Momentum Management Strategies for Solar Cruiser and Beyond (ISSS 2023)

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Abstract

Solar Cruiser is a small (ESPA-class) satellite Technology Demonstration Mission (TDM) to mature solar sail propulsion technology using a solar sail larger than 1600 square meters, demonstrating performance both 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). To ensure attitude control throughout the mission, momentum accumulated on the reaction wheels (RWs) used for attitude control must be managed such that the sailcraft does not lose control due to RW momentum saturation. Momentum builds up on the wheels from environmental disturbance torques caused by solar radiation pressure combined with a center of mass (CM)/center of pressure (CP) offset, deformed sail shape, and an off-sun pointing angle, plus other factors. Solar Cruiser mitigates this momentum build up by utilizing an Active Mass Translator (AMT) that maintains pitch and yaw momentum by trimming the CM/CP offsets, and thrusters to maintain roll momentum. A survey was conducted by the Solar Cruiser team to assess the feasibility and tradeoffs of novel momentum management concepts such as Reflectivity Control Devices (RCD's), different thruster configurations, and control vanes and other articulated control surfaces. In addition, techniques to reduce disturbance torque buildup, such as reducing boom tip deflections and clock angle control, were assessed. Similar sailcraft momentum management strategies can be used for future missions such as space weather monitoring and Earth magnetotail science missions.

Keywords: Solar Cruiser, Momentum Management, GNC, ADCS

Nomenclature

ACC	Active Clock Control
AMT	Active Mass Translator
ADCS	Attitude Determination and Control System
GNC	Guidance, Navigation, and Controls
L1	Sun-Earth Lagrange Point 1
RCD	Reflectivity Control Device
RCS	Reaction Control System
RCD	Reflectivity Control Device
SIA	Sun Incidence Angle

1. Introduction

The need for momentum management system integrated with the ADCS is crucial for the success of solar sail missions as once the control actuators become saturated, the sailcraft loses control. NASA's Solar Cruiser utilizes four reaction wheels as the primary control actuators for controlling roll, pitch, and yaw attitudes. Disturbance torques build up because of different environmental factors and sail shape. For pitch and yaw momentum management, Solar Cruiser utilizes an AMT to trim the CM/CP alignment and create a restoring moment to desaturate the wheels. For roll momentum management, the baseline Solar Cruiser design features RCDs and RCS thrusters which create an opposing moment to desaturate the reaction wheels. An additional study after Solar Cruiser PDR was completed investigated alternative roll momentum management techniques such as control vanes.

The ADCS configuration of Solar Cruiser is seen in Figure 1. The RCDs are laid upon as part of the sail membrane and are deployed as part of the sail deployment sequence. The AMT is part of the Solar Cruiser satellite bus along with the RCS thrusters denoted on the figure as IFMs.

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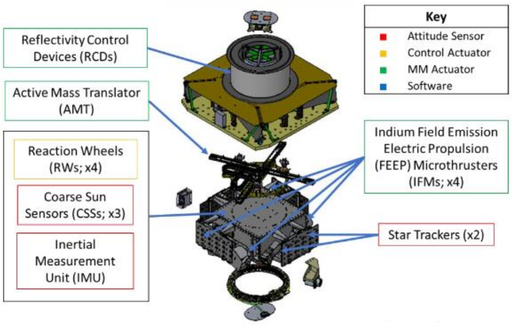


Fig. 1. ADCS Configuration of Solar Cruiser [1]

Solar Cruiser's overall mission is to serve as demonstration mission for solar sailing technology in a sub L1 halo orbit, then demonstrate a plane change maneuver to raise the orbit above the Earth's orbital plane after completion of the primary mission phase. Solar Cruiser features Heliophysics scientific instruments and will also serve as demonstration mission for technologies key for larger future solar sail missions such as the RCDs and AMT.

2. Disturbance Torques

The primary design driver for MM systems, especially the sizing of MM actuators, is the disturbance torques experienced by the sailcraft, dominated by those originating from the solar radiation pressure (SRP) on the sail. Given the amount of uncertainty inherent in these SRP-derived disturbances, detailed and conservative modeling of this effect was implemented on Solar Cruiser, as is advisable for other solar sail missions [1].

The SRP-induced disturbance torque is the sum of the CM/CP offset torque and the net applied torque due mainly to a deformed (i.e., non-flat) and asymmetric sail shape. For given sail size, optical properties, and distance from the sun, these torques are only a function of sun-incidence angle (SIA) and clock angle (assuming an anisotropic shape, such as a square sail). SIA and clock angle are the second and third Euler rotations, respectively, in a Z→Y→Z rotation sequence, where Z is normal to the sail plane facing toward the sun. Effectively, SIA is the half-cone angle of the sun with respect to the sail normal and the clock angle orients the SIA axis of rotation relative to the sail body.

The CM/CP offset torque can be broken into two components: a specular effect caused by the normal component (specular reflection) of the net force to the sail applied at a moment arm in the sail plane and a diffuse effect caused by the tangential component (diffusive reflection) of the net force. The specular effect can be a considerable contribution to pitch/yaw disturbance torques (i.e., those applied about the in-plane axes, X and Y, of the sail) and has been traditionally used to size actuators [2]. The diffuse effect is a result of light scattering upon reflecting at a non-zero angle of incidence on a realistic sail with some degree of diffusivity. According to the McInnes solar sail force equations, the specular effect monotonically decreases in magnitude with the cosine squared of SIA, whereas the diffuse effect varies with the product of the cosine and sine, peaking at 45 degrees, and can result in both pitch/yaw and roll (about sail normal) disturbance torques [3]. Therefore, for realistic sails without perfect specular reflection, even perfectly flat sails, care must be taken to ensure adequate 3 axis control for mission attitude profiles that require considerably large SIAs nearing 45 degrees.

$$\vec{\tau}_{\frac{CM}{CP}} = \vec{r}_{\frac{CM}{CP,in-plane}} \times \vec{F}_{specular} cos^2(SIA) + \vec{r}_{CM/CP} \times \vec{F}_{diffuse} \cos(SIA) \sin(SIA) \tag{1}$$

In addition, the shape of the sail can cause applied torques at the CP, independent of CM location. The net applied torque is a result of the imbalance in local torques applied across the sail due to varying local SIAs. This effect can be modeled using a mesh model and calculating and summing the forces and torques applied at each element, as if the sail consists of many smaller sails with slightly different SIAs, or by using a reduced-order model, such as the Rios-Reyes generalized sail tensor model, to represent the problem in a more computationally efficient manner, as is done on Solar Cruiser [4]. The sail shape-induced disturbance torques can be relatively large in all axes, generally dominating the disturbance torques about the roll axis, and highly variable with SIA and clock angle, given some anisotropy in the shape (square sail and asymmetric shape deformations). Figures 2 and 3 shows a graphical representation of the summation of disturbance torques.

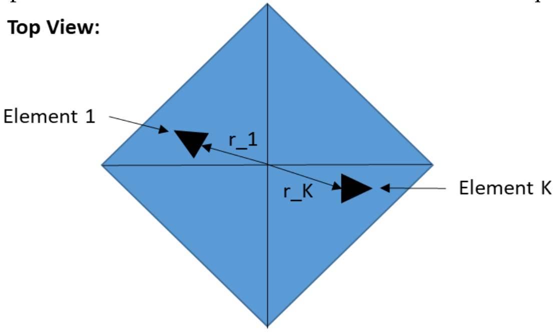


Fig. 2. Elements of a sail membrane

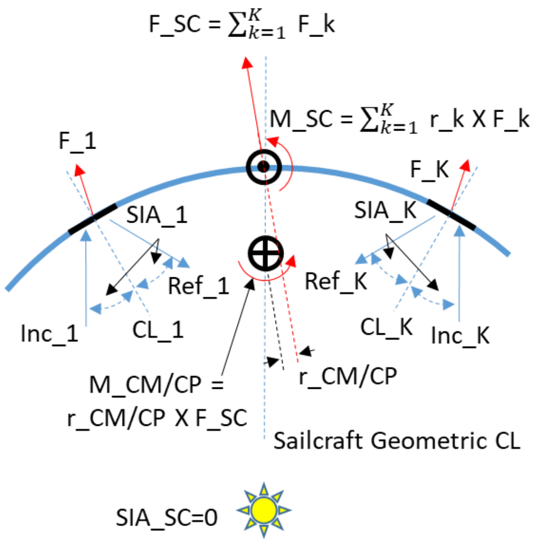


Fig. 3. Disturbance torque analytical model

Combining all these effects together leads to a complex disturbance torque “profile” as a function of several mission and system design parameters. Figure X illustrates the effect various sources of disturbance torques has on the overall profile. The different features of this profile have different impacts on the selection, sizing, and design of MM systems. E.g., a large CM/CP offset torque, especially a large specular component, may make use of a CM/CP control actuator, such as an AMT, favorable. Or large asymmetric shape deformations that make disturbance torque highly variable with clock angle may drive the use of constraints on, or control of, clock angle for the purpose of minimizing torques. The logic and considerations for these kinds of design decisions is further discussed in following sections. Graphs of the largest disturbance torque models for Solar Cruiser are shown in Figures 4 and 5.

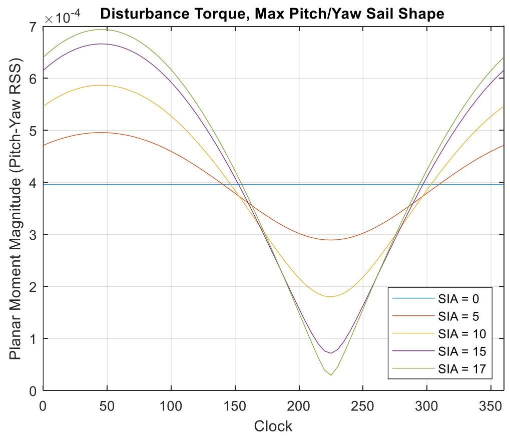


Fig 4: Max Pitch/Yaw Disturbance Torques

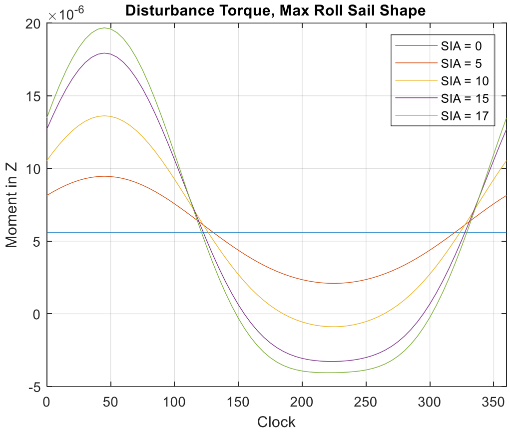


Fig 5. Maximum Roll Disturbance Torque

3. Pitch and Yaw Momentum Management

Torque on a solar sail consists of two components, one from the 3-dimensional shape of the sail and the other from the sailcraft CM crossed with the sail force. For pitch and yaw control, the displacement of the CM in the plane of the sail directly results in torques in those axes that can be used for momentum management about those axes.

Solar Cruiser, like the Near Earth Asteroid (NEA) Scout solar sail mission before it, was developed to use an Active Mass Translator (AMT) to change the CM/CP offset of the sail for pitch/yaw momentum management of the RWs. The effectiveness of this technique depends on the sailcraft having large bus mass relative to the sail (>= ~1:1 ratio) and range of motion from the mass translation actuators, which the Solar Cruiser design is well suited to.

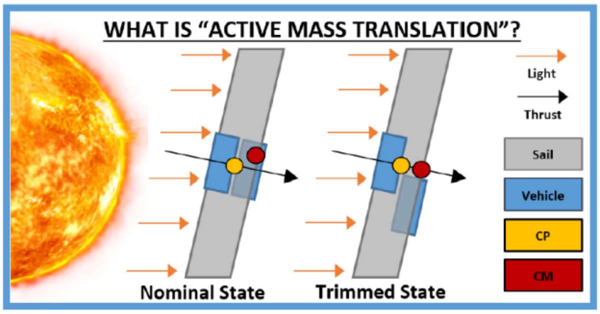


Fig 6: AMT Trimming the Sailcraft (5)

The displacement of the CM in the trimmed satellite can be seen in Figures 6. The differences in CM and CP create a restoring moment on the torque axis to desaturate the reaction wheels and can also be used to find a neutral state to prevent buildup of momentum in the sailcraft. Figure 7 shows the control method for the AMT.

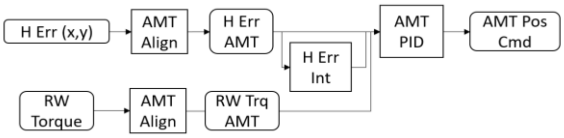
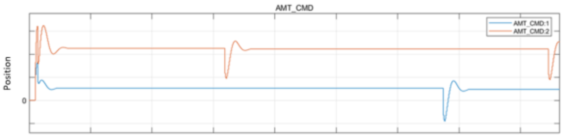
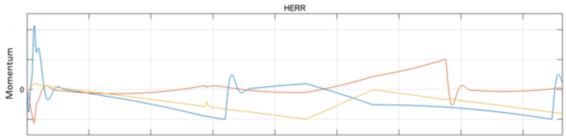


Fig 7: AMT Control System (1)

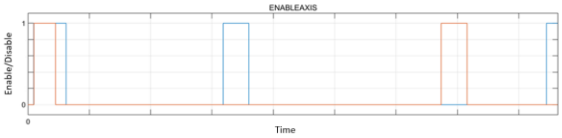
The controller is designed to help move the AMT to desired position where it will actively desaturate the wheels. A demonstration of the AMT control in the Solar Cruiser GNC simulation is shown below:



(a) AMT Position Command



(b) Pitch/Yaw Momentum Error



(c) AMT Axes On/Off States

Fig 8: AMT Simulated Example

As the AMT moves, it changes the center mass which can be seen as the AMT is commanded to different positions and lead to decreasing in overall momentum error per axis. The red color refers to the pitch axis, blue color represents the yaw axis, and yellow represents the roll axis. Each movement of the AMT can betide to a decrease in momentum in each given axis.

However, sail designs with a small bus mass or difficult moving the CM would require other methods like vanes, shape deformation, or optical property control at the edges or corners of the sail to change the pitch/yaw torque.

4. Survey of Roll Momentum Management

As part of the development for Solar Cruiser, a survey of different actuators for roll momentum management was conducted. These methods include utilizing RCS thrusters, a novel RCD, control vanes, and active roll management control of the system. Each of these design trades focused on trade space of the effectiveness of the design, technical maturity, and integrated system analysis.

The baseline design of Solar Cruiser features RCDs as the primary roll momentum desaturation actuator and IFM RCS thrusters as a backup option with active clock control to minimize disturbance torque buildup during long periods of attitude hold.

4.1 RCD

RCDs are innovative devices that are selected as baseline to perform roll momentum management for solar cruiser. The IFM thrusters are back-up actuators in case of RCDs underperformance. The functionality of RCDs have been made possible by a new generation of electroactive polymer-dispersed liquid crystal (PDLC) material. When a voltage is applied to the RCD panel, the PDLC material changes reflectivity. The molecules in the PDLC material are randomly oriented and the RCDs are reflective when no voltage is applied. However, with applied voltage, the PDLC molecules are reoriented, and the RCDs becomes transmissive and active. Multiple RCD coupons are mounted as a panel with a tent angle near the sail boom tips. 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. To determine whether Counterclockwise (CCW) or Clockwise (CW) moment must be applied, a controller logic is designed for RCDs (Figure 9).

Reaction wheels are Solar Cruiser’s main control actuators for all phases of the mission. As momentum accumulates on the wheels and there is a need for desaturation, ADCS algorithms will perform MM using the available MM actuators on the sail. Once the sail is deployed, RCDs are the main roll MM actuators. At a very high level, to perform moment management, RCD controllers deactivate when the momentum, H Err, drops below a set deactivation threshold, and reactivate when momentum increases above an activation threshold. Figure 10 shows RCDs are triggered when the roll momentum accumulation on reaction wheels increases above the activation threshold. RCDs apply moment in the CW or CCW direction to decrease the momentum until it is lower than deactivation threshold.

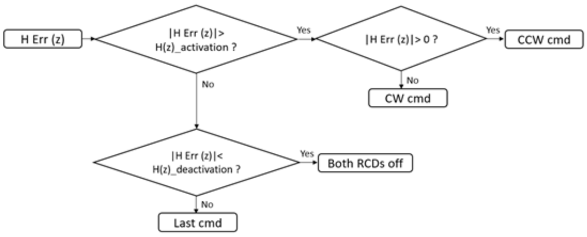


Fig 9. RCDs Roll Momentum Controller (1)

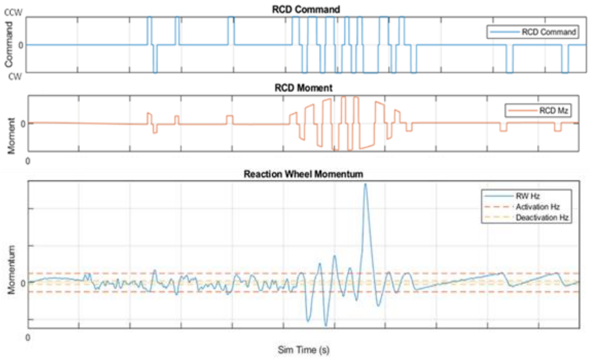


Fig 10. RCDs roll momentum controller performance

4.2 *RCS*

The IFM RCS thrusters as part of Solar Cruiser design for as backup in case the RCDs do not perform as desired. The design space is similar to RCDs with the SSADCS having activation and deactivation thresholds to keep the roll momentum within desired thresholds. An example of the IFM thrusters being used for momentum management can be seen in Fig 11.

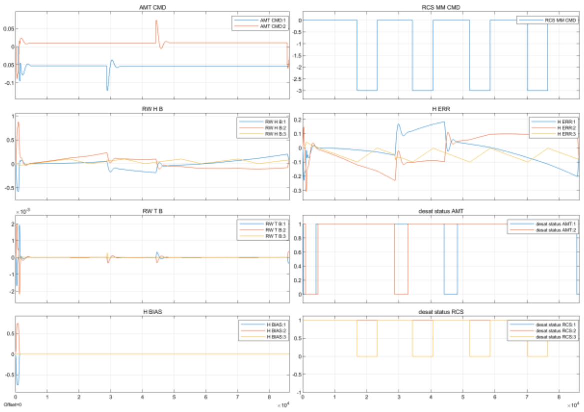


Fig 11. IFM RCS Roll Momentum System in Action

In Fig 11, it's possible to activation points for the IFM RCS thrusters. The design of the RCS control system is like the RCDs where a desired activation and deactivation threshold are defined, and it induces an opposing moment to decrease the momentum build up on the reaction wheels.

With RCS thrusters, there are some system wide challenges introduced as part of it. These include sizing the propellent tank to account for all the momentum dumping burns, and power and thermal constraints for firing the thrusters at different intervals and how long for the thrusters to fire. These efforts must be coordinated with other subsystems

4.3 *ACC*

Another option that can be used in conjunction with other design actuators is implementing an ACC as part of the ADCS algorithms. This implementation controls the clock angle of the sailcraft to minimize roll momentum buildup. Additionally, this method can be used in conjunction with the pitch/yaw channels to minimize momentum build up. This method has the advantage of being able to use existing control actuators to implement this momentum management strategies and supplement other methods.

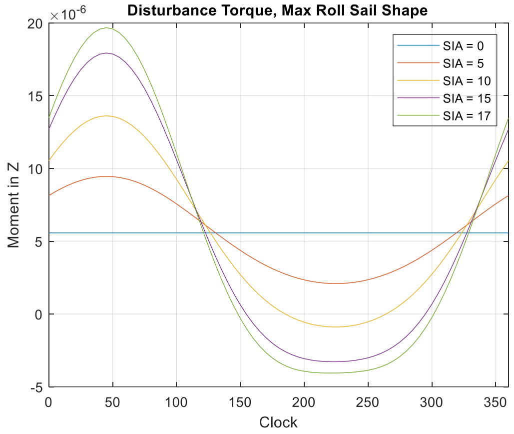


Fig 12. Maximum Roll Disturbance Torque

These figures 12 was generated to represent the worst-case disturbance torques would look with different SIA angles and sail shapes contributing to differences in magnitude of disturbance torques. If a zero crossing exists at the sailcraft SIA's as shown in Fig 12, it enables the active roll controller to utilize that zero crossing to have a set angle offset to desaturate the reaction wheels during periods of attitude hold.

The ACC works by observing the torque build up on the reaction wheels and takes a pre-designated step in the direction to offload the momentum build up. These steps take effect over extended periods of time as the roll momentum buildup is a slow process and if the ACC acts too quickly, it might interfere with flex modes of the spacecraft. A flow diagram of this control process is seen in Fig. 13.

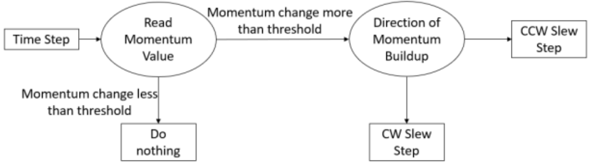


Fig 12. ACC Algorithm Flow Chart

However, if the roll disturbance torques do not have a zero crossing, the active roll controller focuses on minimizing the disturbance torque build up on the sailcraft as indicated by the local minimums. To best manage roll momentum levels utilizing ACC, other momentum management actuators for the roll channel must be used due to the lack of guarantee for a zero-crossing.

4.4 Control Vanes

Attitude control using solar radiation pressure was first proposed by Sohn in 1959 [6]; and since then, the use of solar radiation pressure to perform attitude control has been studied extensively in references 7-12, not an exhaustive list. The use of solar pressure for attitude control was implemented on geostationary satellites as well as interplanetary, including OTS, TELECOM 1, IMMARSAT, INSAT and GOES satellites [12].

The principle of a control vane is fundamentally the same as the solar sail, that reflecting photons that generate an equal and opposite momentum. Satellites have used solar pressure to control attitude by gimbaling solar panels or reflective trim tabs, as control vanes, to generate solar torques needed to control attitude dynamics. Control vanes at the tip booms would scale with sail size by taking advantage of increased moment arm for an increased solar sail size. Figure 13 shows boom tip mounted control vanes proposed by NASA JPL as early as 1977. Also, boom tip control vanes had been proposed for the NASA Sunjammer mission concept in 2014, later canceled, including development of the control architecture and simulated performance [13].

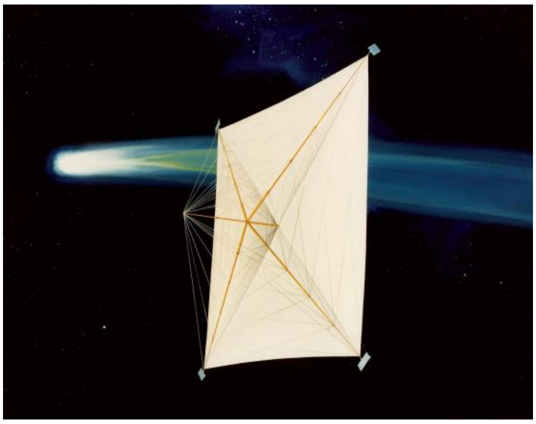


Figure 14: An 800x800-m solar sail proposed by JPL in 1977 for a rendezvous mission with the Halley's comet for the 1986 passage.

However, the challenge with boom tip mounted control vanes for solar sails is not in its fundamental working principles, which are well understood and proven, but on its practical implementation. Storing and deployment of solar sails and booms require the sail and boom structure to be highly flexible to fit the deployer and be capable of recovering its shape after deployment. Therefore, a boom tip vane control mechanism that can be steerable while also flexible to be stored and deployed poses structural design challenges.

Furthermore, a control vane would need a gimbal system and a motor driver. The Motor driver would need power and control commands from the flight computer. The power and command would need to run along boom cables to the spacecraft bus.

Alternatively, power could be generated locally, and control commands may be sent wirelessly from the bus to a local control vane board system. Finally, having control vanes implies having a moving mechanism, which adds a layer of complexity and therefore additional failure modes. Failures could include, inadequate deployment of the control vane, or failure of gimbal and motors mechanisms, which may cause a control vane to remain stuck in an undesirable attitude. Therefore, the challenge of control vanes is not on its fundamental acting principle but on the complexity of its implementation, adding potential failure modes.

5. Comparison of Roll Momentum Management Methods

Each of these different momentum management strategies have different advantages and disadvantages relative to the other systems. These differences can be seen in the table below.

Table 1. Comparison of Roll Momentum Management Methods

Roll Momentum Management Actuator	Advantages	Disadvantages
RCS	Commercial offerings readily available for mission use	Requires mass of the propellent to be carried as well as possible thermal and power constrains from thruster firings, limited fuel which constrains firing time
RCD	Low mass, volume, and power requirements	Low TRL system, Potential RCD degradation over time, Requires wiring and control at RCD location which ideally is near the sail edge

Control Vanes	Proven fundamental principle, high Technology Readiness Level. Scalable with sail size when used at boom tips.	Storage and deployment for tip vanes may be challenging. Additional moving mechanisms including motor and gimbals, which add risk for additional failures modes. Require power and control commanding at boom tips.
ACC	Can be directly implemented into the ADCS design in conjunction with other methods	Potential for no zero-crossing due to sail shape and SIA induced moments

Each solution has unique advantages and disadvantages as individual systems. For example, the control vanes are a high TRL technology on their own and have been proven to be successfully utilized in mission but have challenges with integrating with the sailcraft. RCS thrusters are available commercially-off-the-shelf (COTS) which provide a seemingly simple solution by firing thrusters in the opposite direction to create an opposing moment. Although RCS provides a stable COTS solution, there are some system level challenges faced with RCS such as thermal and power constraints from when firing the RCS as well as sizing a propellent tank to ensure RCS can serve the duration of the mission. RCDs function similarly to RCS thrusters in terms of control systems design where RCDs can contribute opposing moments and similar challenges to control vanes with integrating to the deployed sail surface. However, RCDs offer the advantages of both where RCDs don’t require propellent and could be easier to integrate with a sailcraft versus control vanes. ACC requires no additional hardware as part of the sailcraft and just integration within the GNC design of the sailcraft. However, ACC runs into areas where there isn’t a zero-crossing allowing the ACC to unload the roll momentum.

Understanding each option for roll control is key as one single option for roll momentum management is not sufficient to completely manage the roll axis. The baseline design for Solar Cruiser features RCDs to desaturate the reaction wheels as the primary method, ACC to minimize roll disturbance build up, and RCS as a backup in case RCD performance is not to the level as predicted or any degradation in RCD performance.

6. Conclusions

Momentum management is a critical part to ensure mission success for large sailcraft. Momentum will build up throughout a mission as when a sailcraft slews to desired attitudes to fulfil its mission or holds an attitude. Solar Cruiser utilizes an AMT for the pitch/yaw momentum management and a combination of ACC, RCDs, and RCS for roll momentum management. These systems can be utilized for future similar sized solar sails as well as further investigation into other roll momentum management actuators such as control vanes.

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