ATTITUDE CONTROL APPROACH FOR SOLAR CRUISER, A LARGE, DEEP SPACE SOLAR SAIL MISSION

Daniel Tyler[*], Benjamin Diedrich[†], Benjamin Gauvain[‡], John Inness[‡], Saba Ramazani[‡], Andrew Heaton[§], Juan Orphee[**]

Solar Cruiser is a small satellite Technology Demonstration Mission (TDM) to mature solar sail propulsion technology using a solar sail larger than 1600 square meters, demonstrating performance as a propulsion system and a stable pointing platform for science observations in an artificial halo orbit sunward of the Sun-Earth Lagrange Point 1 (sub-L1). For the "sailcraft" to meet mission objectives, there are several unique attitude control challenges that the Attitude Determination and Control System (ADCS) must overcome. Large disturbance torques, primarily due to sail deformations coupled with off-sun pointing angles, make it more difficult to maintain adequate controls performance and manage accumulated momentum on the control actuators. The large-amplitude, low-frequency flexible body modes of the sail, in concert with noisy sensors and actuators, make it challenging to mitigate control-structure interactions and maintain fine pointing capabilities. Stability and control performance during sail deployment is complicated by rapidly and widely varying inertias. The Solar Cruiser ADCS effectively addresses these challenges using a simple, traditional control system – including momentum management actuators that use bang-bang control to constrain internal accumulated momentum, a low-pass controls filter and an attitude determination Kalman Filter (KF) that blends multiple star tracker solutions, and a reaction wheel assembly (RWA) with controller gains tuned to specific configurations or inertias. Solar Cruiser's attitude control approach, and lessons learned from its development, establishes a state of the art of high value to future solar sail missions and other small spacecraft with large deployable structures operating in deep space.

[*] Aerospace Engineer, MSFC/EV42, NASA Marshall Space Flight Center, MSFC/EV42, Huntsville, AL 35812
[†] Aerospace Engineer, MSFC/EV42 [ESSCA], Axient Corp., MSFC/EV42, Huntsville, AL 35812
[‡] Aerospace Engineer, MSFC/EV41, NASA Marshall Space Flight Center, MSFC/EV41, Huntsville, AL 35812
[§] Aerospace Engineer, Supervisor, MSFC/EV42, NASA Marshall Space Flight Center, MSFC/EV42, Huntsville, AL 35812

[**] Aerospace Engineer, Team Lead, MSFC/EV42, NASA Marshall Space Flight Center, MSFC/EV42, Huntsville, AL 35812

INTRODUCTION

The Solar Cruiser Mission

Solar Cruiser is a Small Satellite Technology Demonstration Mission (TDM) to mature solar sail propulsion technology to enable near-term, high-priority breakthrough science missions as defined in the Solar and Space Physics Decadal Survey. It "demonstrates a 1,653-m^2 solar sail-propelled, stable imaging and science instrument platform to serve as a pathfinder to enable near-term missions to observe the solar environment from unique vantage points, such as sustained observations away from the Sun-Earth line (SEL); sustained sub-L1 (sunward of the Sun-Earth Lagrange point L1 along the SEL) station keeping for improving space-weather monitoring, prediction, and science, advancing a capability within the range of interest to NOAA, and supporting human spaceflight crew safety and health needs; sustained in-situ Earth magnetotail measurements; and, in the mid-term, those that require a high inclination solar orbit; Earth polar-sitting and polar-viewing, as well as missions of interest across a broad user community."1

Solar Cruiser builds on a heritage of previous and ongoing solar sail missions. JAXA's IKAROS mission successfully flew and controlled a 200-m^2 spin-stabilized, boomless solar sail in deep space.2 NASA's NanoSail-D (10 m^2) demonstrated deployment in Earth orbit. The Planetary Society's LightSail 2 (32 m^2) operated in Earth's orbit and maintained attitude control using RWs and momentum management (MM) using magnetorquers.4 The most direct heritage of Solar Cruiser, from which it's Attitude Determination and Control System (ADCS) was derived, is NASA's Near-Earth Asteroid (NEA) Scout, an 86-m^2 sail designed to operate in deep space, using an ADCS architecture with many similarities to that of Solar Cruiser.5 Solar Cruiser applies lessons learned from these predecessors and scales up and adapts the technologies, especially the ADCS technologies, to demonstrate effective operation of a very large solar sail in deep space for future high-value science missions.

SSADCS

The Solar Cruiser sailcraft employs an ADCS to enable thrust vector control for orbital maneuvers and station keeping as well as demonstrate fine pointing and rate control for extensibility to future Heliophysics missions involving solar sails. By following uplinked attitude commands produced by the Solar Cruiser Mission Design and Navigation team, minimizing attitude estimation noise, control error, and rates (e.g., jitter), and managing the momentum of the attitude control actuators, this system helps prove the feasibility of solar sails as stable imaging and science instrument platforms. The sailcraft ADCS is comprised of a suite of sensors, actuators, and software systems working in conjunction to ensure adequate stability and control.

Table 1. Solar Sail Attitude Determination and Control System (SSADCS) ConOps

Mission Phase	SSADCS Critical Functions
Sail Deployment	Sun-pointing attitude hold with reaction wheels (RWs) and manage pitch/yaw momentum with Active Mass Translator (AMT)
Sailcraft Commissioning	Characterize sail disturbance torques and slew performance with attitude profile, momentum management (MM) performance, and pointing performance
Solar Sail Transfer & Station Keeping	Follow uplinked attitude commands while managing momentum
Plane Change Demonstration	Acquire and hold maximum achievable sun incidence angle (SIA) while maintaining MM capabilities to change heliocentric inclination

	at a target minimum rate

The SSADCS performs critical functions across seven different phases of the Solar Cruiser mission: Sail Deployment, Sailcraft Commissioning, Solar Sail Transfer, Solar Sail Station Keeping, Safe Mode, Plane Change Demonstration, and Roll Rate Control Demonstration. A representative timeline of many of these phases is depicted in Figure 1. These critical functions are summarized in Table 1. Solar Sail Attitude Determination and Control System (SSADCS) ConOps. Note that this is not an exhaustive list of functions performed by the SSADCS, but rather points of emphasis to highlight the primary concerns and challenges in the SSADCS design and operations.

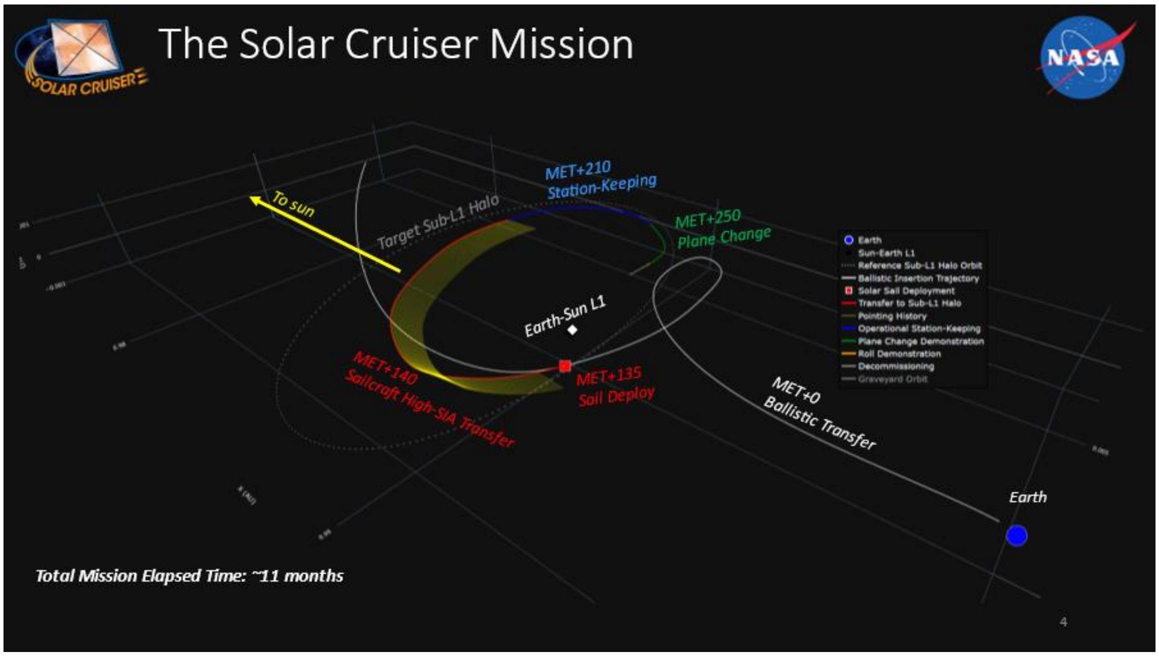


Figure 1. Solar Cruiser Mission Timeline

The SSADCS uses a suite of attitude determination sensors, attitude control actuators, (MM) actuators, and software to enable adequate attitude control over all phases of the Solar Cruiser mission, from just prior to sail deployment to decommissioning. Its architecture is shown in Figure 2.

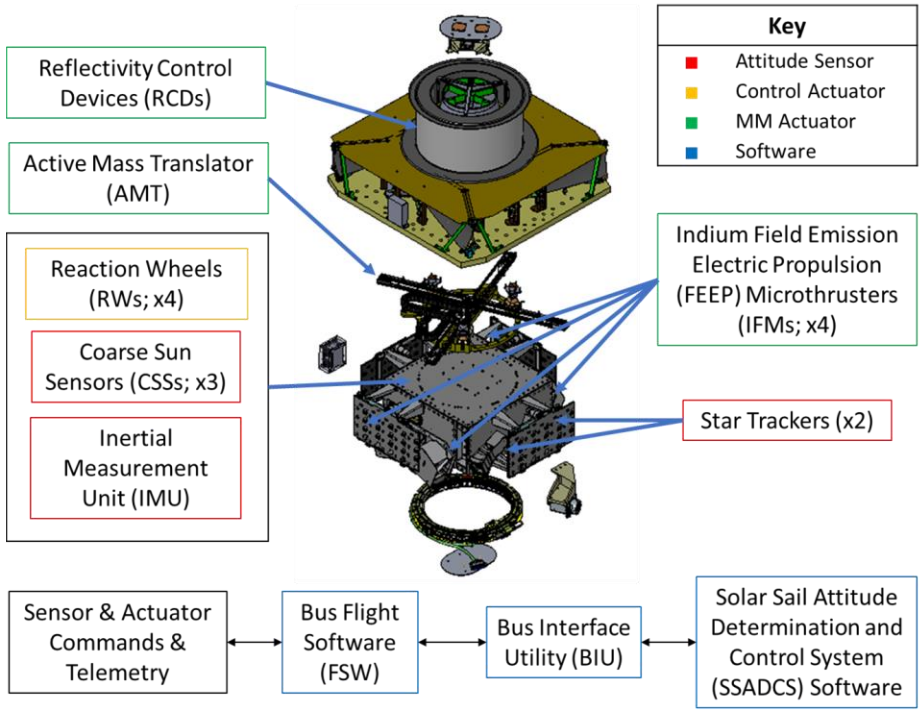


Figure 2. SSADCS Architecture

MOTIVATION AND PROBLEM FORMULATION

Sail Shape, Disturbance Torques, and Momentum Management

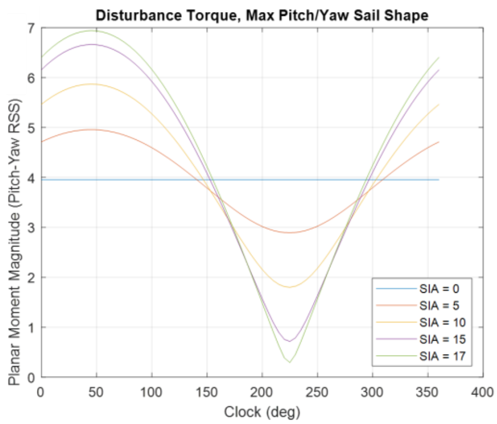
Accurate modeling of the deformed sail shape is critical for predicting and bounding disturbance torques and sizing actuators accordingly. Analyses conducted for Solar Cruiser demonstrated that thermal loads on the booms, driven primarily by uneven heating from the sun, have a large effect on boom tip deflection, which is the primary driver for global sail shape. They also showed that these boom tip deflections, in turn, have a significant effect on disturbance torques, especially deflections out of the sail plane. Due to having a much smaller impact on disturbance torques and the added modeling complexity, in-plane effects were neglected. Each sail membrane quadrant was assumed to deflect out of its local plane according to a biaxial sinusoidal shape function with a maximum deflection occurring at its centroid and its edges being fixed to the adjacent booms.

Table 2. Sail Shape Model Input Parameters

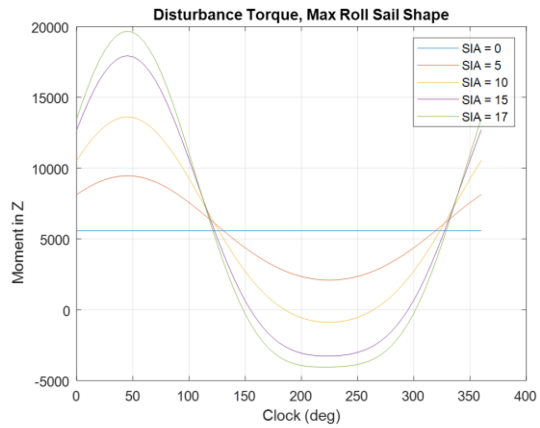
Parameter	Description
Membrane Deflections	Out-of-plane, billowing shape with peak/trough at the centroid of each quadrant. The magnitude was held constant, and the direction varied in the sail out-of-plane axis.
Nominal Boom Tip Deflections	Out-of-plane, increasing parabolically from root to tip. The magnitude and direction (out of the sail plane and toward the sun) were held constant.
Boom Tip Deflection Errors	Random/uncertain out-of-plane boom tip deflections due to manufacturing and assembly tolerances, tension changes in the membrane, and thermal load uncertainties. The magnitude was held constant, and the direction var-

	ied in the sail out-of-plane axis.
In-Plane Center of Mass (CM) Offsets	The difference in the center of mass in-plane position with the AMT homed relative to the designed geometric center, due to manufacturing and assembly tolerances.
Attitude	SIA varied from 0 to 17 degrees (target for Plane Change Demonstration) and clock angle varied from 0 to 360 degrees.

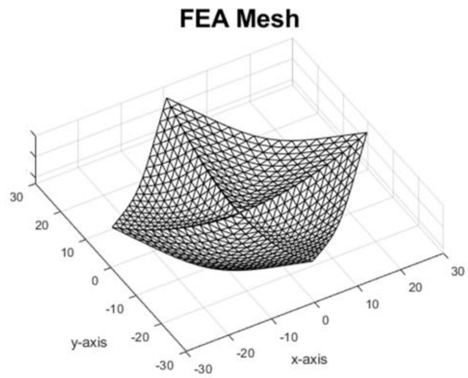
A series of parametric studies were conducted to determine worst-case deformed sail shapes which produce bounding disturbance torques. The input parameters varied in the parametric sweep are described in Table 2. The results of the parametric study yielded a large database of sail shapes and corresponding disturbance torques, calculated using a Rios-Reyes reduced order generalized sail model.6 After post-processing, two were selected as reference worst-case shapes: one which produced the highest pitch/yaw root-sum-squared (RSS) torque, and one which produced the highest roll torque, as shown in Figure 3. These solar radiation pressure-induced disturbance torques are a significant driver of control actuator selection, sizing, and design.



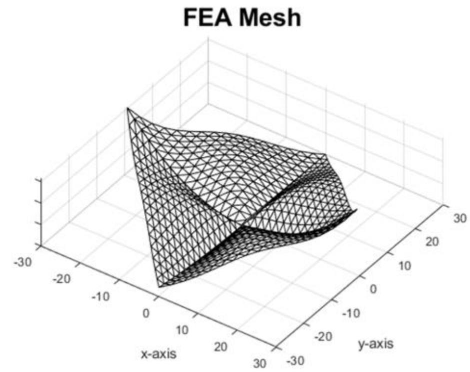
(a) Bounding Pitch/Yaw Disturbance Torques



(b) Bounding Roll Disturbance Torques



(c) Bounding Pitch/Yaw Sail Shape



(d) Bounding Roll Sail Shape

Figure 3. Bounding Disturbance Torques and Sail Shapes

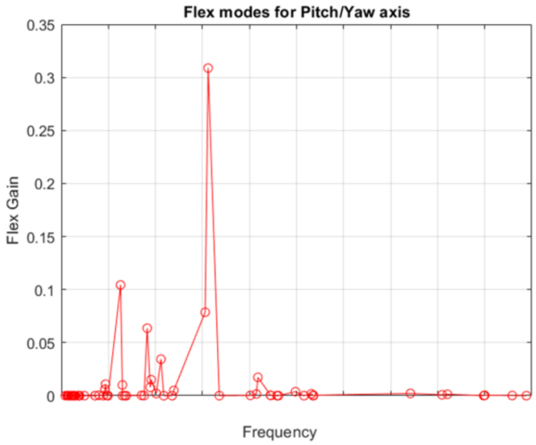
RWs counteract the disturbance torques to control attitude and accumulate momentum as a result. A separate momentum management (MM) system keeps the wheel momentum below a saturation threshold by overpowering the disturbance torques and forcing the RWs to apply control torques in a manner that reduces the accumulated momentum. MM is particularly important for Solar Cruiser, as the disturbance torques produced by the solar radiation pressure acting on the very large sail is orders of magnitude greater than that of traditional spacecraft. As a result, the total impulse required to desaturate momentum accumulated from solar torques using traditional propulsive methods results in large propellant mass, which reduces the performance of a solar sail. Furthermore, flying in interplanetary space where the magnetic field is minimal, makes traditional magnetic torque rods ineffective to counteract disturbance torques. Therefore, a less traditional, tailored MM approach must be pursued on Solar Cruiser and similar future solar sail missions.

Generally, the worst-case actuator performance and disturbance torques expected within the operational bounds of the mission are used to size the MM actuators. In contrast, the average duty cycle over time scales much larger than an on/off cycle of the actuator is used as a proxy measure of control authority for the purposes of requirements verification and Technical Performance Measure (TPM) tracking. Therefore, both worst-case disturbance torques and the disturbance torque profile over a range of attitudes (SIAs and clock angles) are important to model. The sail shape modeling approach on Solar Cruiser is intended to both bound the disturbance torques in support of MM actuator sizing analysis early in the design process, as well as produce detailed disturbance torque profiles for implementation in attitude dynamics simulations used for conducting design studies and verification analysis.

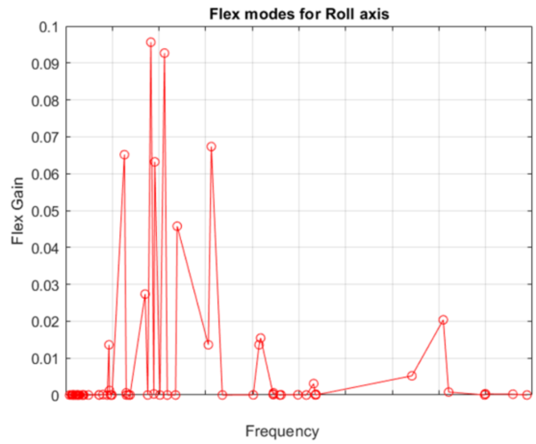
Flex, Slewing, and Pointing

One of the main drivers of slew and pointing performance is the flexible dynamics of the deployed sailcraft. The flex modes impart undesirable noisy motion and disturbance torques on the sailcraft when excited by ramping into or out of slews and RW noise from spin imbalances, for example. The residual flex response upon settling into an attitude hold state after a slew is an especially important driver of how quickly, and of what quality, science instrument measurements can be made. The flex response at the location of the attitude sensors and control actuators are of keen interest, as they affect the stability and accuracy of the control system, limiting the effective slew rate capabilities and ability to maintain adequate pointing control in an attitude hold state. Some flex modes are particularly driving, namely those which cause the greatest amplitude of motion at the bus, where the sensors and actuators are mounted, for a given intensity of flex loads (forces and moments that excite the modes). Figure 4 shows some of these significant modes.

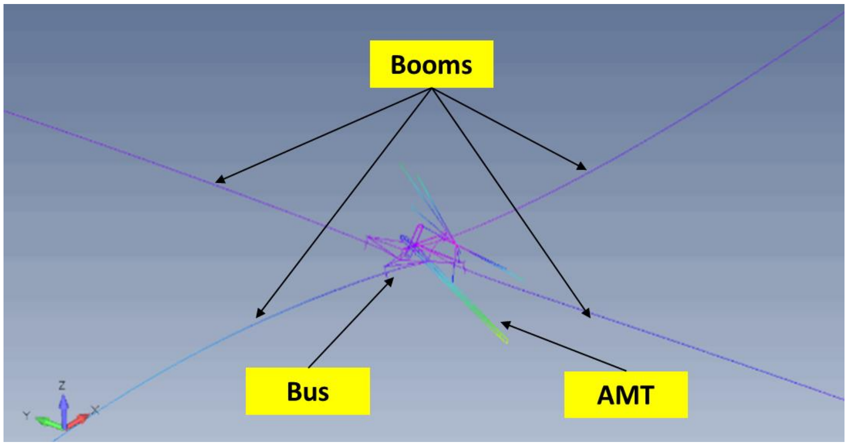
The flexible modes drive different design parameters of the deployed sailcraft attitude control system such as the low-pass controls filter design, for which the cutoff frequency must be sufficiently lower than the lowest fundamental frequency of the flex modes to prevent instabilities. The Proportional-Integral-Derivative (PID) controller gains must also be tuned according to the flex characteristics to ensure adequate controller gain and phase stability margins. A visualization of significant flex modes can be found in the figures below.



(a) Pitch/Yaw Flex Gains*



(b) Roll Flex Gains*



(c) Dominant Flex Mode

Figure 4. Flex Modes

*** Flex gain is a ratio representing the amplitude of motion due to a flex mode seen at an attitude sensor relative to the load applied to that flex mode by a control actuator.**

The flexible body modes impact the slew capabilities of the sailcraft in two ways: by limiting the quickness of slews, both the steady state slew rate and rate of transition between states, and by limiting the responsiveness of the control system to changes in target attitudes. The former constraint is derived from the need to prevent large excitations in flex modes induced by the heightened control activity associated with transient state between slewing and holding attitude. The latter constraint is a side effect of the lag in the controls response introduced by the filtering of attitude errors necessary for the sailcraft to maintain stability in the face of flex dynamics.

To demonstrate that sailcraft pointing control and attitude stability is comparable to that achievable with traditional platforms to validate sailcraft usability with science instruments, Solar Cruiser must exhibit sufficient pointing accuracy, jitter, and stability. Optical science instruments typically require a certain level of performance with respect to these three metrics to enable effective operation and high data quality in their measurements, minimizing detrimental effects such as motion blur. For example, the sailcraft attitude performance requirements for Solar Cruiser are set considering a standard solar remote sensing instrument as envisioned in the High-Inclination Solar Mission (HISM). The pointing accuracy is set to be compatible with a range of possible Heliophysics science instruments. Stability and jitter requirements are set by exposure time and spatial resolution.

Sail Deployment

Sail deployment is a critical mission event that can nominally take 45 minutes. It is considered a time-sensitive critical event – a high-risk period of transition between lower-risk and more well-defined states. Given the highly uncertain, indeterministic, and underconstrained characteristics of the sail shape (and, therefore, disturbance torques), mass properties, and overall sail behavior during deployment, capable and robust attitude control and MM is necessary to reduce risk of instability and poor pointing performance which could lead to catastrophic tumbling or loss of power. The NEA Scout mission had relatively high thrust cold gas thrusters, which were more than sufficient to arrest the buildup of rates during deployment. Solar Cruiser only has reaction wheels available, which presents more of a challenge. The sailcraft inertia and solar radiation pressure quickly grow by several orders of magnitude, with large uncertainties, during deployment, also contributing to large changes in disturbance torques and flex modes. The attitude control and MM system software needs to accommodate these changing and uncertain sail dynamic properties over the duration of sail deployment by continuously adjusting parameters (i.e., gains, filters, and principal axis transformations) to match the transient state of the system at any point.

DESIGN

SSADCS Software

Table 3. SSADCS Software Subsystem Functions

Subsystem	Primary Functions	Key Design Parameters
Command & Data Handling	Processes I/O; checks input validity; handles exceptions	--
Attitude Estimation	Generates filtered rate estimates from input attitude estimates	Rate low-pass filter parameters (cutoff frequency and order)
Attitude Guidance	Activates Slew Mode when needed; constructs smooth slew commands for the Controller; commands Safe Mode attitude	Max commanded slew rate; slew ramp rate; attitude error threshold for slew de/activation
Attitude Control	Generates control actuator commands; computes control torques; computes filtered attitude errors	RW PID gains; attitude error low-pass filter parameters (cutoff frequency and order)
Momentum Management	Generates MM actuator commands; controls de/activation of MM systems	De/activation thresholds; AMT PID gains
Mission & Fault Management	Manages mode transitions (including Safe Mode); detects and responds to faults	Fault monitor thresholds

SSADCS Software performs autonomous sailcraft attitude control and reaction wheel momentum management starting from the ballistic transfer phase and just prior to sail deployment. To perform this role, SSADCS Software implements the following core functionality (as depicted in Figure 5):

- Uses the estimated attitudes from the Bus attitude determination system to compute attitude and attitude rate commands

- Executes positioning commands uplinked form the ground for maintaining trajectory and maneuvers.

- Receives accumulated angular momentum data on the sailcraft from the Bus FSW

- Generates actuator commands to achieve desired attitude and rates

SSADCS Software consists of several subsystems that work to maintain attitude using the reaction wheels as the primary actuators. The functions described above are achieved by allocating the subfunctions detailed in Table 3. The key design parameters that enable these subsystems to effectively carry out these functions is also described.

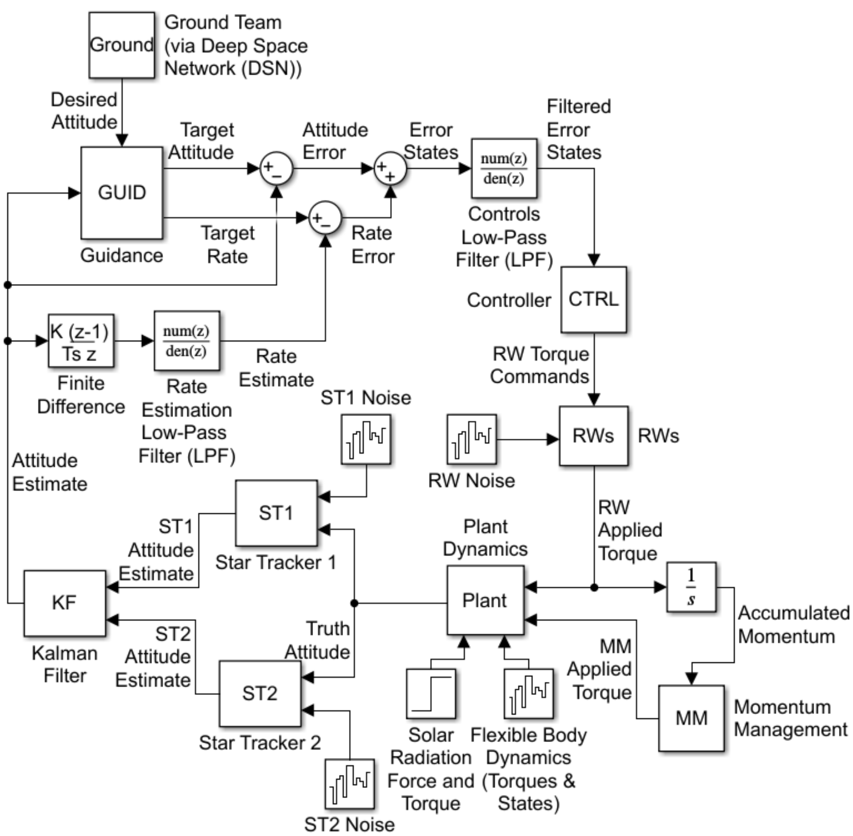


Figure 5. SSADCS Closed-Loop Control Functional Block Diagram

Momentum Management

Solar Cruiser employs a suite of MM actuators to desaturate accumulated momentum and reduce residual disturbance torques. These actuators are activated upon the angular momentum error ("H Err"), defined as the difference between the desired momentum, or "H Bias", (for slewing and preventing low-frequency RW noise and static friction effects) and the net RWA momentum, or "RW H Body", exceeding a pre-determined activation threshold stored as a software parameter, as shown in Figure 6. They are deactivated when this “H Err”, as well as the residual RW torque in the pitch/yaw channels, falls below a deactivation threshold. These thresholds may vary by actuator, mission phase, or other pertinent conditions.

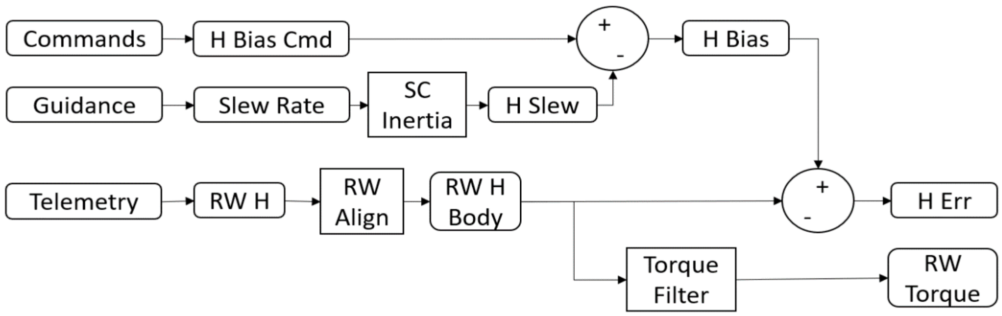


Figure 6. Momentum Management Error and Torque

Reaction wheel momentum in the pitch and yaw axes (in the sail plane) is managed by the Active Mass Translator (AMT), which takes advantage of the solar pressure on the sail, and associated thrust force, to shift the center of mass (CM) of the spacecraft relative to the center of pressure (CP) of the sail to induce counteracting pitch/yaw solar torques. The AMT splits the spacecraft into two parts, one with the sail and the other with the spacecraft bus and shifts them relative to each other using rails and drive motors. The MM software monitors the pitch and yaw axis momentum of the wheels and generates AMT position commands using a PID controller, as depicted in Figure 7. The integral is critical because it minimizes the solar torque, allowing the controller to deactivate once momentum (“H Err”) and torque have fallen below specified thresholds. Steps are taken to reset and prevent windup of the integrator. By letting the integrator minimize the torque before deactivation, the momentum takes longer to accumulate until the next activation, which reduces the duty cycle on the AMT hardware. Because the AMT can only shift the CM relative to the sail geometry without impacting the CP of the solar radiation pressure, it only has two degrees of freedom of control, both orthogonal to the CP line of action (i.e., mostly in the sail plane).

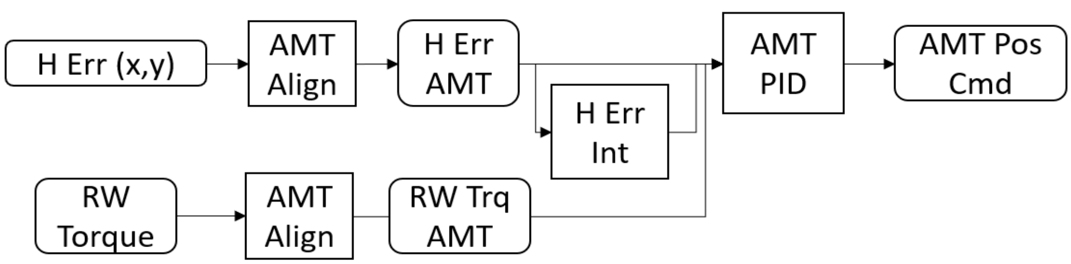


Figure 7. AMT pitch/yaw momentum controller

Roll torque is managed separately because an AMT can only control the pitch/yaw axes. Roll torque is typically much smaller than pitch/yaw torques, and therefore Solar Cruiser can use small, low force devices, including Indium Field Emission Electric Propulsion (FEEP) Microthrusters (IFMs) and Reflectivity Control Devices (RCDs). IFMs are used for momentum management in all three axes prior to sail deployment, as they are oriented to have control authority in all axes and disturbance torques are very small compared to post-sail deployment. They are also used for roll MM during sail deployment, if needed, as the RCDs do not deploy until the sail is fully deployed; although, no significant roll momentum is expected to accumulate during this phase.

RCDs are the main roll MM actuators once the sail is deployed, with IFM thrusters as backup in case of RCD underperformance. RCDs are innovative devices, and, at a high level, their functionality is made possible by a new generation of electroactive polymer-dispersed liquid crystal (PDLC) materials that change in reflectivity with applied voltage.7 As a result, the reflected light from the RCD becomes more specular when active. Thus, when two opposing RCDs are in opposite states, one "off" and one "on" a differential force that acts tangent to the sail plane at a large moment arm near the boom tips produces a roll torque. A controller logic is used for RCDs that determines whether Counterclockwise (CCW) or Clockwise (CW) moment must be applied (Figure 8).

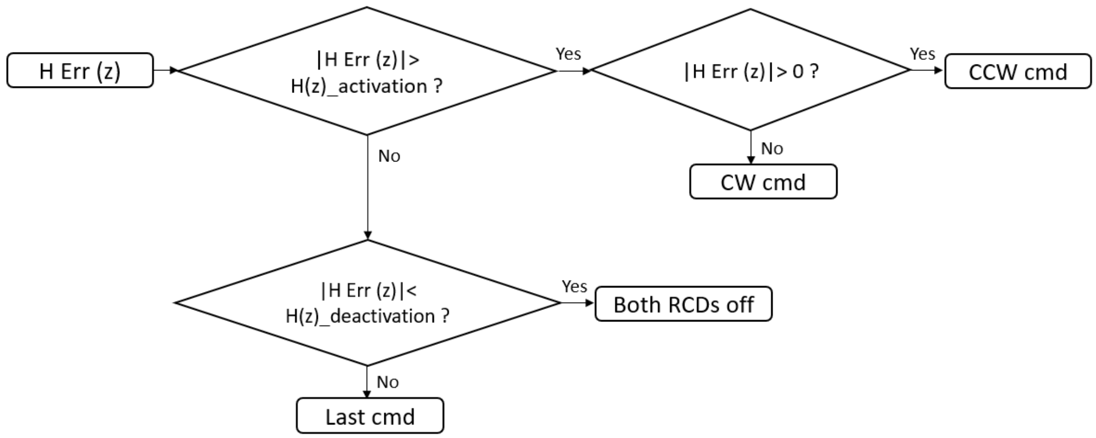


Figure 8. RCDs roll momentum controller

The primary indicator of MM actuator performance is its control authority, the difference between the control torque capabilities and the disturbance torques, expressed as a ratio of disturbance torque magnitude. The control authority can be thought of as operational margin; the lower the margin, the harder the actuator must work (i.e., with a higher duty cycle) to counteract the quasi-static disturbance torques while having enough performance leftover to desaturate the moment accumulated on the RWs. In fact, the control authority is simply the inverse of the duty cycle expressed as a ratio (on time over total time). The MM actuators are sized to provide sufficient control authority over the predicted worst-case disturbance torques, with some uncertainty margin applied, up to SIAs of at least 17 degrees, per the technology demonstration objectives of Solar Cruiser, as shown in Figure 9. The key design parameter of the AMT is its total range of motion, while the ratio of bus mass to solar sail technology system mass is a driving constraint. Key design parameters of the RCDs include total RCD area, the locations of the RCD "clusters" (i.e., individual control surfaces) on the sail (for maximum moment arm), and their out-of-plane ("tent") angle for optimizing the force normal to the moment arm (in the sail plane).

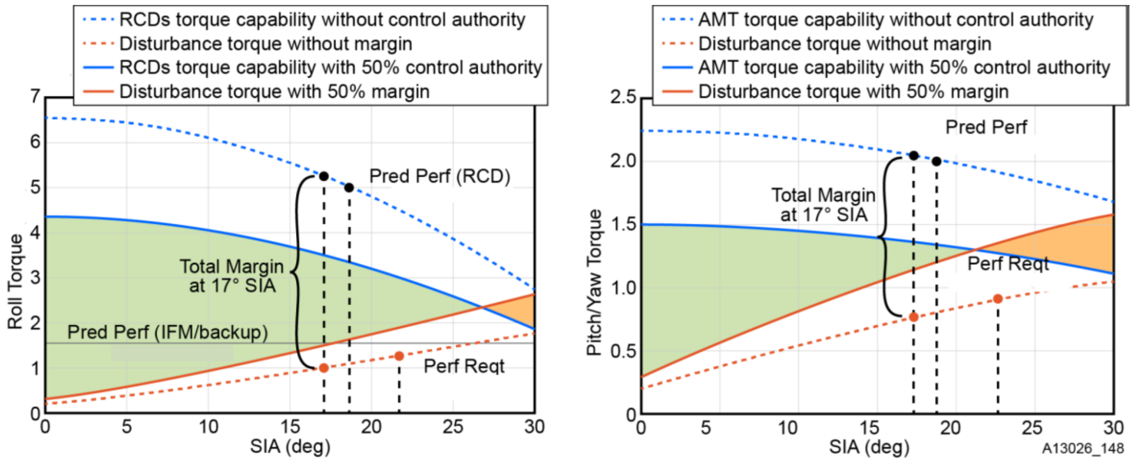


Figure 9. MM Actuator Sizing Approach

Estimation and Controls Filtering

The Bus FSW attitude determination system employs a Kalman Filter (KF) to blend the attitude solutions from multiple sources (nominally, two star trackers and an IMU). This filtering is used to partially correct for measurement noise by taking advantage of the fact that the star tracker measurement noise in the cross-boresight axes is significantly lower than the about-boresight axis, and that the star trackers are oriented nearly orthogonal to each other. The filtered attitude estimate is input to the SSADCS Software, where it is differentiated using a simple finite difference of consecutive samples to produce a raw attitude rate estimate. However, this raw attitude rate estimate is generally so noisy that it can result in undesirable control system performance when fed into the derivative controller, for example. Therefore, the SSADCS Software uses a low-pass filter (LPF) to attenuate the higher frequency content of the attitude rate signal. The rate filter is optimized to reduce lag and enables greater responsiveness of the control system to large, relatively quick fluctuations in rigid body attitude rate error while maintaining stability.

The attitude control system also employs an LPF to the attitude estimate received from the bus to attenuate the noise induced by the flexible body dynamics of the sailcraft on the attitude error signal passed into the PID controller. The PID control gains are designed in conjunction with the filter to achieve the desired frequency response. This controls filter is designed with a cutoff frequency below the first fundamental frequency of the sail flex model with margin to account for frequency uncertainties and the gradual gain attenuation in the transition band of the filter. The large inertia and slender, flexible booms of the sail cause very low-frequency and high-amplitude flex modes that require heavy filtering for the purpose of stability but, consequently, significantly constrain the frequency response and slew rate achievable by the PID controller.

RW Attitude Control

Solar Cruiser's ADCS system uses an assembly of four RWs for attitude control. The RWs are oriented to provide capacity and redundancy in all 3 spacecraft axes. The attitude control logic calculates a desired command torque about the principal body axes, which is then allocated to the four RWs with individual torque commands projected into each RW's local spin axis using a pseudoinverse method that minimizes error in net RW torque relative to the desired principal axis torques. The controller gains for each sailcraft configuration are designed assuming fixed inertia values. As the inertia is updated, the PID gains are scaled accordingly and transformed to control purely about the principal axes. During sail deployment, the inertia changes dramatically: by several orders of magnitude. To maintain reaction wheel control throughout, the RW PID control gains and principal axis to body transformations are designed at the initial, final, and intermediate points of deployment. The solar sail deployment system reports a percentage status of deployment, which the SSADCS software uses to interpolate the gains and transformations between these points. A preliminary implementation used undeployed gains and transformations at 0% deployment and switched to fully deployed values from 10-100% deployment. Further refinement of the controller used gains and body-to-principal transformations at 50% as well, and interpolated between these values throughout deployment.

PERFORMANCE

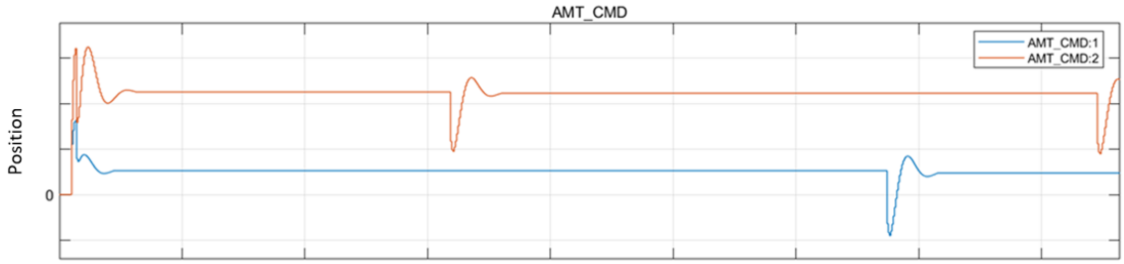
The performance of the SSADCS is measured by its capabilities in several areas, including MM control authority; slew rate capabilities; pointing accuracy (the sum of control error and knowledge error), jitter, and stability; and control stability gain and phase margins. These capabilities are critical to enabling adequate MM, slewing, pointing, and control during sail deployment. The baseline SSADCS design described in the previous section meets all the performance requirements associated with these critical functions.

Momentum Management

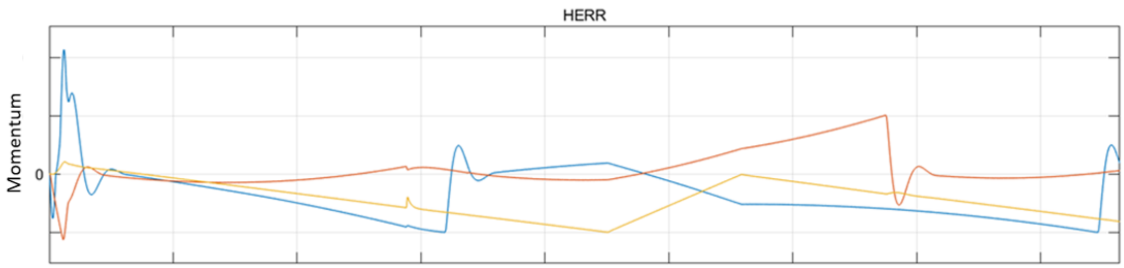
As Solar Cruiser operates with its sail deployed, disturbance torques will build up momentum on the reaction wheels. If left to grow without mitigation, it would lead to saturation of the reaction wheels and the loss of control of the sailcraft. Therefore, the MM actuators (AMT for pitch/yaw, and RCDs and/or IFM thrusters for roll) must activate frequently throughout the life of the mission to keep the accumulated wheel momentum within acceptable bounds. Although the AMT has the effect of trimming out pitch/yaw disturbance torques for a given attitude, the constant maneuvering required to station keep with a solar sail – as the attitude of the entire sailcraft is used to change the thrust vector – causes the trim location to shift, driving up activation frequency and duty cycle. The roll MM system can similarly be triggered by slews, which require some temporary momentum buildup on the RWs.

In addition, MM actuators consume shared resources of the sailcraft and mission, including power draw (both long-term power positivity and short-term battery discharge), operational lifetime (driving mission life), and thermal budget (limiting heat generation from components). Both the activation frequency and the duty cycle impact the utilization of one or more of these resources. If the MM actuator is not design with enough control authority, not only is risk of RW saturation heightened, but risk of excessive power draw and total battery discharge is as well. If the MM actuator activates too frequently, there is increased risk of mechanical failure due to excessive cycling, but if the actuator undergoes longer on/off cycles, the temperature may rise above acceptable levels while the actuator is active for a long period.

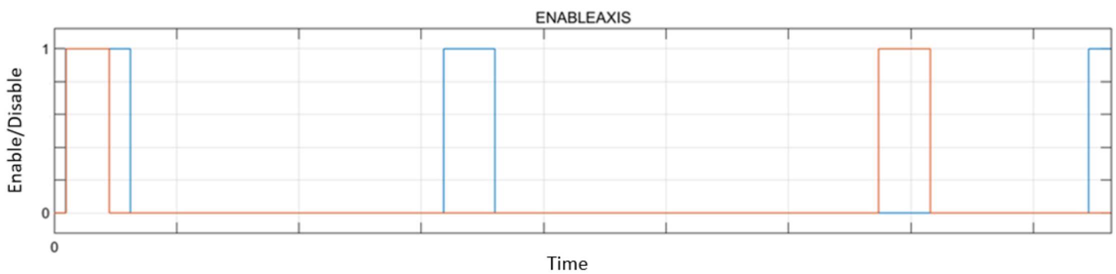
All these concerns must be considered and balanced in the sizing and control system design of MM systems. The Solar Cruiser SSADCS design meets the MM needs dictated by the mission ConOps and requirements while remaining within constraints driven by the shared resources of the sailcraft. The predicted behavior of the AMT and RCDs during a stressing case (slewing to and holding 17° SIA) is shown in Figure 10 and Figure 11, respectively.



(a) AMT Position Command

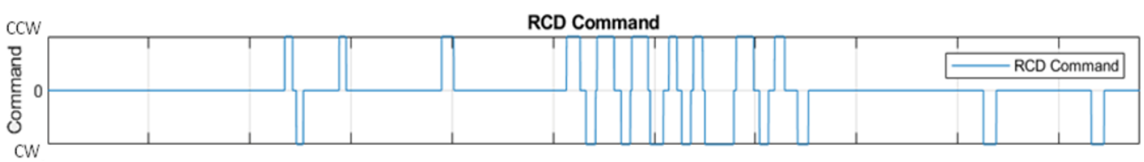


(b) Pitch/Yaw Momentum Error

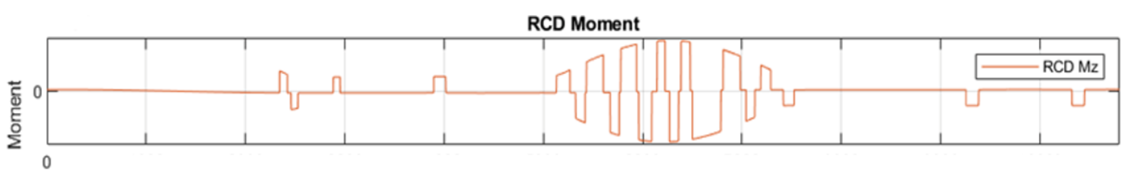


(c) AMT Axes On/Off States

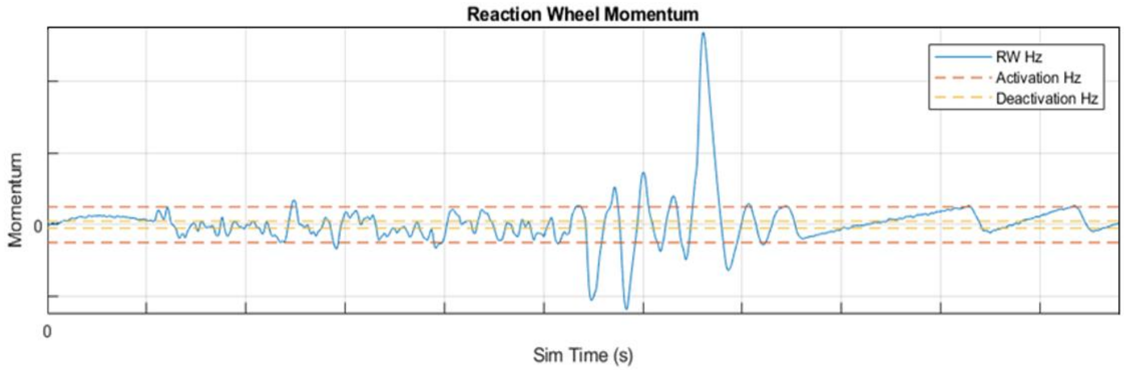
Figure 10. AMT MM Performance



(a) RCD Torque Direction Command



(b) RCD Control Torque

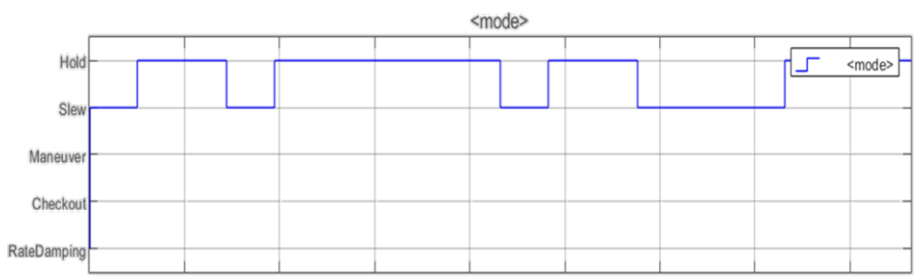


(c) RWA Roll Momentum

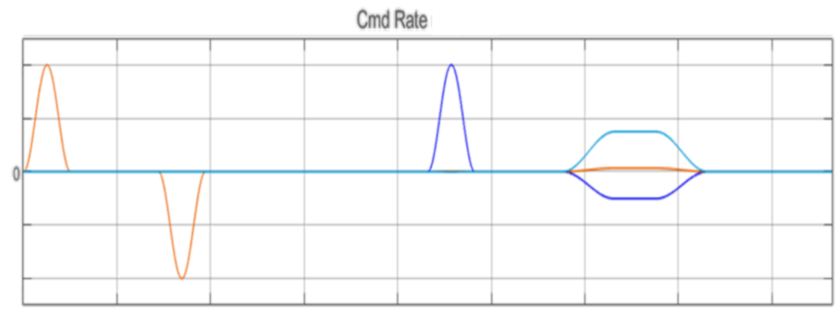
Figure 11. RCD MM Performance

Slewing and Pointing

Characterizing slewing and pointing performance is critical for station keeping, orbital maneuvering, and pointing (for science measurements) performance. The slews are enabled with a ramp up before reaching maximum slew rate then ramping down prior to completion of the slew. The transition between attitude hold and slew states is smoothed, with the intent of mitigating excitation of flex modes, by a combination of the attitude and rate error-limiting guidance algorithm coupled with the low-pass controls filter. This smoothing adds lag to the response of the control system to slew commands, however, limiting effective slew rate – particularly for short slews – and imposing constraints on the associated design parameters. Effectively balancing these performance drivers, Solar Cruiser's SSADCS enables rapid slewing that meets slew rate requirements while maintaining stability and good attitude control performance. The response of the sailcraft system to a series of slews performed during the sail characterization phase of the mission is shown in Figure 12. Some residual RW control activity – due to controller overshoot and settling of the rigid body and flexible body dynamics (enabled by the estimation and controls filters) – can be seen at the end of each slew. The SSADCS is designed to enable transition between successive attitude hold states at a sufficient rate for the sail characterization sequence to be completed within the allotted time, as this phase drives the slew capability requirements.

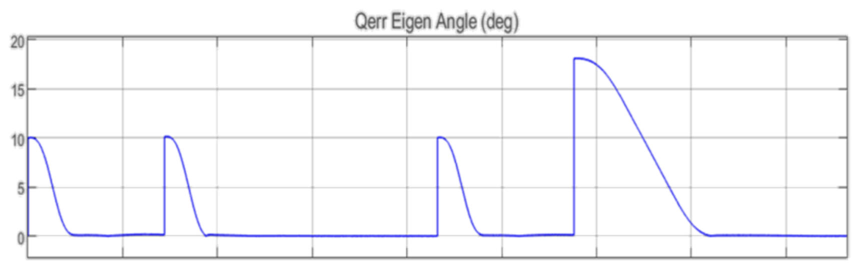


(a) Guidance Mode

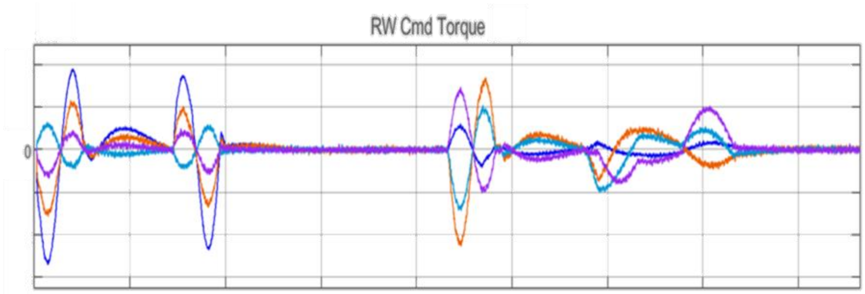


(b) Commanded Rate

(Blue: Pitch, Orange: Yaw, Cyan: Roll)



(c) Attitude Error Angle

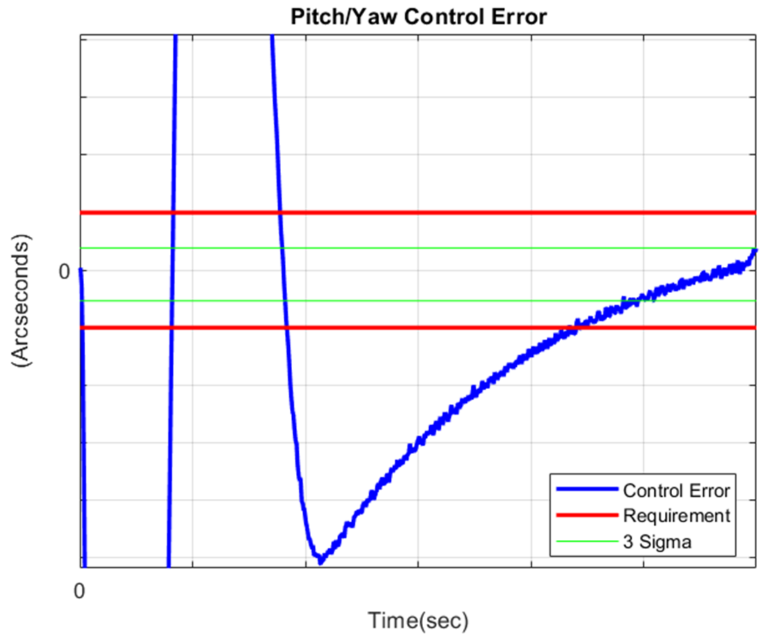


(d) RW Command Torque

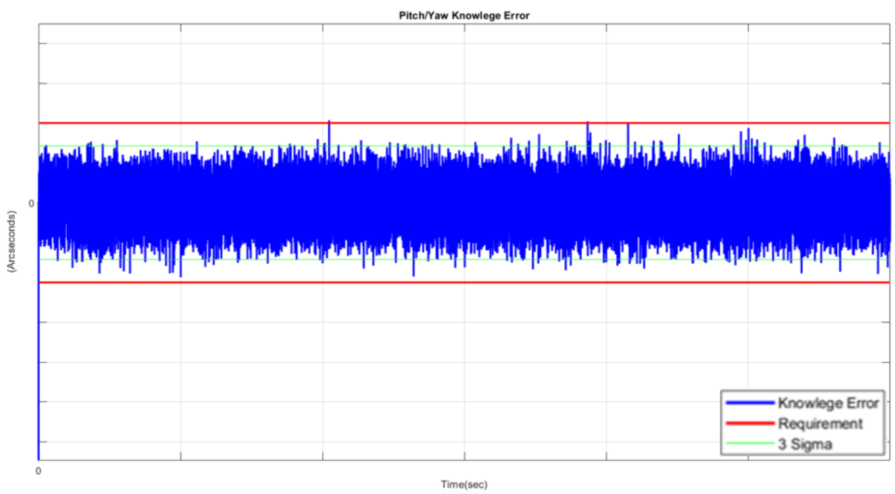
(Each color represents 1 of the 4 RWs)

Figure 12. Slew Performance

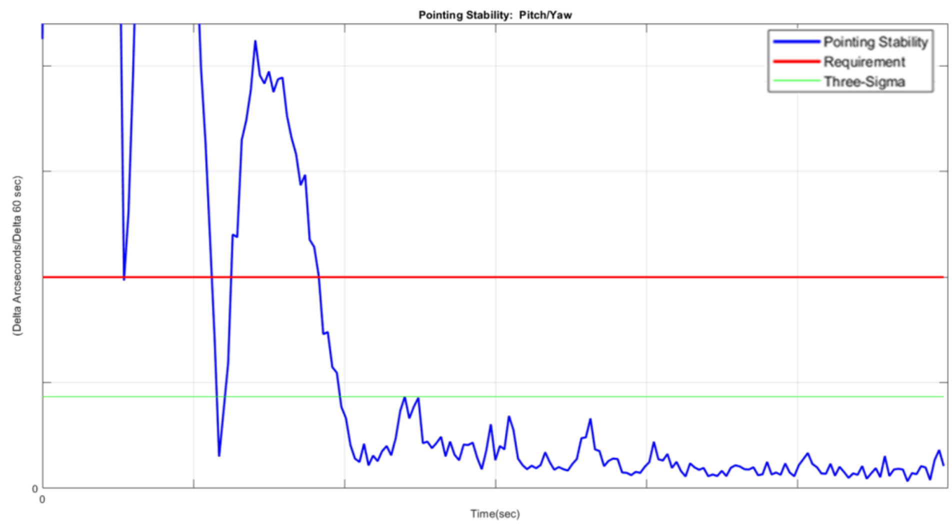
Upon settling into an attitude hold after a slew, there is residual pointing error caused by flexible body dynamics, excited both by the ramp out of the slew (eventually damped out by structural damping effects) and continuously by the noise induced by imbalances in the spinning RWs. This residual noise is the primary driver for pointing performance during hypothetical science observations. All these effects are managed by a combination of the estimation and controls filtering and the tuning of PID controller gains. While this pointing performance is an important indicator of the quality of science instrument measurements, the effective settling time to reach this level of performance upon reaching a target attitude is a key indicator of the quantity of good data samples. Solar Cruiser can achieve the pointing performance necessary, and within a reasonable amount of time, to be effective as an imaging platform for its target instruments and design reference missions, from which its pointing requirements were derived. Figure 13 shows an example of the sailcraft pointing performance converging to within requirements upon transitioning to an attitude hold state from a slew.



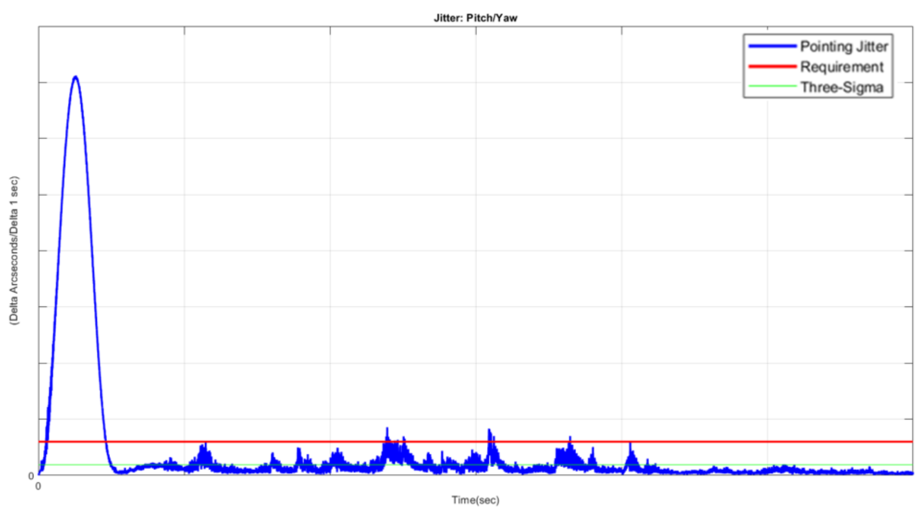
(a) Pitch/Yaw Attitude Control Error



(b) Pitch/Yaw Attitude Knowledge Error



(c) Pitch/Yaw Pointing Stability



(d) Pitch/Yaw Pointing Jitter

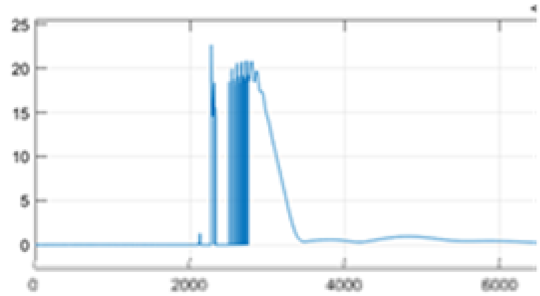
Figure 13. Pointing Performance

Sail Deployment

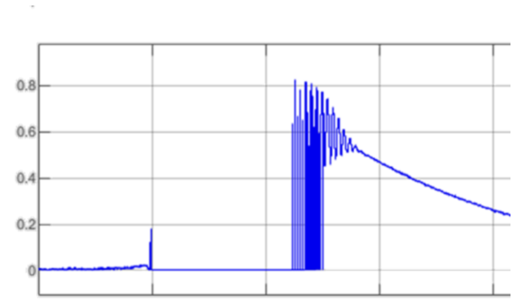
Attitude rate errors, when coupled with (i.e., integrated over) latencies in the SSADCS that make attitude estimates slightly "stale" by the time they are input to the controller, contribute to attitude knowledge error. This is especially critical when attitude rates dominate the error signals during relatively dynamics events, such as sail deployment. Therefore, the attitude rate filter is a key design driver of attitude error during sail deployment given the potentially large and rapid changes in rates due to the rapidly varying and highly uncertain disturbance torques and sailcraft inertia as the sail unfurls.

The preliminary design for the sail deployment attitude controller was less than optimal because it used interpolated PID gains and principal-to-body transformations for the 0% and 100%

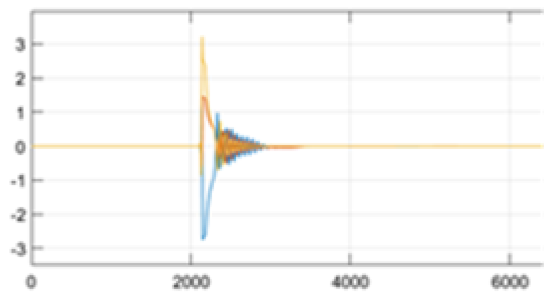
deployed configurations, where it switches to 100% deployed values at 10% deployment. The attitude error grows to over 20 deg in this case. The performance improved dramatically by using 0%, 50%, and 100% gains and transformations, and an updated rate filter, bringing the attitude error below 1 deg throughout deployment. The effects of the design change are shown in Figure 14.



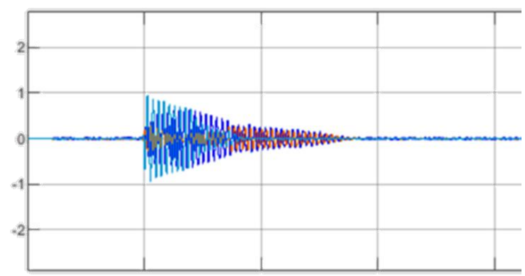
(a) Previous Attitude Error



(b) Updated Design Attitude Error



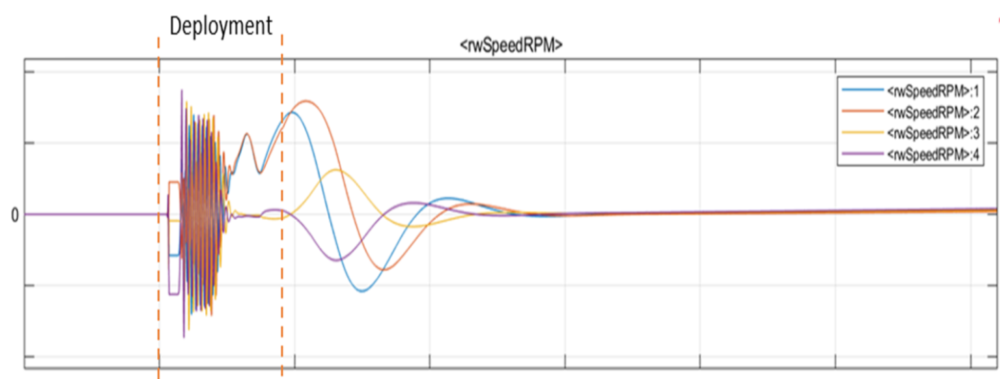
(c) Previous Attitude Rate Error



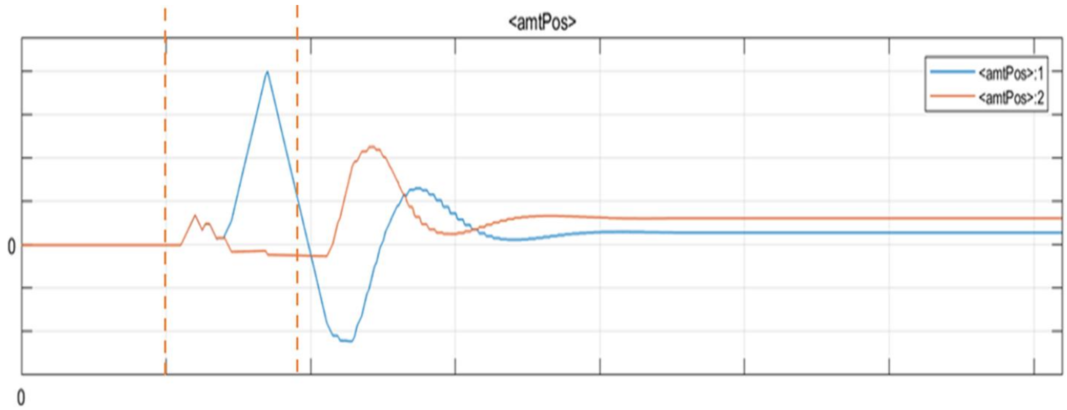
(d) Updated Design Attitude Rate Error

Figure 14. Sail Deployment Attitude Control Performance

The AMT operates during sail deployment to manage the pitch & yaw wheel momentum. It manages the momentum successfully, though with more position and wheel speed variations than during post-deployment operations (see Figure 15). Future tuning of the reaction wheel sail deployment controller should improve this response.



(a) RW Speed vs. Time



(b) AMT Position vs. Time

Figure 15. Sail Deployment MM Performance

DISCUSSION

Lessons Learned

Table 4. Solar Cruiser SSADCS Lessons Learned

Name	Lesson Learned	Recommendation
Slew & Flex Coupling	Slew performance is constrained by flex dynamics directly, considering the excitation of flex modes by the relatively large torques imparted on the sail for slewing, as well as by the use of filtering to mitigate control-structure interactions, which delays the response of the control system to rapid changes in desired attitude, such as at the start and end of a slew.	Early simulations demonstrating slew performance that include a preliminary flex model and controls filter design is necessary to have an accurate understanding of the system's slew capabilities, especially a system with very low-frequency flex modes such as a solar sail. Therefore, the flex model and controls filter design must be tracked as dependencies for any slew performance simulation and analysis product. Preliminary flex model can added a simple first order model and a parametric sweep of the different results can be analyzed.
Attitude Rate Filter Design	The attitude rate filter design significantly impacts stability and control when rates dominate attitude errors, such as during a dynamic event occurring while holding attitude. Too much attenuation of the rate signal can lead to inadequate rate damping and, as a result, poor attitude stability and control performance.	Design the attitude rate anti-aliasing filter, such as a low-pass filter, independently of the controls filter used for attitude errors, as these two filters are likely to have different design drivers and stressing cases. Identify the stressing case(s), looking for situations where disturbances are highly variable and/or induced rates dominate attitude errors, and simulate them to test the performance of the attitude rate filter.
Actuator Power, Thermal, & Lifetime Considerations in Controls Design	The various design goals (e.g., MM control authority) and constraints (power, thermal, and lifetime) of actuators are likely to compete, requiring suboptimiza-	Consider power, thermal, and lifetime constraints, in addition to control authority, when designing controllers for actuators, especially on Class D small spacecraft missions where these constraints may be tight

	tion of performance to balance these various concerns in the controller design. Because actuators consume integrated system resources (e.g., power), integrated system performance requirements that flow down to the actuator may be solution dependent. E.g., a high-power actuator could require higher torque capabilities for reducing long-term power draw than what is needed for a low-power actuator to provide a certain level of MM control authority.	due to limited budget, mass, and volume. Preliminary modeling of these constraints - whether as assumptions or specifications from analysis, test, or flight data - can help identify disconnects, sensitivities, and higher priority aspects of the design or system behavior to study further. Identify constraints and assumptions associated with the baseline actuators and requirements that could be impacted by changes to them. If these impacts are considered high-risk, invest in early studies to reduce uncertainties and firm up these constraints and assumptions.

Several lessons were learned over the course of development of the SSADCS for Solar Cruiser, as detailed in Table 4. Solar Cruiser SSADCS Lessons Learned. These lessons may be insightful to any team developing a similar ADCS for future large, deep space solar sails.

Forward Work

There are several ongoing and planned activities to mature relevant models, improve the design and technology maturity of the SSADCS, and better understand performance drivers and requirements. For example, there is ongoing work by the Solar Cruiser Project to increase the fidelity of the sail shape model for more accurate disturbance torque predictions on Solar Cruiser and future solar sail missions. Further design modifications to SSADCS Software include finer tuning of gains during deployment and the attitude rate filter, integration of mission and fault management capabilities (including better definition of a safe mode while the sail is deployed), and strategies for improving the robustness of MM (e.g., by controlling clock angle to reduce disturbance torques). Finally, SSADCS Software and other SSADCS technologies, namely MM actuators, are undergoing or plan to undergo further technology maturation on several fronts – through Solar Cruiser and other research and development opportunities – before flight.

CONCLUSION

Large solar sails operating in deep space, such as Solar Cruiser, face several unique attitude control challenges that the Attitude Determination and Control System (ADCS) must overcome. Many important lessons were learned, and technologies matured, from the Solar Cruiser mission that are crucial to the success of similar future missions in which Solar Cruiser technology will be infused, including Sun-Earth sub-L1 space weather science and monitoring missions and high-inclination solar observation missions, such as HISM. These future missions will need to overcome the attitude control and MM challenges associated with disturbance torques induced by solar radiation pressure coupled with a non-ideal, deflected sail shape and center-of-mass/center-of-pressure offset, which will grow considerably with increased sail size. Additionally, the large-amplitude, low-frequency flexible body modes of the sail will also worsen, becoming lower and frequency and greater in magnitude, further hindering slewing and pointing capabilities. Finally, larger sails are likely to have even longer-duration deployments that Solar Cruiser, making the tuning of the control system for this transient state more challenging. The simple, traditional control system employed by Solar Cruiser to address all these challenges can be further matured, extended, and scaled to address all these challenges effectively, as has been done for the Solar Cruiser mission. Therefore, Solar Cruiser's attitude control approach, and lessons learned from its development, establishes a state of the art of high value to future solar sail missions and other small spacecraft with large deployable structures operating in deep space.

ACKNOWLEDGEMENTS

The authors would like to thank the Solar Cruiser Project for the opportunity to perform this exciting work and for providing the funding with which it was completed and this paper was written. Thanks to Redwire Corp. and ATA Engineering for the solar sail design and modeling inputs used in the sail shape analysis. Thanks to NeXolve Holding Company, LLC, for providing technical data on the sail membrane and RCDs used in the SSADCS team's modeling and analysis. Thanks to Blue Canyon Technologies, Inc. for the design and modeling inputs related to the bus-mounted sensors and actuators. Thanks to MSFC/ES22 for providing the flexible body dynamics models and graphical depictions used in the SSADCS analyses and this paper. Thanks to the NEA Scout project, and especially the NEA Scout Guidance, Navigation, and Control team for the knowledge they passed down and previous modeling, analysis, and software work that was used as a starting point for Solar Cruiser SSADCS. Finally, thanks to all former SSADCS team members, including interns and detailees, and those Marshall Space Flight Center engineers who worked on or provided inputs to models and software tools used by the SSADCS team.

APPENDIX: ACRONYMS

Table 5. Glossary of Acronyms

Acronym	Meaning
ADCS	Attitude Determination and Control System
AMT	Active Mass Translator
BIU	Bus Interface Utility
CSS	Coarse Sun Sensor
CTE	Coefficient of Thermal Expansion
FEEP	Field Emission Electric Propulsion
FSW	Flight Software
HISM	High-Inclination Solar Mission
IFM	Indium FEEP Microthruster
IMU	Inertial Measurement Unit
KF	Kalman Filter
L1	(Sun-Earth) Lagrange point 1
LPF	Low-Pass Filter
MM	Momentum Management
NEA	Near-Earth Asteroid

PDLC	Polymer-Dispersed Liquid Crystal
PID	Proportional-Integral-Derivative
RCD	Reflectivity Control Device
RW	Reaction Wheel
RWA	Reaction Wheel Assembly
SEL	Sun-Earth Line
SIA	Sun Incidence Angle
SSADCS	Solar Sail Attitude Determination and Control System
TDM	Technology Demonstration Mission
TPM	Technical Performance Measure

REFERENCES

[1] Johnson, L., Everett, J., McKenzie, D., Tyler, D., Wallace, D., Newmark, J., Turse, D., Cannella, M., Wilson, J. and Feldman, M. The NASA Solar Cruiser Mission – Solar Sail Propulsion Enabling Heliophysics Missions. 36th Annual Small Satellite Conference. 2022.

[2] Tsuda, Y., Mori, O., Funase, R., Sawada, H., Yamamoto, T., Saiki, T., Endo, T., Yonekura, K., Hoshino, H., & Kawaguchi, J. (2013). Achievement of ikaros — japanese deep space solar sail demonstration mission. *Acta Astronautica*, *82*(2), 183–188. https://doi.org/10.1016/j.actaastro.2012.03.032.

[3] Johnson, Les & Whorton, Mark & Heaton, Andrew & Pinson, Robin & Laue, Greg & Adams, Charles. (2011). NanoSail-D: A solar sail demonstration mission. Acta Astronautica. 68. 571-575. 10.1016/j.actaastro.2010.02.008.

[4] Spencer, D. A., Betts, B., Bellardo, J. M., Diaz, A., Plante, B., & Mansell, J. R. (2021). The lightsail 2 solar sailing technology demonstration. Advances in Space Research, 67(9), 2878–2889. https://doi.org/10.1016/j.asr.2020.06.029

[5] Orphee, J., Diedrich, B., Stiltner, B., Becker, C., & Heaton, A. Solar Sail Attitude Control System for the NASA Near Earth Asteroid Scout Mission. International Symposium on Solar Sailing. No. M17-5741. 2017.

[6] L. Rios-Reyes and D. J. Scheeres, “Generalized Model for Solar Sails,” Journal of Spacecraft and Rockets, Vol. 42, Jan. 2005, pp. 182–185, 10.2514/1.9054.

[7] Murray, Joseph & Ma, Dakang & Munday, Jeremy. (2016). Electrically Controllable Light Trapping for Self-Powered Switchable Solar Windows. ACS Photonics. 4. 10.1021/acsphotonics.6b00518.