Paper No: SSC24-VII-06
Small Satelllite Conference
August 3-8, 2024 Utah State University Logan, Utah

Controls Modeling Approach for Deployment of a Large Thin Structures for Solar Sails

John Inness[1]*, Benjamin Diedrich[2], Brian Valdez[1], Daniel Tyler[1], Brian Sanders[3]

[1] *Marshall Space Flight Center, Huntsville, AL, USA*
[2] *NASA MSFC/ESSCA/Axient Corporation, Huntsville, AL, USA*
[3] *Redwire Space, Longmont, CO, USA*
* Corresponding Author and presenter email: john.p.inness@nasa.gov

Abstract: One of the principal challenges with solar sails is to safely deploy the large sail structures while simultaneously maintaining attitude control. This challenge includes changing moments and products of inertia along with large sail shape uncertainties as it transitions from stowed to the fully deployed shape at the end of the deployment. With these changes, the control system must manage any potential momentum buildup and keep the pointing within mission requirements. The attitude determination and control system team for Solar Cruiser, a 1653 square meter solar sail project out of Marshall Space Flight Center, approached this problem by modelling the nominal moments and products of inertia for different stages of deployment from 10% to 100% in 10% increments. At each step, the inertias were used to generate tuned PID gains, which were used as part of a nominal deployment analysis to prevent unintentional slewing and tumbling. The team created and analyzed off nominal cases, where the moments of inertia and products were changed to induce uncertainties for the control system to manage during deployment. These cases helped verify that the control system can handle off-nominal deployments as well as any uncertainties occurring during deployment of the space sail system. This paper will show this method can be successfully used for modelling solar sail deployments as part of the attitude control system.

Nomenclature

ADCS	Attitude Determination and Control
AMT	Active Mass Translator
IMAP	Interstellar Mapping and Acceleration Probe
KDP-C	Key Decision Point C
L1	Lagrange Point 1
MET	Mission Elapsed Time
MM	Momentum Management
MOI	Moments of Inertia
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
PDR	Preliminary Design Review
PID	Proportional, Integral, Derivative
POI	Products of Inertia
SIA	Sun Incidence Angle
SRP	Solar Radiation Pressure
SSADCS	Solar Sail Attitude Determination and Control System
TRL	Technology Readiness Level

I. SOLAR CRUISER MISSION OVERVIEW

Solar Cruiser was a 1653 square meter solar sail designed to help mature key solar sail technologies to enable future space weather missions utilizing solar sail technologies. The original planned mission scope for Solar Cruiser included 115 days of sailing to maintain a sub L1 orbit followed by an inclination change demonstration. These sailing portions of flight were preceded by a ballistic transfer portion and then sail deployment approximately on day 135 after launch as a secondary payload with IMAP, an upcoming NASA heliophysics mission built by John Hopkin's Applied Physics Laboratory. A detailed overview of Solar Cruiser's planned conops can be seen in the figure below:

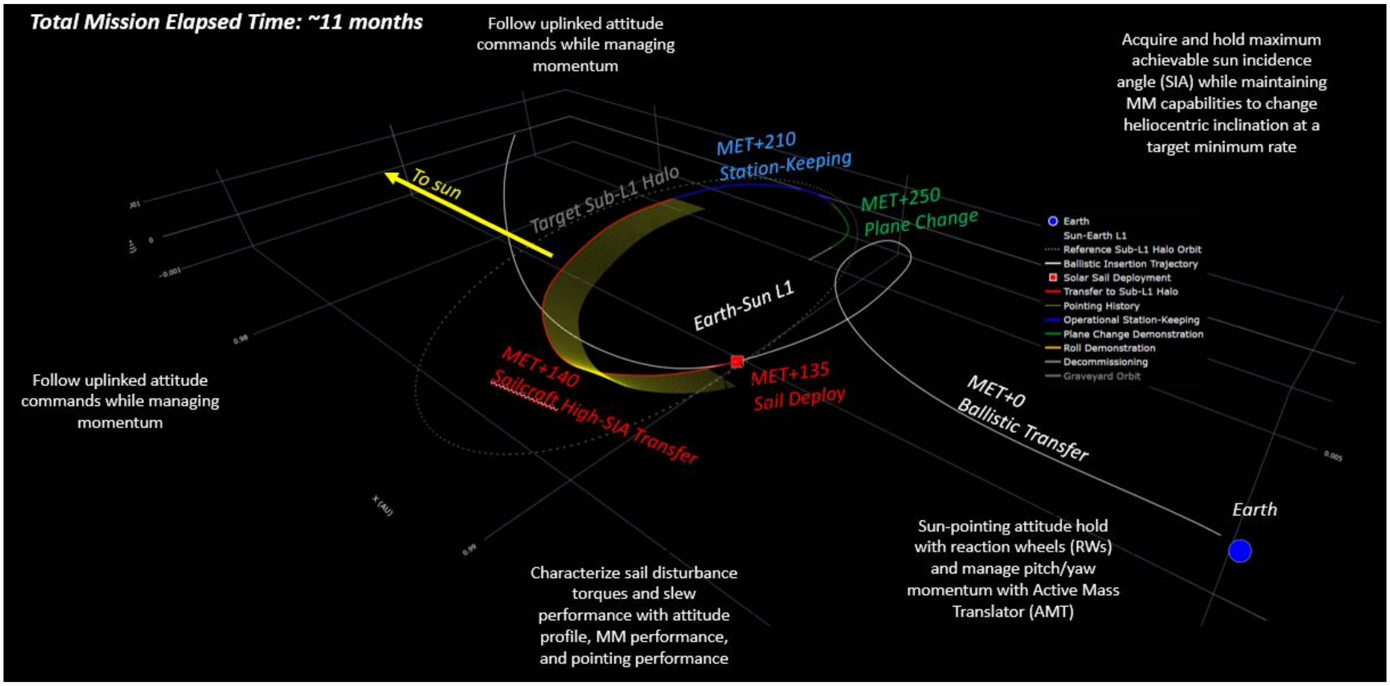


Figure 1. Solar Cruiser Planned Conops

Solar Cruiser successfully passed PDR in summer of 2022 but did not get approved to proceed past KDP-C due a design challenge related to outside of the sail system of spacecraft that slipped Solar Cruiser readiness after the planned launch of IMAP. In the aftermath of the discontinuation of Solar Cruiser, the program was approved to proceed forward with some key tasks to help reduce risk for future space sail missions such as improved sail shape modelling and maturing the sail deployment system to TRL 6. As part of these efforts, the ADCS team worked to improve sail deployment modelling in the control system sim. The sail deployment was one of the most difficult portions of the flight due to rapidly changing moments of inertia and a tight control window.

II. Solar Cruiser Sail Deployment Hardware and TRL 6 Testing

NASA Marshall Space Flight Center (MSFC), in collaboration with Redwire and NeXolve developed a 1,653 m^2 Solar Sail System (SSS) (Figure 2) for the Solar Cruiser mission. The Solar Cruiser team developed key components, including: the Sail Deployment Mechanism (SDM) (Figure 3), high strain composite Triangular Rollable and Collapsible (TRAC) booms and the ~ 413 m^2 thin film sail quadrants. Additionally, an Active Mass Translator provided the Sail Craft the ability to translate the center of pressure relative the center of mass to control the sail craft (1).

Figure 2. Solar Cruiser TRL 6 Demonstration Unit Following Single Quadrant Deployment Testing

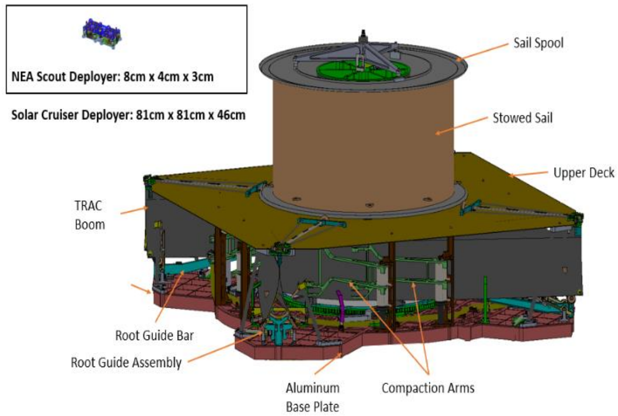


Figure 3. Solar Cruiser Sail Deployment Mechanism

The SDM deploys four 30m long TRAC booms from the center of the 1,653 m^2 Solar Cruiser solar sail. The TRAC booms are carbon fiber reinforced plastic (CFRP) utilizing a laminate architecture referred to high strain composites. A cross section of the TRAC boom can be seen in Figure 4. The SSS was brought to a TRL 6 level of readiness after completing testing and deployment in 2024.

Figure 4. TRAC Boom Cross Section

The concept of operations for the Solar Sail System was designed for the Solar Cruiser Design Reference Mission. The SSS is launch locked to a sail craft bus during launch. After sail craft commissioning, the AMT launch locks are released and the X/Y translation is verified. When the sail deployment location is reach, notionally 100 or so days after launch for the Solar Cruiser Design Reference Mission, the sail deployment is initiated. A single TRAC boom and sail restraint launch lock is disengaged and then the mechanism begins to deploy just under 30m of TRAC booms in approximately 90 minutes. A diagram depicting the AMT mechanism can been seen below in Figure 5.

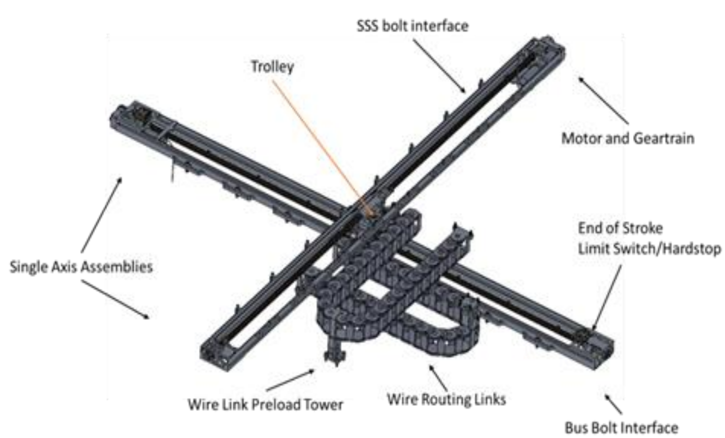


Figure 5. Active Mass Translator

A brushless DC motor drives deployment using an encoder that correlates motor revolutions to boom deployment distance. The information is reported to the sail craft and informs commands to start deployment and stop deployment if issues are encountered. Initially the booms are deployed slowly to disengage the sail restraint cover [1] from around the sail spool at a rate less than 0.5cm/sec. As the deployed length increases to approximately 1m, the deployment rate is increased to a few cm/sec. At any time, the sail deployment can be halted based on sail craft self-monitoring or via ground command. When the TRAC booms approach the final meter of deployed length, the deployment speed is slowed to less than 0.5cm/sec. When the full deployed length is reached, end of travel switches which are activated, and deployment is stopped. Constant force springs attached at the distal end of each boom enable equal loading to each sail quadrant. A picture of the sail spool can be found in Figure 6.

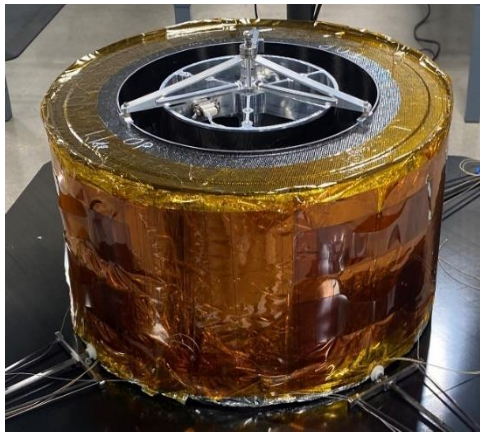


Figure 6. Sail Spool with Sail Restraint

The deployed membrane is a 2.5-microcn-thick Vapor Deposited Aluminum (VDA) Clear Polyimide 1 (CP1) from NeXolve and is 2.5microns thick and has a total mass of nearly 7kg for the four quadrants. The sail is folded in such a manner to allow air to escape from between folds during manufacturing and unfold predictably upon deployment. The solar sail is modeled to predict the membrane stress field and is designed to allow for thermal and solar loading conditions. Additionally, the sail is grounded to prevent charge build up between the sail and bus.

Each sail quadrant is supported distally by two adjacent TRAC booms with constant force springs at those interfaces to provide an equal and known load. The nearly right-angle corner of each quadrant closest to the sailcraft has a two meter diameter circular opening that is interconnected with adjacent quadrant openings to form a hoop around the sail craft which connects all quadrants [1]. A complete view of the Solar Cruiser SSS deployed can be seen in Figure 7.

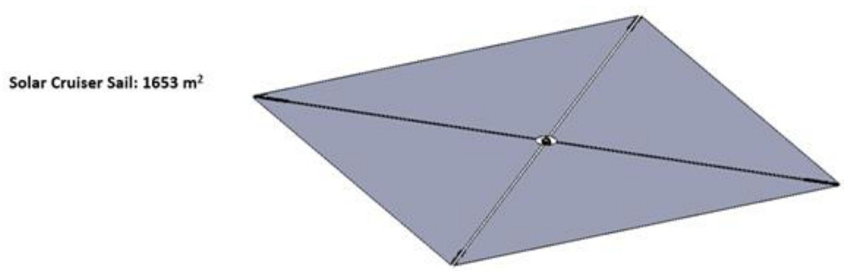


Figure 7. Solar Cruiser Sail Size and Geometry

The SDM, TRAC booms and sail were modeled to understand deployed sail shape and flatness. This modeling effort, and uncertainties, helped to inform the system shape and flatness which drives SSADCS performance. Initial sail characteristics were quantified and where subsequently refined for greater fidelity models during the Solar Cruiser program development.

III. Solar Cruiser Deployment Modeling and Controls Design

The deployment of the solar sail is an especially dynamic event during the Solar Cruiser mission that requires special Attitude Determination and Control System (ADCS) design and analysis considerations. Transitioning between the two more well-defined states of pre- and post-sail deployment, the sailcraft momentarily enters a more nondeterministic state with large uncertainties in system characteristics and behavior. Uncertainties in inertia properties and solar radiation pressure-induced disturbance torques acting on the sail are particularly driving of the ADCS design and performance. In addition, the moments of inertia (MOI) vary by orders of magnitude within minutes, requiring controller gains to vary rapidly in response. Thus, the implementation of a robust controller tailored to the sail deployment mission phase is needed to ensure adequate control is maintained throughout event. The performance of such a controller is measured by the maximum pointing error over the time of deployment relative to the sun-pointing target attitude.

The controller is designed to use telemetry from the Sail Deployment Motor (SDM) that indicates the percent completion of deployment to determine the appropriate controller gains to use for a given partially deployed state. The controller is tuned to optimize performance for point designs for various partially deployed states, using nominal predicted inertial properties, at intervals of 10% of deployment. This approach allows for finer tuning of the controller around local regions of partial deployment states to account for how multiple variables that factor into the system dynamics and controllability – including inertial properties, flexible body dynamics, and disturbances – may vary differently and unpredictably with % deployment. This would make controller robustness difficult to achieve using an alternative method of applying a simple gain scaling law over the entire deployment. A previous iteration of the controller used only one intermediate point design at 50% of deployment completion. The 10% increment design results in marginal performance improvement over the 50% increment design, suggesting that the discretization of 10% is sufficient. Between these 10% increments, gains are scaled according to the magnitudes of the MOIs to smooth the controller response and provide improved performance in these regions.

The true MOI may be higher or lower in magnitude than the predicted value to which the controller is tuned. There are also products of inertia (POI) that cause the principal axes of inertia to be misaligned with the body axes, resulting in cross-coupling torques. The MOI are modeled as being either above predicted values to stress the responsiveness of the controller, such as sluggishness in arresting rates and returning the sail pointing vector back to the target, or below predicted values to stress sensitivity of the controller, such as degree of overshoot. Thus, the controller must be tuned to provide a balanced response that is neither too aggressive nor too unresponsive to attitude and rate errors to ensure adequate performance for a wide range of possible MOIs. POI are not directly addressed by the controller, but the system is assessed for robustness to POI by varying their magnitude over several simulations. The robustness of the controller is assessed by looking at sensitivity of the pointing accuracy to MOI errors and POI. These value as varied can be seen in Figures 8 and 9.

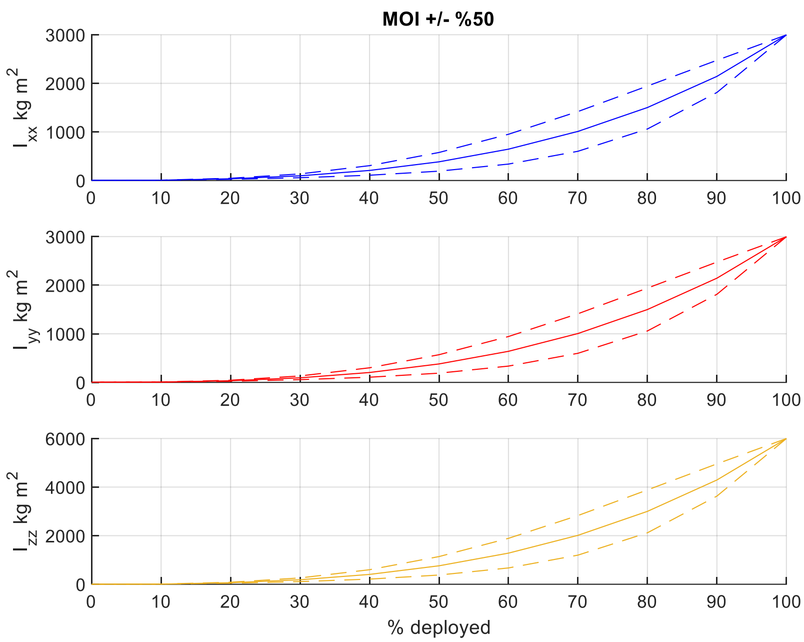


Figure 8. Moments of inertia (nominal and +/- 50%) variation from 0 to 100% deployment

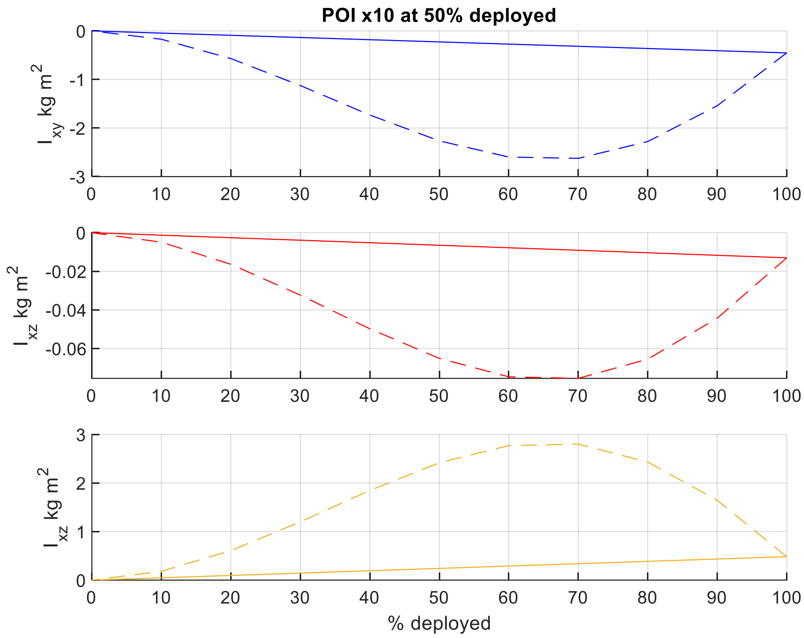


Figure 9. Nominal and 10x products of inertia variations over sail deployment

The solar radiation pressure (SRP) induced disturbance torques, due primarily to sail shape deformations and center-of-mass/center-of-pressure (CM/CP) offsets [2], are scaled from a conservative model of a fully deployed sail proportionally to the area of sail deployed. Although billowing, ripples, and wrinkling in the sail membrane are largely nondeterministic while the sail is in a partially deployed shape, previous sail disturbance torques studies have shown relatively low sensitivity to membrane deflections independent of out-of-plane boom deformations (i.e., deflections along the normal vector of the sail plane) [3]. In addition, thermal gradients, which are the dominant driver for out-of-plane boom deformations, would be small at the start of deployment due to lack of direct radiation heating on one side from the sun while housed in the SDM. Thus, the steady state thermal gradients which drive the sail shape models of the fully deployed sail are bounding of any thermal gradients expected during deployment. Overall, the modeled SRP-induced disturbance torques are expected to be conservative but representative enough to assess ADCS performance and sensitivities.

The control logic is shown in Figure 10. Based on ground commands, the attitude controller receives a command indicating the current spacecraft configuration. When the configuration is Sail Deploy, the controller also takes the sail deployed percentage reported by the sail deployer and uses it to lookup the PID parameters needed to control the sail at that stage. If the configuration is not Sail Deploy, then the controller uses corresponding fixed PID parameters to control the attitude. The parameters include PID gains, filter coefficients, and principal-to-body coordinate transformations.

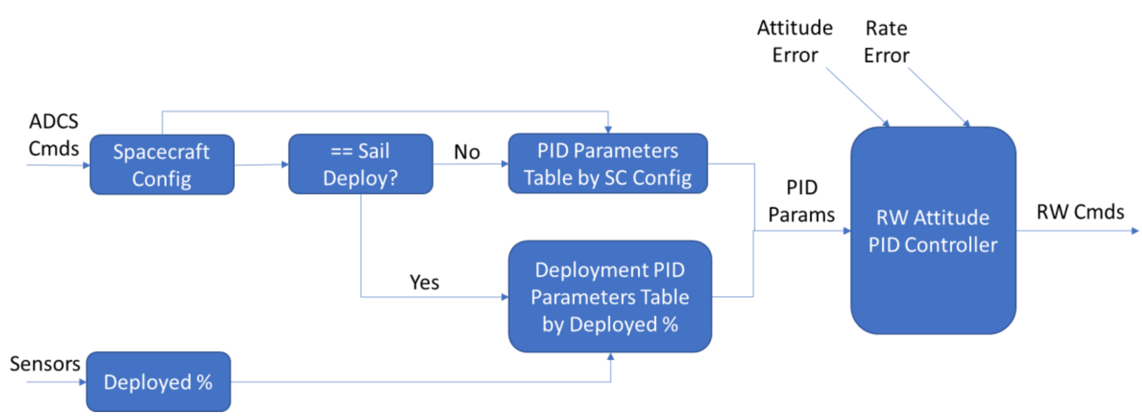


Figure 10. Deployment control logic

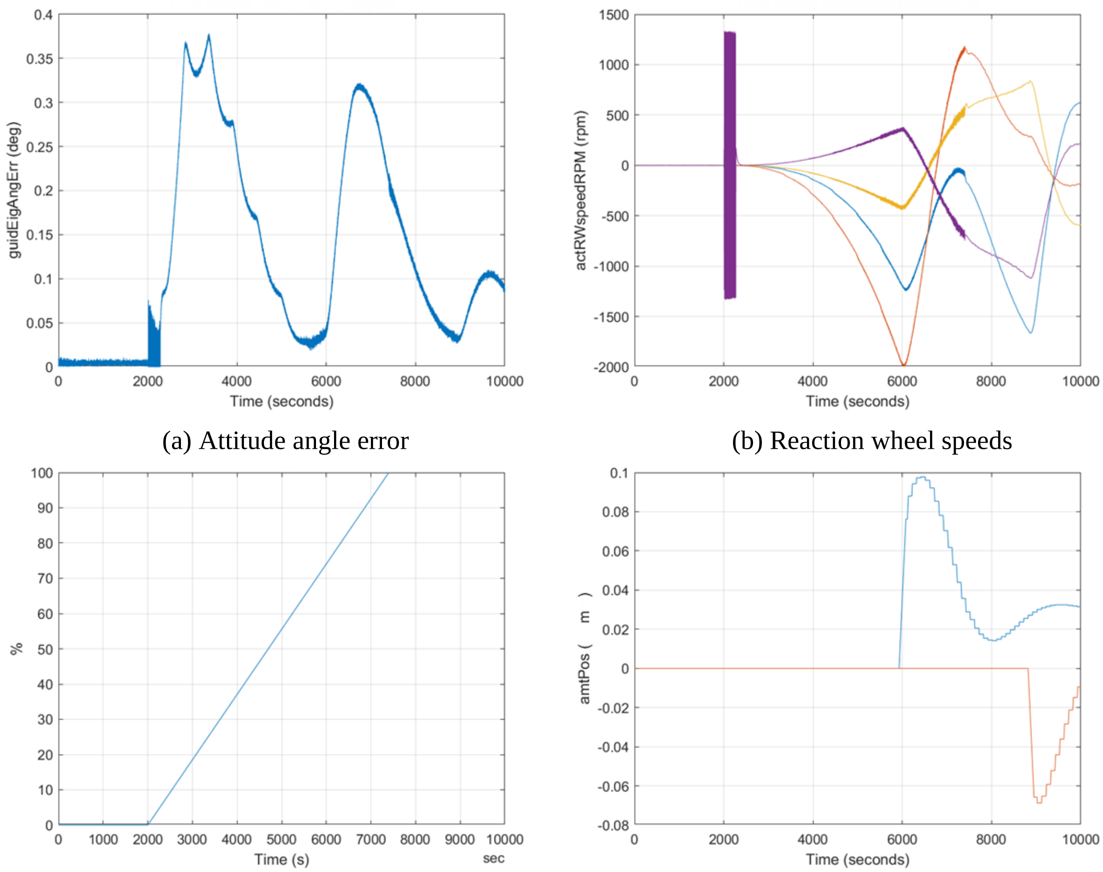
IV. Deployment Control System Results

Simulations of the sail deployment were run with nominal moments & products of inertia compared to those run with high & low moments and high products of inertia. A total of 10 cases were run and are listed in Table *1* to test the ability of the controller to maintain attitude with large uncertainties in the inertia of the sail while it is between stowed and fully deployed. Each listed variation was applied to all the MOIs or POIs. The variations were applied as a sine curve going from 1x at 0% deployment to the indicated factor at 50% deployment, then returning to 1x at 100% deployment.

Table 1: Factors Applied to Inertia Variation Simulations

Factor applied to inertia variation simulation cases
Nominal (1x predicted MOI and POI)
+/- 10% (0.9x & 1.1x) MOI
+/- 25% MOI
+/- 50% MOI
2x POI
5x POI
10x POI

The nominal predicted inertias were used for the first simulation to test functionality of the controller and as a performance baseline. Sail deployment took 90 minutes between 0% and 100% deployment and starts after 2000 seconds to allow the other control system dynamics to settle before deployment starts. At 2000 seconds, the configuration is switched to Sail Deploy and the lookup table gains are used. The results shown in Figures 11, 12, and 13 include some high frequency reaction wheel behavior shortly after the initiation of deployment that quickly settles after ~5% deployment. The rest of deployment goes smoothly with a maximum angle error less than 0.4 degrees. That initial disturbance may require further optimization of the first entry in the PID parameter lookup table.



(a) Attitude angle error

(b) Reaction wheel speeds

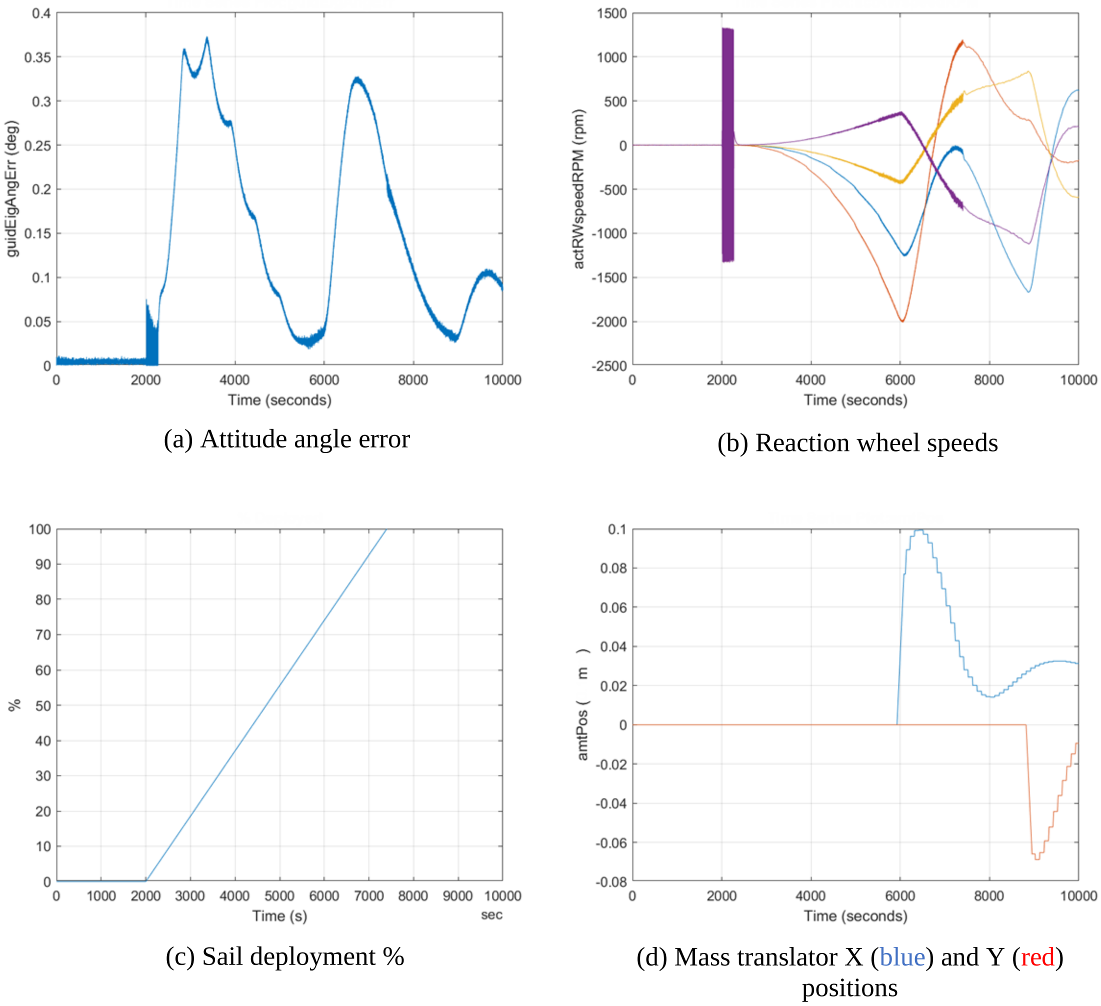
(c) Sail deployment %

(d) Mass translator X (blue) and Y (red) positions

Figure 11. Nominal inertia simulation results

These nominal results show the sailcraft remains under control during deployment. As mentioned earlier, there is some initial disturbance at a high frequency but quickly dissipates as the deployment process continues. The attitude error remains small during deployment and remains within the requirements of the sailcraft system. Additionally, since the sailcraft is in attitude hold during deployment, the AMT translates to trim the sailcraft out to reduce the load on the reaction wheels during deployment. More details on the momentum management system can be found in [2].

Then, simulations were run for the 3 high MOI, 3 low MOI, and 3 high POI inertia variations. Results were very similar to those for nominal inertias, demonstrating an insensitivity to large deviations from the predicted inertia throughout deployment. To illustrate, results for the highest MOI and POI variations are shown. The results for the +50% moments of inertia are shown in Figure 12. The results for the 10x products of inertia are shown in Figure 13.



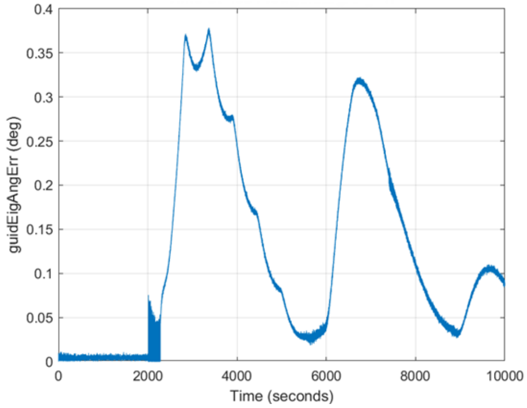
(a) Attitude angle error

(b) Reaction wheel speeds

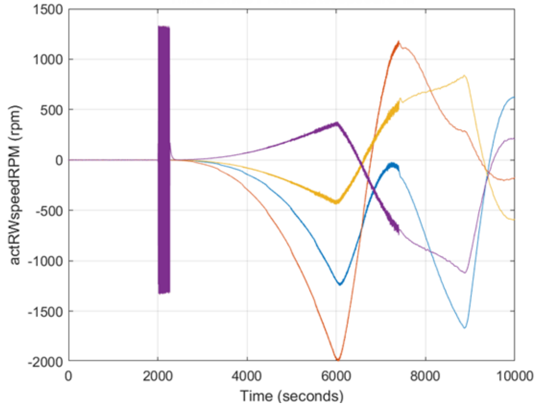
(c) Sail deployment %

(d) Mass translator X (blue) and Y (red) positions

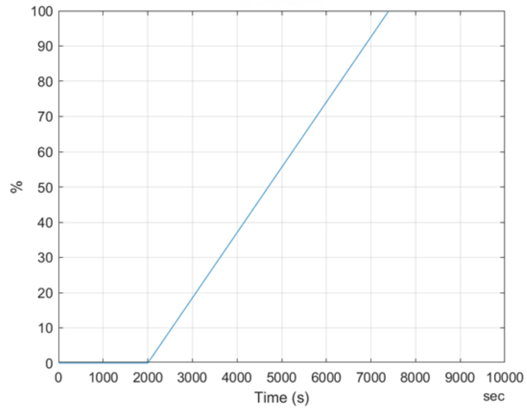
Figure 12. Moments of inertia +50% results



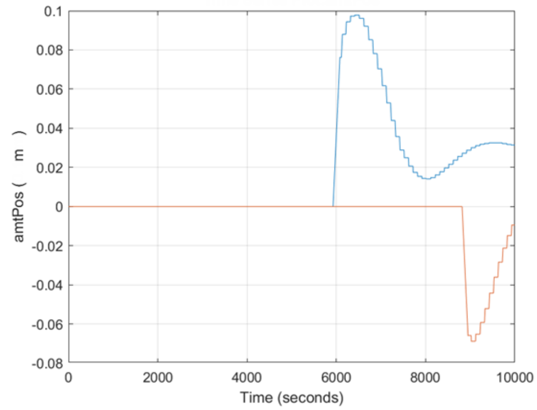
(a) Attitude angle error



(b) Reaction wheel speeds



(c) Sail deployment %



(d) Mass translator X (blue) and Y (red) positions

Figure 13. Products of inertia 10x results

These results with the off-nominal cases with the different moments of inertia and products of inertia shows that the gains scaled for the nominal deployment are robust for off nominal cases. Additionally, these cases remain with a similar attitude error buildup which helps meet the pointing performance requirements for the sailcraft during deployment.

V. Conclusions and Other Applications

These results show that using current modeling techniques, it is possible to deploy a large solar sail (>1600 square meters) while maintaining attitude control of the system. These techniques helped mature the Solar Cruiser ADCS and understanding of deployment, a critical moment during flight. The same methodology that was used for modeling Solar Cruiser deployment can be used for other applications such as large deployable structures such as a lightweight solar array or large deployable antenna. Although Solar Cruiser isn't proceeding to flight, this body of work can help inform future solar sail missions and ensure the sailcraft have controllability during sail deployment.

VI. Acknowledgements

The team would like to acknowledge the Solar Cruiser principal investigator, Les Johnson, and project manager, Leslie McNutt for working to securing funding for continuing work on Solar Cruiser and maturing key portions of Solar Cruiser to bring it closer to flight.

References

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