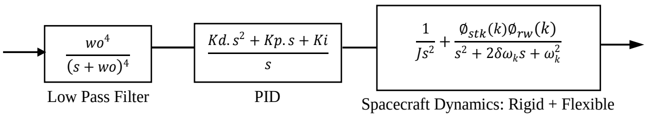


Figure 2. Open loop block diagram

Table 1. Open loop block parameters

Parameter	Value Per Axis		
	X	Y	Z
wo (rad/sec)	$2\pi 0.1$	$2\pi 0.1$	$2\pi 0.1$
Kp	0.011	0.012	0.002
Kd	1.479	1.530	0.804
Ki	0.133	0.138	0.008
$J(kg\ m^2)$	15.975	16.525	32.217
$\phi_{stk}(k)$, $\phi_{rw}(k)$, $k=1,2,3$	0.770	0.531	1.340
ω_k *(rad/sec)*	2πα1.45	2πα1.21	2πα0.67
δ *(%)*	0.1	0.1	0.1
α	0.7	0.7	0.7

The uncertainty factor is applied since the frequencies are derived from analysis only, and validation using modal testing of the deployed sail would be impractical under earth gravity loads. Also, modal damping is assumed to be conservatively filter, the PID and the spacecraft plant model which includes rigid and flexible body dynamics on a per axis basis. The rigid body dynamics are represented by the principal moment of inertia of the spacecraft and added to the flexible dynamics which assume a second order behavior with a modal gain equal to the multiplication of the normalized eigenvector rotational component at the sensor, $\phi_{stk}(k)$ for the star tracker, and actuator, $\phi_{rw}(k)$ for the reaction wheel, where k is the axis to be evaluated, $k=1,2,3$ for x, y, z axis, respectively. The Bode plot of the discretized open loop is shown in Figure 3 for the roll axis. The bode plot shows the system bandwidth to be approximately 0.067 Hz, and the first

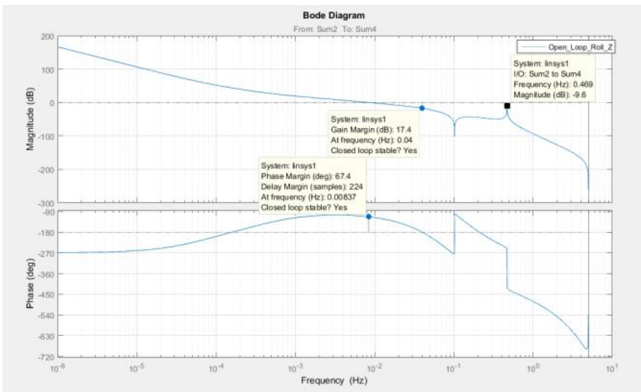


Figure 3. Bode plot of discretized open loop

roll mode sail peak response at 0.47 Hz, with the uncertainty factor applied. The system minimum stability margins for the open loop roll axis are 16dB in gain and 67deg of phase, well above the requirements. Similarly, Table 2 summarizes stability margins for the pitch and yaw axis as well. All axis meet the minimum stability margins of 6dB in gain and 30 deg. in phase.

Table 2: Stability margins per axis.

	Value Per Axis		
	X	**Y**	**Z**
Gain Margin (dB)	10.7	10.4	17.4
Phase Margin (deg)	50.4	49.5	67.4

3.5. Time Domain Results

The frequency domain analysis proved stability of the control system, but the time domain results shown below will prove the ability of NEA-Scout to meet the mission requirements. The time domain analysis includes a high fidelity spacecraft plant modeling, including sail flexible dynamics, AMT motion and its associated spacecraft mass property changes, and reaction wheel dynamics with static and couple imbalances. Also, the time domain results include star tracker and IMU sensor modeling, which use noise parameters derived from in-house testing. The first ACS mission requirement is to be able to meet a 1 degree pointing error for communication and a stringent 0.5 deg. mission pointing error. Figure 4 shows the attitude error during a ninety degree slew, with maximum slew rate of 0.04 degrees

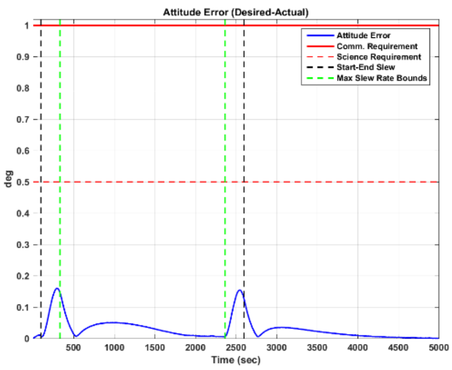


Figure 4. Attitude pointing error

per second. Dashed black lines indicate the beginning and end of the slew maneuver, while the green dashed lines show that the maximum slew rate was achieved after a ramp period. Through the slew maneuver the attitude error remains below 0.2 degrees. During the subsequent pure attitude hold condition, including AMT dynamics which constantly finds new equilibrium positions, the attitude error stays below 0.1 degrees, well below the required 0.5 degrees required for mission pointing, denoted by the red dashed line.

The second mission requirement is to have a pointing stability of 13 arc seconds during a period of 0.7 seconds, which guarantees small drift across image pixels of the target object. Figure 5 shows the pointing stability for the 0.7 seconds intervals, which is the maximum attitude change during a 0.7 second time windows computed every time step. Because pointing stability is an attitude change which contains contributions from both low frequency and high frequency, usually referred as drift and jitter, respectively, it is referred as Jitter plus Drift in the results below. With the exception of an initial transient peak right at the start of the slew maneuver, the 0.7 second pointing stability remains 4 arc seconds during the slew maneuver, and remains below 1 arc second during attitude hold, which is well below the 13 arc second requirement.

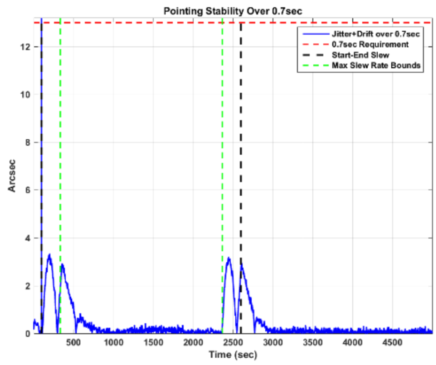


Figure 5. Pointing stability for 0.7 seconds duration

A third mission requirement states that a pointing stability of 130 arc seconds during a period of 60 seconds shall be met. This requirement is an optical navigation constraint which is only needed for the initial capture of the asteroid to help refine its orbit determination. The initial capture requires a series of images taken during a 60 second period. Figure 6 shows the pointing stability during 60 second intervals during a 90 degree slew maneuver and subsequent attitude hold. However, this requirement will only be needed during an attitude hold condition. So after approximately 200 seconds from the end of the slew, the pointing stability quickly drops to less than 50 arc seconds, and after about approximately 400 seconds from the end of the slew, the pointing stability during 60 seconds remains below 10 arc seconds, well below the required 130 arc seconds.

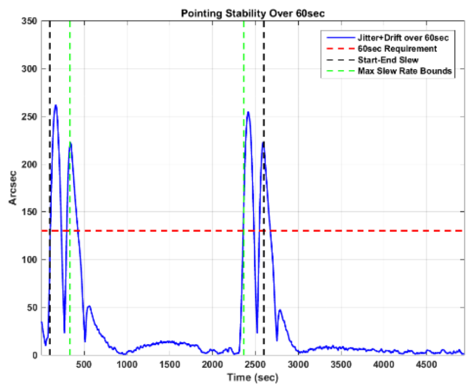


Figure 6. Pointing stability for 60 seconds duration

3.6. Reaction Control System (RCS)

NEA Scout uses a cold-gas RCS to control the spacecraft's attitude at various times during the mission. Specifically, the RCS has five responsibilities:

- Initial spacecraft detumble
- Initial sun-pointing and attitude hold
- Trajectory Correction Maneuver (TCM)

- Reaction wheel momentum desaturation
- Safe mode operation

NEA Scout will be ejected from SLS with some residual angular rates (up to 10 degrees per second on each body axis). The spacecraft power state will also be unknown, as the vehicle could be in storage for up to one year prior to SLS launch. Therefore, the first and second operations are to null the spacecraft angular rates and point toward the sun to charge the batteries. After achieving a power-positive state, the reaction wheels will take over as the primary actuator for the spacecraft.

While the reaction wheels are the primary actuator, attitude control is handed over to the RCS at certain phases of the mission. One example is during the TCM. This maneuver is performed to achieve the desired Earth-Moon orbit, and occurs shortly after ejection from SLS. Here, the axial jets will fire continuously to provide the necessary delta-V, while the RCS jets maintain the spacecraft's attitude during the maneuver. The attitude control is performed by the RCS jets during the TCM because the torques are too high for the reaction wheels. Furthermore, the RCS will be used to desaturate the reaction wheels as needed throughout the mission. This is discussed in Section 4.

The RCS unit is shown in Figures 7 and 8. The unit is approximately 2U of volume on NEA Scout, and contains about 1.25kg of propellant when full. The propellant is a refrigerant R236fa[2]. A conceptual image of the RCS unit is shown in Figure 7. The four circular features at the corners represent the RCS jets, and arrows are used to show the direction of thrust for each jet. The two circular features in the center of the RCS unit are the axial jets, with force components along the negative z-axis (into the page). The four RCS jets are located at the corners of the unit, and are oriented so that firing any pair of jets creates torque about one of the spacecraft body axes.

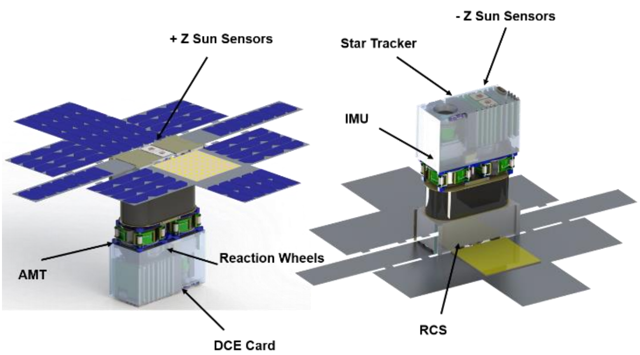


Figure 7. NEA Scout ACS Hardware

[2] https://www.chemours.com/Refrigerants/en_US/products/Suva/Suva236fa.html

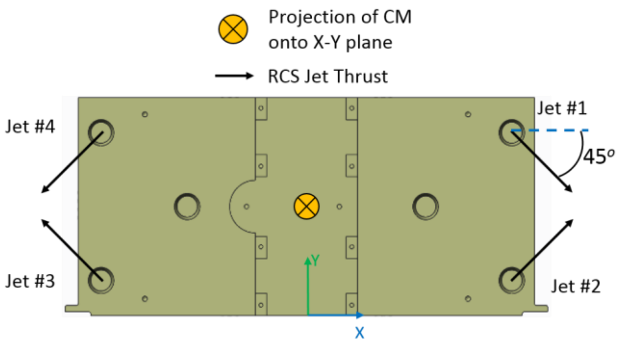


Figure 8. NEA Scout RCS Layout

NEA Scout uses a simple logic known as a phase-plane control system for the RCS. This type of control is sometimes referred to as a Schmitt Trigger [13] or a bang-off-bang controller. A phase-plane controller is best described visually as shown in Figure 9. The figure depicts a Cartesian coordinate frame with the attitude error on the x-axis, and angular rate error on the y-axis. The *red* lines on the plot denote the switching lines, while the *grey* inner-region denotes the quiescent region, or deadband. In this logic, the angular rate error and attitude error are evaluated for each vehicle body axis. If the values are outside the deadband, a pair of RCS jets are commanded to open, driving the system back toward the quiescent region.

A theoretical system trajectory is shown in Figure 8 and is

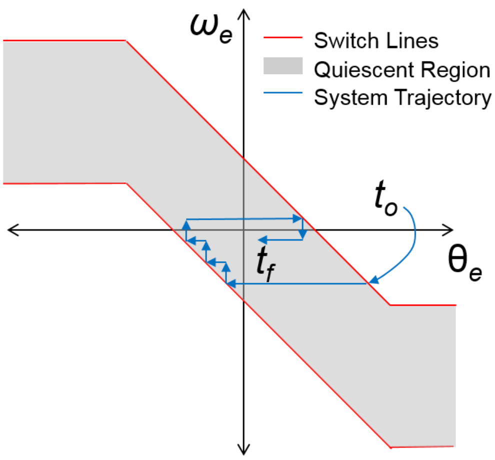


Figure 9. RCS Phase Plane Control Diagram

depicted with blue arrows. At t_0, the rate and attitude errors are outside the deadband, so a pair of RCS jets are opened. This drives the state into the 4th quadrant of the phase plane until hitting the upper switching line. At this point, the jets are closed and the system is quiescent. But, because the angular rate error is non-zero, the system's attitude error drifts across the deadband until hitting the lower switching line. The resulting stair case is caused by opening and closing the jets, and is the result of a digital (non-continuous) control system. Once the angular rate error is positive, the attitude drifts back across the phase plane toward the upper switching line. If there are no disturbance torques on the vehicle, this system will continue to circle the origin of the phase-plane as is partially shown in the figure.

A plot of spacecraft's performance is shown in Figure 10. This plot provides the simulated results of the spacecraft's body angular rates during the initial detumble. As shown, the vehicle is rotating at ten degrees per second about each axis. The RCS then dampens the rates within 25 seconds.

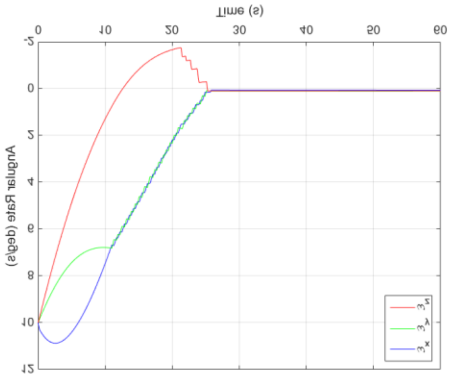


Figure 10. Simulated results of the initial de-tumble.

Last but not least, is also responsible for the trajectory correction maneuver (TCM). After ejection from SLS, NEA Scout's trajectory must be corrected in order to achieve the desired lunar gravity assist. The RCS will perform this maneuver by firing two axial jets, shown in Figure 7. These jets will provide the necessary delta-V to achieve the desired lunar flyby, and the RCS jets will control the spacecraft's attitude during the burn.

4. Momentum Control System Design and Results

The momentum management system monitors the momentum of the four reaction wheels, projects that into the three dimensions of the body axes, and uses a combination of three controllers to keep their momentum under control. The controller can receive a momentum bias command to increase margins for slews. During slews, the commanded spacecraft rate and estimated inertia are used to calculate a momentum bias, increasing system performance.

Before sail deployment, the RCS is used for all three axes. After sail deployment, the AMT is used to control the in-plane (X and Y) momentum by shifting the center of mass to produce solar torques. Roll (Z) axis momentum is controlled either by the RCS or body roll angle to trim the in-plane solar torque. These three methods are discussed in more detail below. Figure A1 shows a diagram of how the momentum management system works.

4.1. Active Mass Translator (AMT)

The primary actuator for momentum management is the Active Mass Translator (AMT), which moves part of the cubesat bus in order to shift the center of mass (CM) relative to the center of pressure of pressure (CP). The AMT is used to manage torques and momentum about the in-plane body axes of the sail (which align with the booms). As depicted in Figure 11 the Momentum Management System for the AMT uses a Proportional-Integral (PI) controller on the reaction wheel momentum projected into the X and Y (in-plane) body axes.

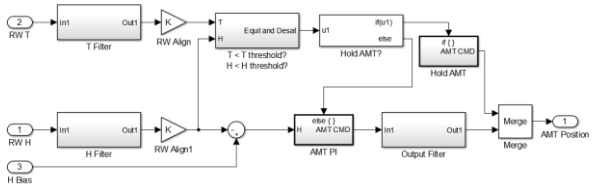
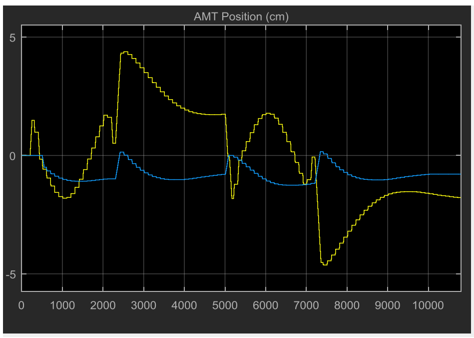
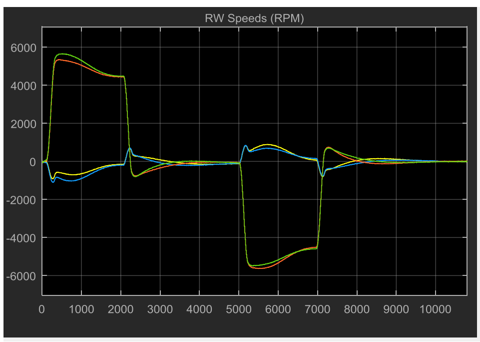


Figure 11. Diagram representing AMT X and Y momentum management controller

Steps are taken to reduce the duty cycle of the AMT. Filters are used to smooth the reaction wheel speed measurements so that AMT position commands and smooth. The AMT controller activates when the momentum in each of the X and Y axes reaches a threshold, and deactivates when both the momentum and torque reach deadbands, meaning that the wheels are desaturated and the solar torque has been trimmed out. This results in a system that actuates the AMT during and after slew maneuvers, and otherwise only moves once approximately every 12 hours when maintaining attitude. Figure 12 shows the AMT position and reaction wheel momentum and torques in response to the controller.



(a)



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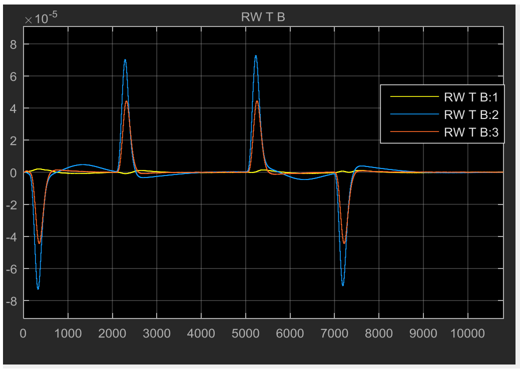

(c)

Fig. A2. Active mass translator response to two 90 degree slews, showing (a) AMT position, (b) reaction wheel speeds, and (c) reaction wheel torques

The AMT can also induce torques on the spacecraft to manage RW momentum buildup in the pitch and yaw axes. RW momentum buildup due to the solar sail roll torque (along the sail normal axis) is managed separately using RCS pulsing. The roll axis momentum desaturation can be successfully managed with propellant because it is 2-3 orders of magnitude smaller than the pitch and yaw torque. Roll torque is on the order of nano-Newton-meters (nano-Nm) while pitch and yaw torques are on the order of micro-Nm. Throughout the duration of the mission, the RCS will serve as a secondary ACS that can be employed for attitude recovery maneuvers resulting from various off-nominal conditions, including a loss of RW control.

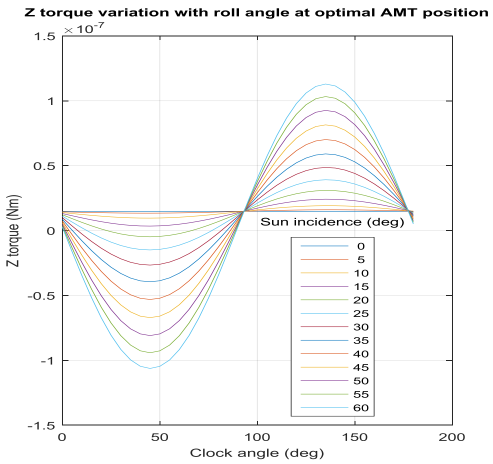

Figure. 13. Residual sail roll torque with trimmed AMT position over sun incidence and roll angle

As seen in Figure 13, Residual roll torque (about the normal vector of the sail, which is the Z-axis) will gradually increase the speed of the wheels, much slower than the torque about the in-plane boom axes. The roll torque varies with roll angle when the sun incidence angle is greater than 0 degrees. Above ~20 degrees, the roll torque variation with roll angle will cross zero, allowing it to be trimmed out and managed purely with roll angle control. During portions of the mission when the SIA is less than 20 degrees, RCS will be used. A worst-case estimate of 1×10^{-7} Nm roll torque for the entire 2.5 year mission duration (not including times when roll control is available) results in a propellant budget of 300 grams. RCS will also be used as a backup to the AMT for all body axes. Figure 2 shows the residual torque about the sail normal (Z) axis when the AMT is in the trim position for a range of sun incidence and clock angles.

4.3. Roll Control

Residual roll torque (about the normal vector of the sail, which is the Z-axis) will gradually increase the speed of the wheels, much slower than the torque about the in-plane boom axes. The roll torque varies with roll angle when the sun incidence angle is greater than 0 degrees. As seen in Figure A3, above ~20 degrees, the roll torque variation with roll angle will cross zero, allowing it to be trimmed out and managed purely with roll angle control. During portions of the mission when the SIA is less than 20 degrees and roll control cannot remove all of the roll momentum accumulation, the RCS which is left on will activate.

The roll angle can be controlled from the ground by adding a roll angle to the commanded quaternion based on roll axis momentum growth. It can also be managed onboard using a PID controller to monitor the Z momentum accumulation and generate a roll command that is added to the commanded quaternion sent to the guidance controller.

5. Conclusions

The NEA Scout Guidance and Control team has designed an ACS to meet all mission requirements before and after the sail is deployed. The reaction wheel control system slews the sailcraft, meets science pointing stability requirements, and can handle the sail flex modes. The RCS performs the initial de-tumble and sun-pointing maneuvers, provides a TCM to correct navigation dispersions after deploy, and provides de-saturation capability for the Z axis. The MMS manages momentum using the AMT for X and Y momentum, and RCS for Z momentum.

All the above requirements are met with restrictive volume and mass constraints from the 6U configuration of the sailcraft and also while subject to flexible body effects from an 86 square meter sail. The inclusion of the AMT for momentum management will be a first for solar sails, and is a novel configuration for using a shift in CM for momentum management.

Overall, the NEA Scout ACS provides a robust control system that provides a model for future solar sail missions as well as future small sat missions.

Acknowledgments

The editorial office appreciates authors' efforts to fully follow this template style.

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