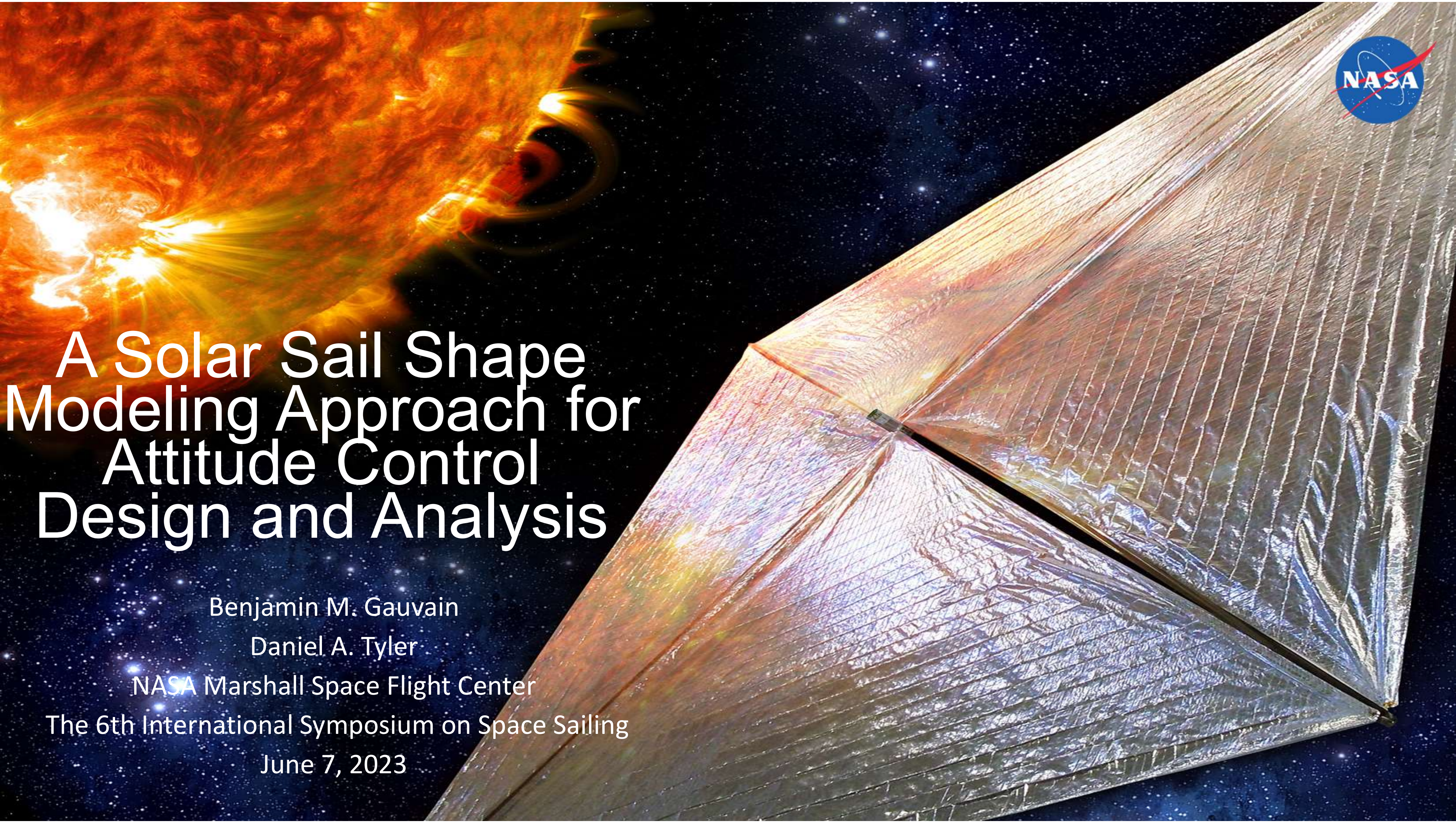

A Solar Sail Shape Modeling Approach for Attitude Control Design and Analysis

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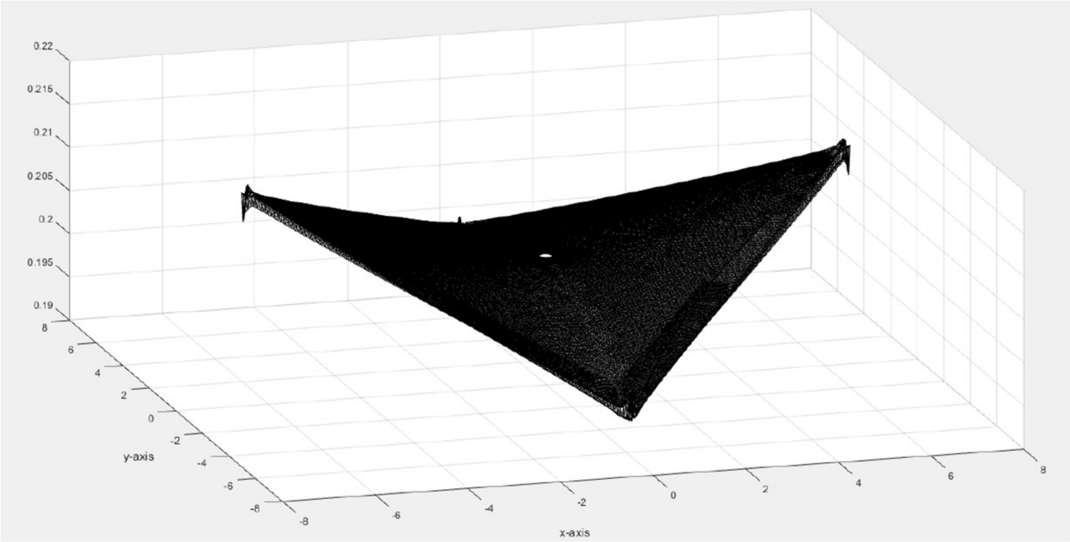
Introduction

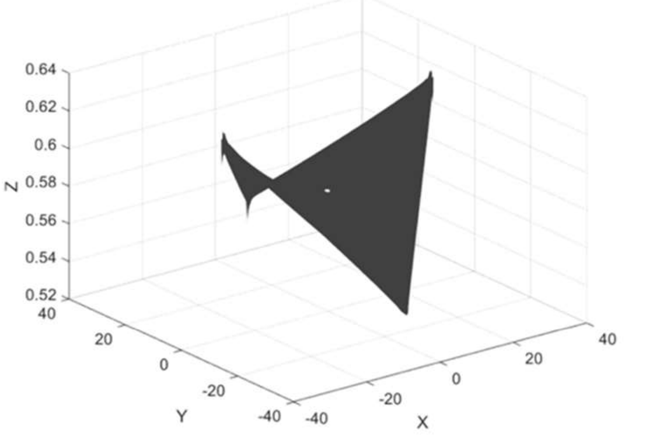
- Solar radiation pressure (SRP)-induced disturbance torques are a major design driver for solar sails, impacting all aspects of the attitude control system, including control and momentum management actuators
- Traditionally, the center of mass (CM)/center of pressure (CP) offset of a flat sail has been the primary metric for predicting disturbance torques [2]
- It was discovered during NEA Scout mission development that deformed sail shape effects were a significant contributor to the overall SRP-induced disturbance torques [3]
    - The strongest determinant of the sail shape is the deflection of each of the four booms
    - A significant known and predictable effect on boom deflections is the thermal distortion caused by the gradient across the booms from the sun-facing side to the space-facing side

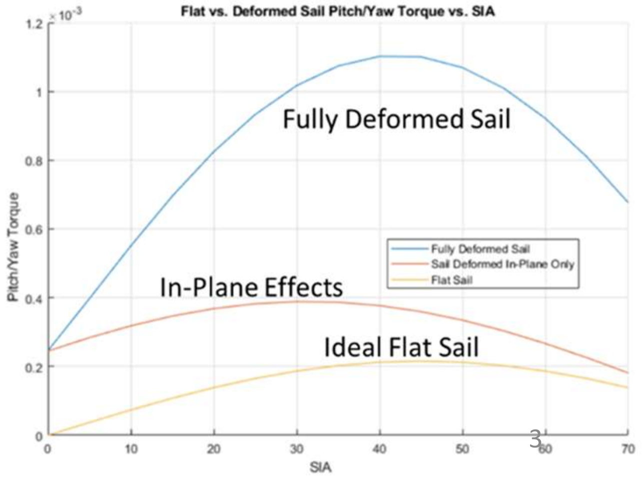


Background: NEA Scout and Solar Cruiser Modeling

- The Solar Cruiser sail modeling methodology derives from NEA Scout [3]
  - Structural FEM created including tension and thermal distortion effects
  - Rios-Reyes/Sheeres generalized sail model [1] numerical implementation
    - FEM with ~66,000 elements transformed into 39 tensor coefficients for force, 45 tensor coefficients for torque
    - Computationally efficient force and torque calculation
- The NEA Scout model was scaled and adapted for Solar Cruiser
- Out-of-plane tip deflections were the biggest driver of disturbance torques
  - Magnitudes >5x than a flat sail of identical dimensions, and >2x for an identical sail with in-plane tip deflections only
- Simple scaling left a lot of uncertainty in its ability to bound the problem, so a higher fidelity methodology was developed for Solar Cruiser

Uniformly-Scaled NEA Scout FEM

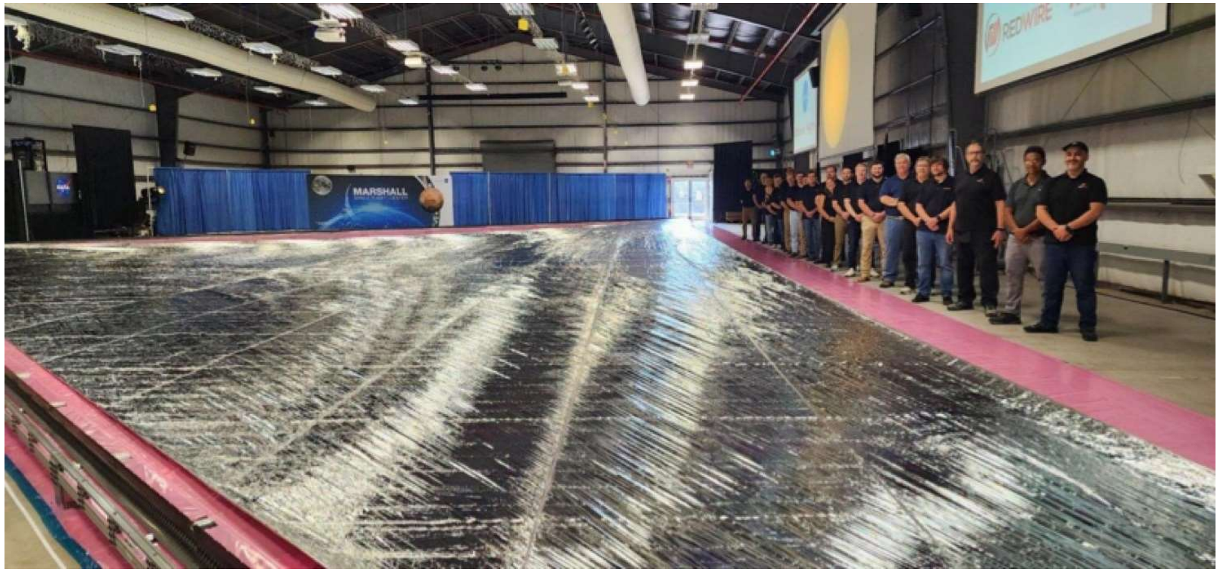




NEA Scout and Solar Cruiser Sail Comparison

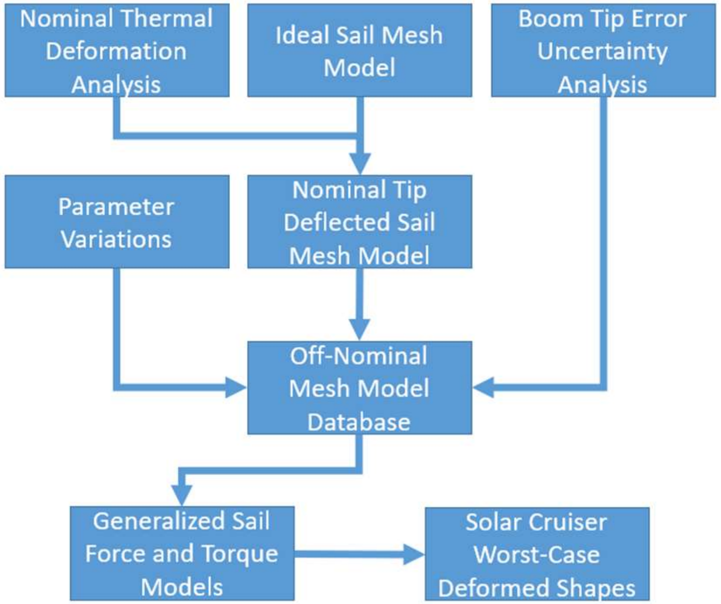
- NEA Scout (~86 m^2)

- Solar Cruiser (~1600 m^2)

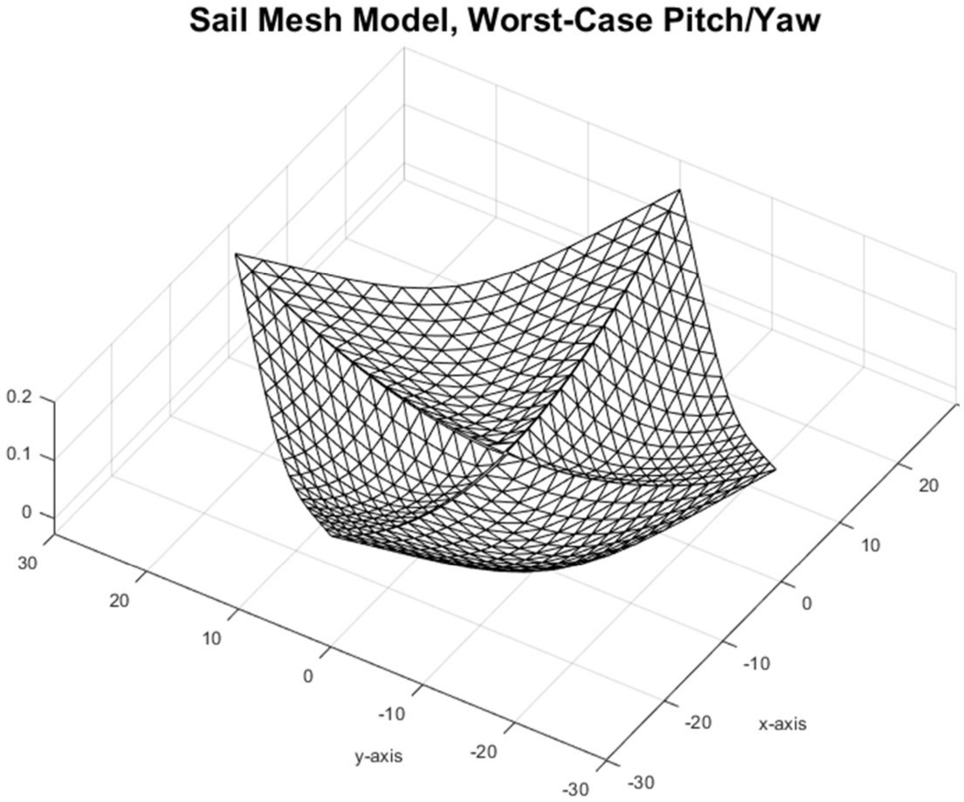


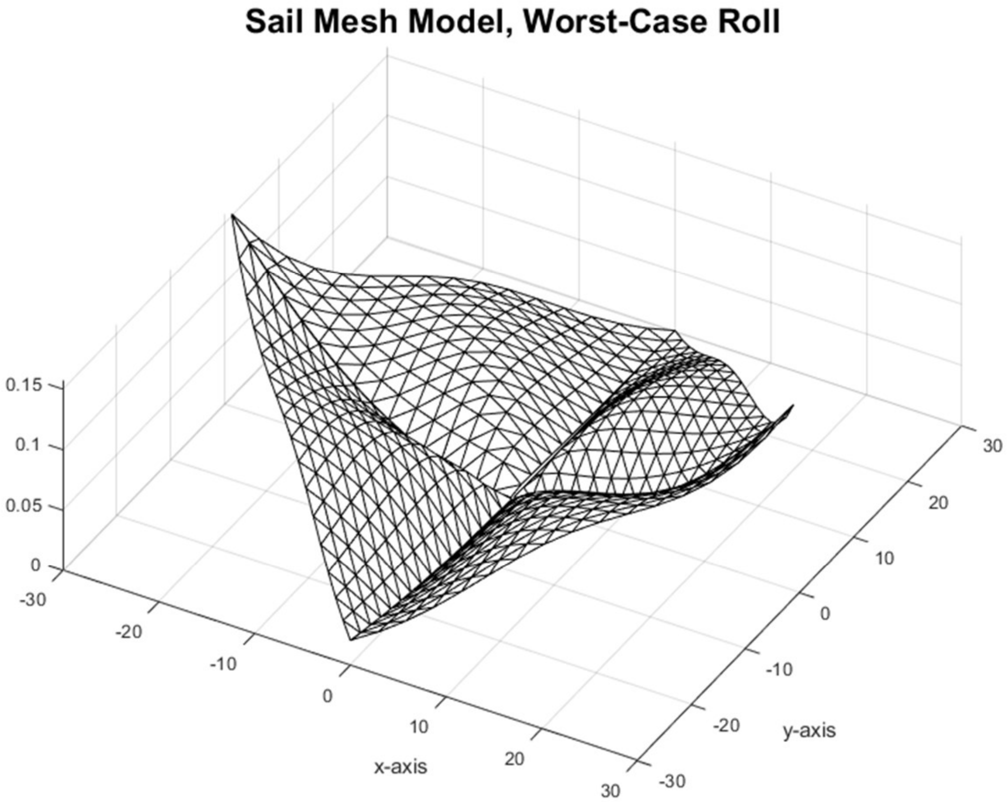
Solar Cruiser Methodology Overview

- Thermal modeling results dictate boom deflections which define the “nominal” sail shape used as a starting point
- Uncertainty/error terms are defined and varied across a large parametric sweep
- The nominal shape is modified for each error term, producing a large database of shapes
- Rios-Reyes/Scheeres generalized sail model [1] process is used to create sail tensors for each shape
- Forces and torques are calculated for each shape across Solar Cruiser mission attitudes
- Force and torque data is post-processed to select two bounding shapes: maximum pitch/yaw (in-plane) torque and maximum roll (out-of-plane) torque



Solar Cruiser Deformed Sail Shapes

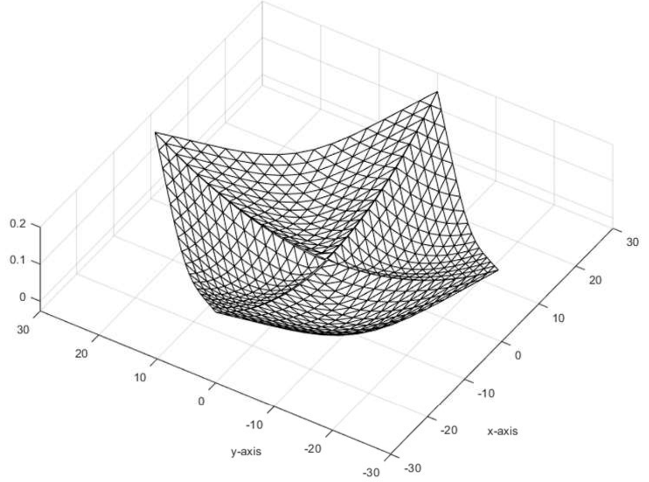




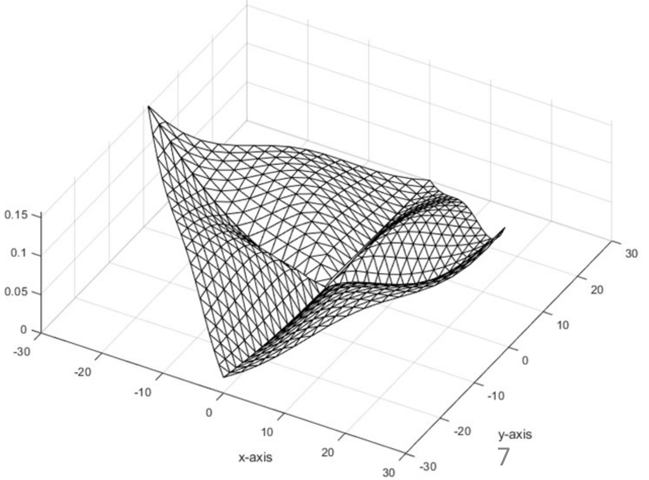
Assumptions and Boundary Conditions

- Booms deflect parabolically, increasing from root to tip
- Membranes deflect according to a “billowing” shape, captured using a 2D sinusoid with maximum deflection occurring at quadrant centroid
- Non-sail membrane surfaces and in-plane deformations or asymmetries are neglected. Wrinkles are not directly modeled but effect is captured through optical properties [3]
- Fixed-fixed boom/membrane interface at the roots and tips without any separation or interference
- Boom tips and sail membranes can deflect out of plane in any arbitrary direction with respect to each other

Sail Mesh Model, Worst-Case Pitch/Yaw



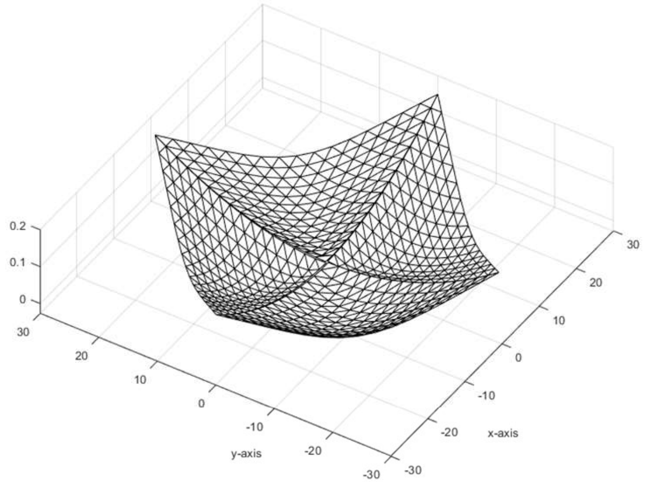
Sail Mesh Model, Worst-Case Roll



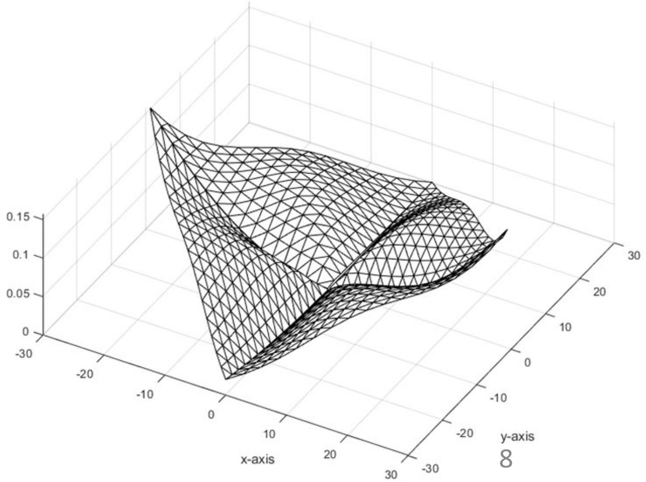
Parameter Descriptions and Variations

- 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.
- Membrane Deflections
  - Out-of-plane, billowing shape with peak/trough at the centroid of each quadrant. The magnitude was varied (0-5cm), and the direction varied in the sail out-of-plane axis.
- 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 varied (0-2x), and the direction varied in the sail out-of-plane axis.
- Center of Mass Offsets
  - The difference in the center of mass in-plane position relative to the designed geometric center, due to manufacturing and assembly tolerances (0-2cm).
- Attitude
  - SIA varied from 0 to 17 degrees (Plane Change Demonstration mission target) and clock angle varied from 0 to 360 degrees.

Sail Mesh Model, Worst-Case Pitch/Yaw

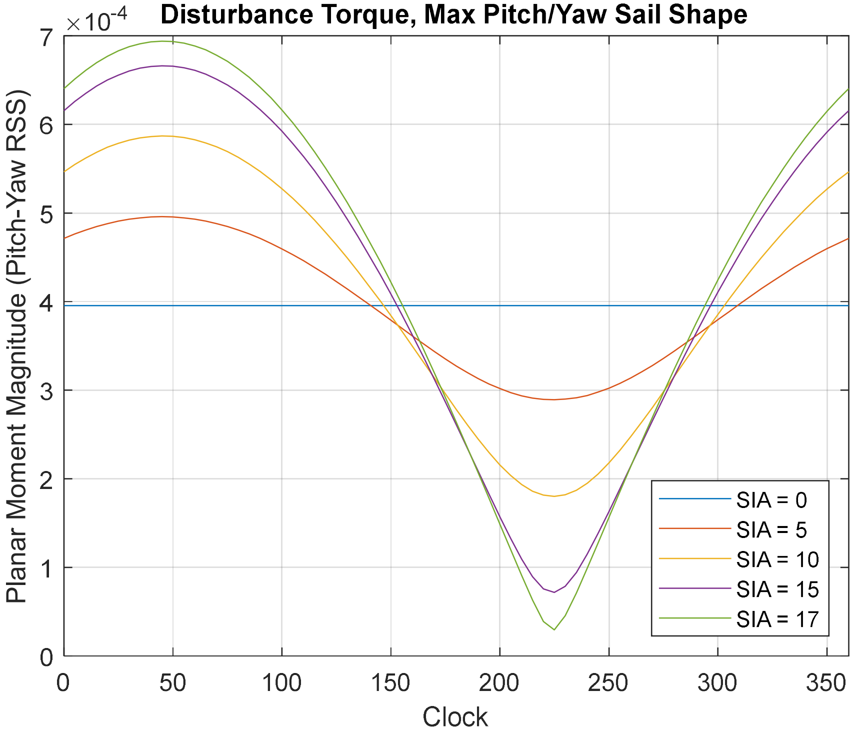


Sail Mesh Model, Worst-Case Roll

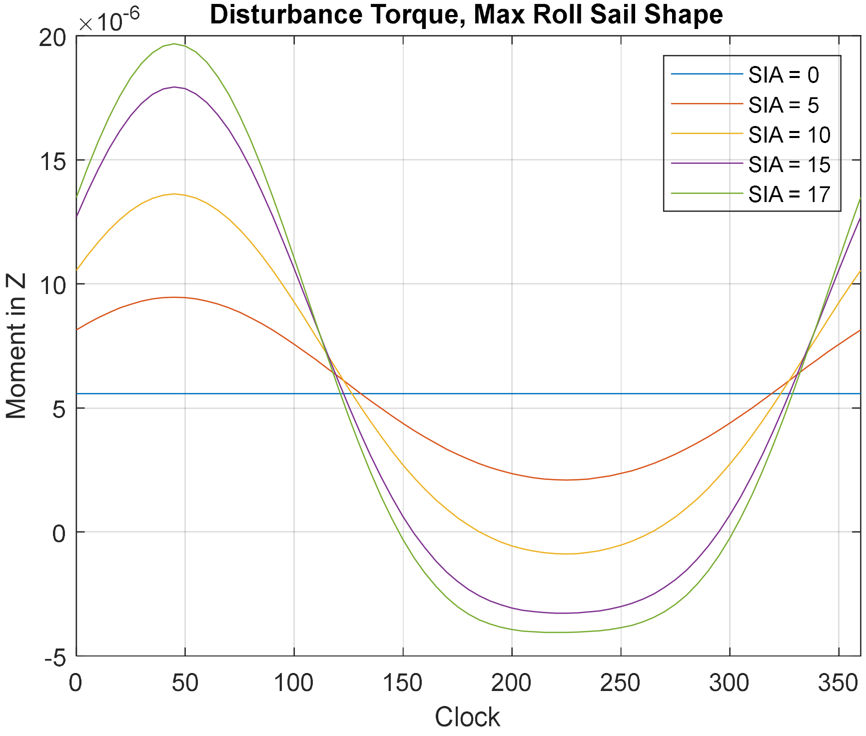


Resultant Torques, Solar Cruiser Deformed Shapes

- Disturbance torque curves shown across range of mission attitudes



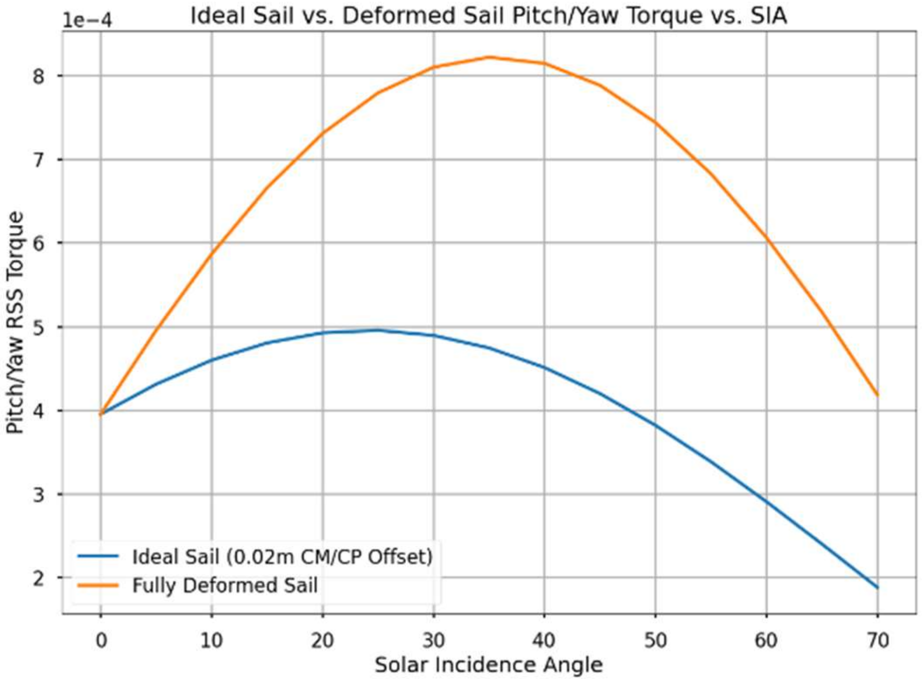
Disturbance Torque, Max Pitch/Yaw Sail Shape

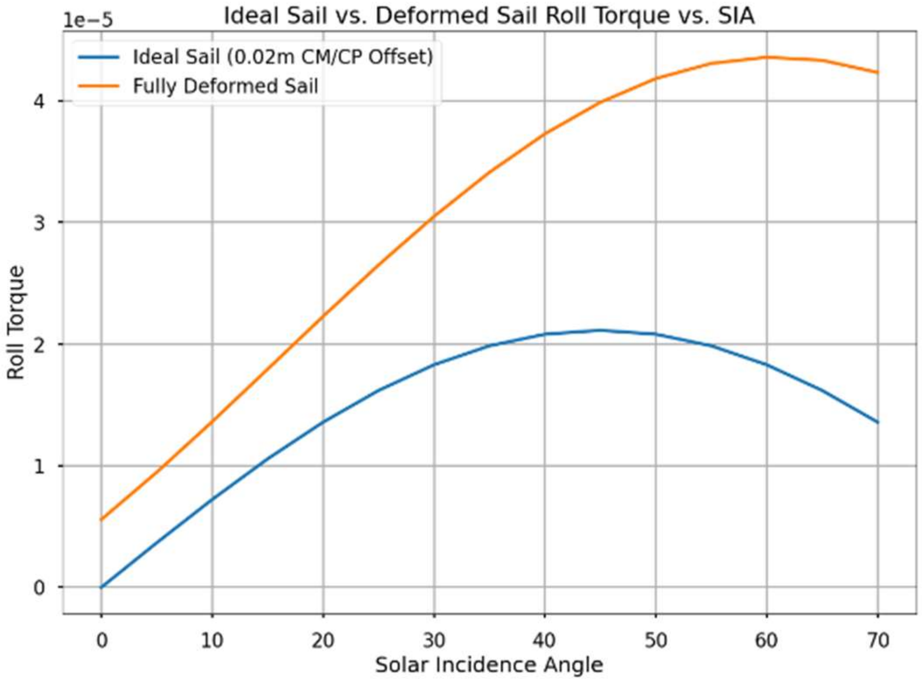


Disturbance Torque, Max Roll Sail Shape

Solar Cruiser Deformed Shapes vs Ideal Sail

- Deformed pitch/yaw shape: 1.66x maximum torque compared to flat sail
- Deformed roll shape: 2.06x maximum torque compared to flat sail



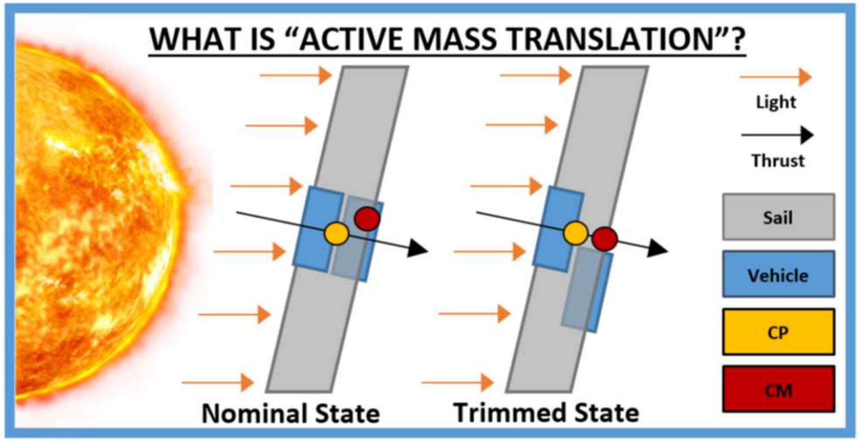


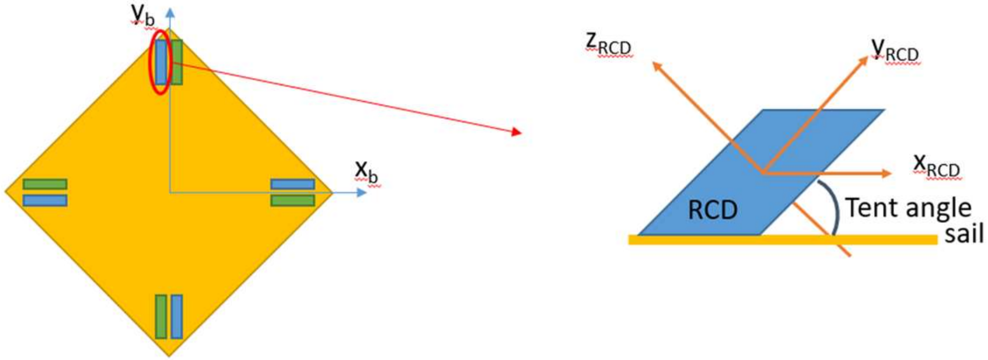
Solar Cruiser Design Considerations

- Disturbance torques from worst-case shapes were considered bounding for the purposes of requirements derivation
  - Sail shape requirements specified to ensure the as-manufactured flight sail deformations would remain within the modeled deformations
    - Tip deflections
    - CM offsets
  - Reaction wheel torque capability (including 100% margin, 2x control authority)
  - Momentum management actuator design
- The disturbances were accounted for in the integrated sailcraft model for requirements verification by analysis
  - Plant dynamics, control system, flight software
  - Sail tensors were integrated into the model, allowing computationally efficient force and torque calculation at simulated attitudes

Solar Cruiser Design Considerations

- Momentum management requirements
  - To desaturate momentum in the pitch/yaw RSS (in-plane) axes, Solar Cruiser utilized an Active Mass Translator (AMT)
    - The torque predictions drive design considerations such as AMT range of motion, rail orientation, and bus mass allocation
  - For roll (out-of-plane) momentum management, Solar Cruiser utilized two actuator systems
    - Reflectivity Control Devices (RCDs) (primary)
    - Indium Field Emission Electric Propulsion Microthrusters (IFMs) (backup)
    - Roll torque predictions drive requirements on RCD surface area, as well as IFM propellant mass needed





Conclusions

- The deformed sail model results demonstrate considerably higher expected induced disturbance torques compared to the simplified assumption of a flat plate sail with a CM/CP offset
- Accurate prediction of these disturbances is crucial when designing the spacecraft attitude control system
- The disturbances drive all aspects of ADCS, ultimately impacting sailcraft characteristic acceleration and mission design as required masses grow
- It is recommended to begin medium/high fidelity modeling as early as possible in the design cycle, even in the early mission concept phase

Forward Work

- The current approach yields a medium-fidelity model where inputs and assumptions on local conditions (e.g., nominal boom tip deflection, tip error uncertainty, and membrane deflection) drive the global sail shape
- Forward work is currently ongoing to improve modeling fidelity
    - Cooperative effort including MSFC, LaRC, Redwire, and NeXolve
- Iterative process where interactions between the boom deformations and the membrane deformations are increasingly refined
    - Top-down approach - "global "boom thermal/structural modeling outputs computed, information used in "local" membrane quadrant models
- Assumed membrane shapes will be replaced with more physically realistic models
- Sail tensors will be regenerated and attitude control metrics reassessed with high-fidelity shapes

Questions

References

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5. J. Orphee, A. Heaton et al. Solar Torque Management for the Near Earth Asteroid Scout CubeSat Using Center of Mass Position Control. Kissimmee, Florida, January 2018. American Institute of Aeronautics and Astronautics Science and Technology Forum. Paper M17-6378.

Backup

Parameter Variations

Parameter	**Tip Error Factor**	**Membrane Billow**	**CM Offset**	**Tip Direction Factor**	**Membrane Direction Factor**
Variation	0	0 cm	0 cm	1x	-1x
	1x	1 cm	+/-1 cm X-axis	Tip A +/-1x	Membrane A +/-1x
	1.25x	2 cm	+/-2 cm X-axis	Tip B +/-1x	Membrane B +/-1x
	1.5x	3 cm	+/-1 cm Y-axis	Tip C +/-1x	Membrane C +/-1x
	1.75x	4 cm	+/-2 cm Y-axis	Tip D +/-1x	Membrane D +/-1x
	2.0x	5 cm	-	-	-