Solar Sail Attitude Control Using Shape Modulation: The Cable-Actuated Bio-inspired Lightweight Elastic Solar Sail (CABLESSail) Concept

Ryan J. Caverly, Keegan Bunker, Nathan Raab, Vinh L. Nguyen, Garvin Saner
Zixin Chen, Tyler Douvier, Richard J. Lyman, Owen Sorby, Benjamin Sorge, Ebise Teshale, Benjamin Toriseva

University of Minnesota, Minneapolis, MN, USA

UNIVERSITY OF MINNESOTA

Partner

Contract #: 80NSSC23K0075
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NASA Collaborator: Daniel Tyler

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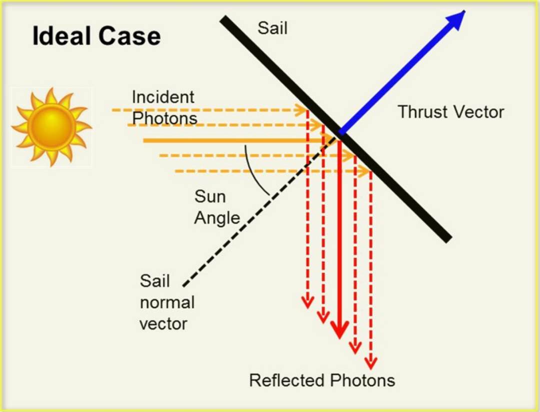
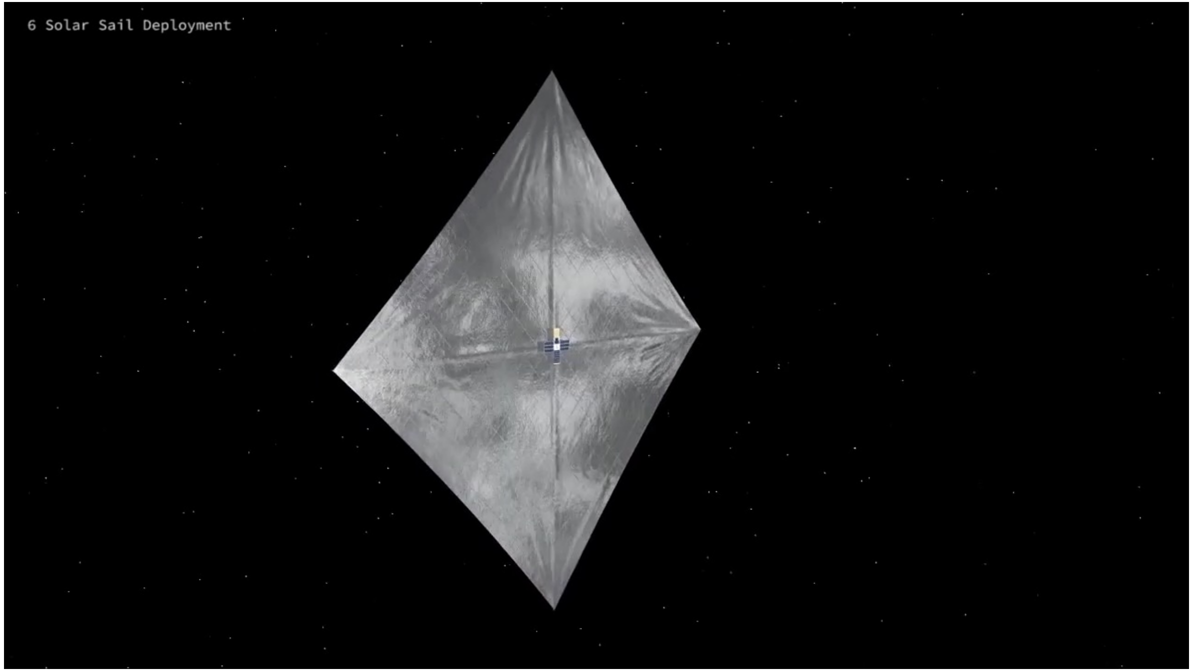
Solar Sails

- Lightweight spacecraft with large reflective surface area that use solar radiation pressure for propulsion.
- No fuel required!
- Enables unique missions:
  - Orbits outside ecliptic plane.
  - Interstellar travel.
  - Statites that “hover.”



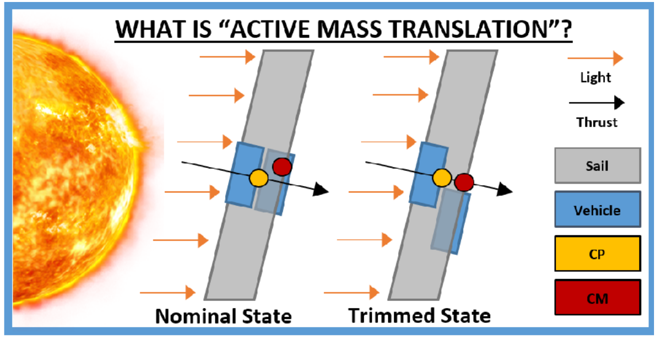
NEA Scout (86 m^2)



Video and image Credit: NASA

Solar Sail Attitude Control Challenges

- Attitude control and momentum management present unique challenges.
- Actuators:
  - Reaction Wheels
  - Control Vanes
  - Reflectivity Control Devices
  - Active Mass Translator
- Challenges in mass, scalability, need for torques in 3 axes.



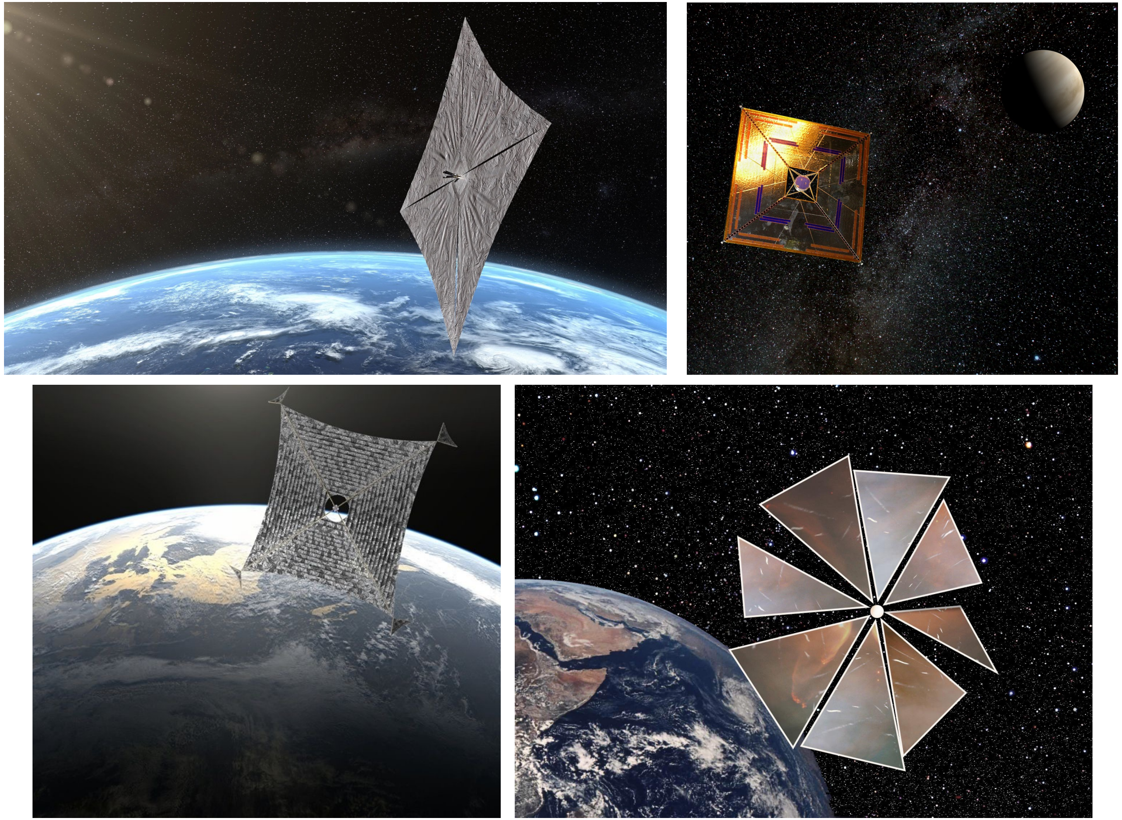
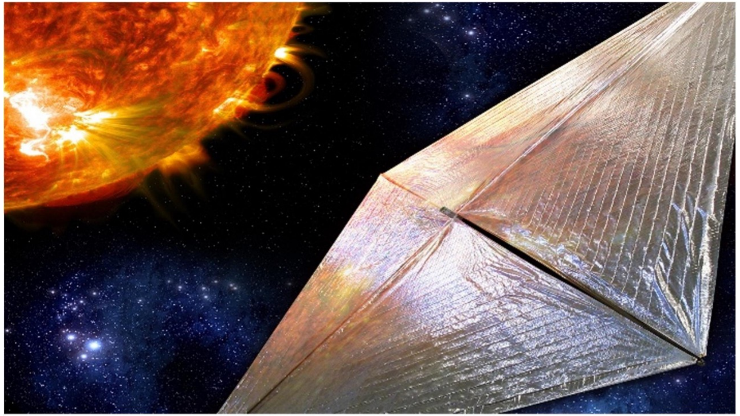


Image Credits: scientificamerica.com, Andrzej Mirecki, John Ballentine, futurecdn.net, and Orphee et al. SciTech 2018.

Solar Sail Attitude Control Challenges

Solar Cruiser (1684 m^2)



Solar Polar Imager (7000 m^2)

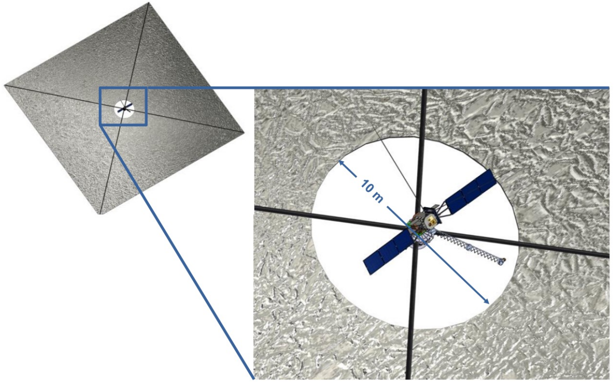
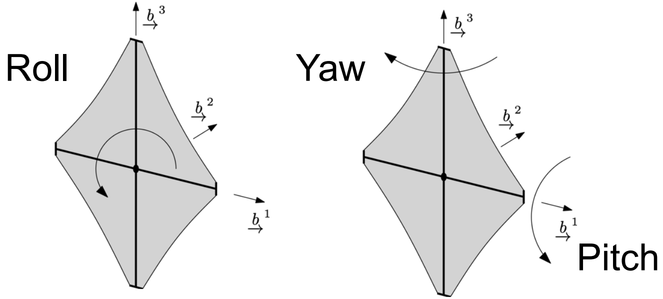


Image Credit: NASA & Thomas et al., ASCEND 2020.

Disturbance Torque Magnitudes

Case	Out-of-Plane (Roll) Torque (N-m)	In-Plane (Pitch/Yaw) Torque (N-m)
Solar Cruiser (1684 m^2) 0^0 SIA	$4.7\text{x}10^{-6}$	$5.5\text{x}10^{-5}$
Solar Cruiser (1684 m^2) 35^0 SIA	$4.9\text{x}10^{-5}$	$2.4\text{x}10^{-3}$
SPI (7000 m^2) 0^0 SIA	$7.7\text{x}10^{-5}$	$4.6\text{x}10^{-3}$
SPI (7000 m^2) 35^0 SIA	$6.4\text{x}10^{-4}$	$4.7\text{x}10^{-2}$



Solar Sail Attitude Control Challenges

Attitude Control Actuator Needs:

- Lightweight.
- Scale with sail size.
- Scale with distance from the sun.
- Scale with sun incidence angle (SIA).
- Produce torques in all 3 axes.
- Ideally use solar radiation pressure.

Requirements:

- Must produce torques with magnitudes larger than disturbance torques for Solar Cruiser and SPI.

Performance Metric:

- Control torque per unit mass of actuator.

Disturbance Torque Magnitudes

Case	Out-of-Plane (Roll) Torque (N-m)	In-Plane (Pitch/Yaw) Torque (N-m)
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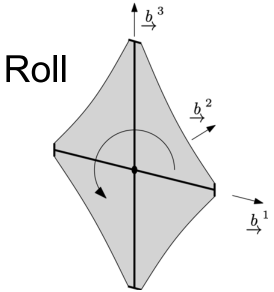
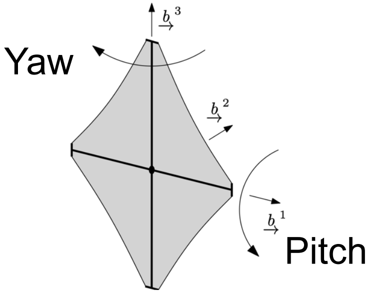
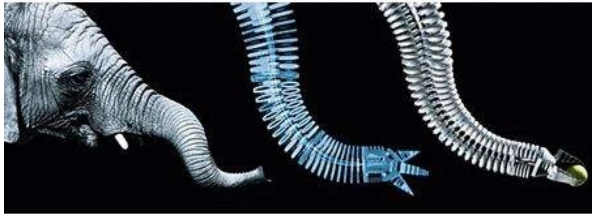
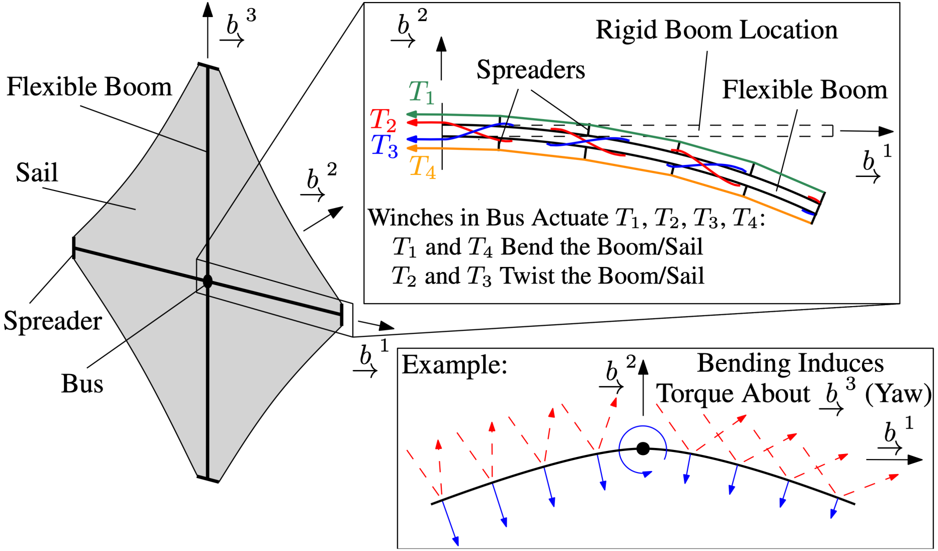




CABLESSail Concept



CABLESSail: Cable-Actuated Bio-Inspired Lightweight Elastic Solar Sail

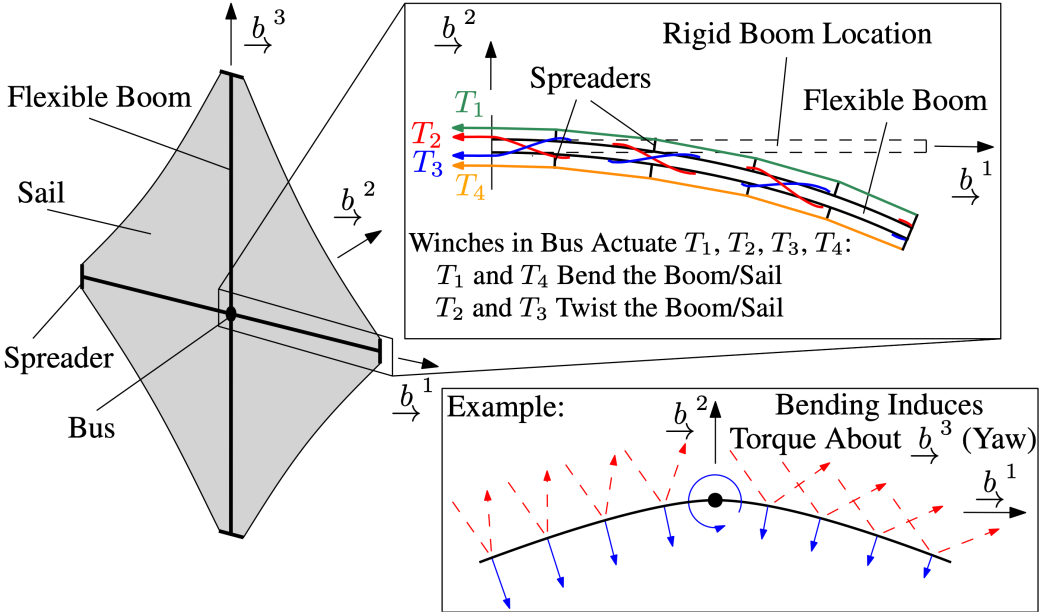


Video Credit: Dr. Rucker, University of Tennessee. Image Credit: softroboticstoolkit.com, festo.com

Outline

- Concept Overview
  - Concept of Operations
  - Design Options
  - Static Simulations
- Dynamic Modeling
  - Simulation Code & Results
- Prototyping
  - Single Boom & 4-Boom Prototypes
- Control & State Estimation
- Conclusions & Future Work

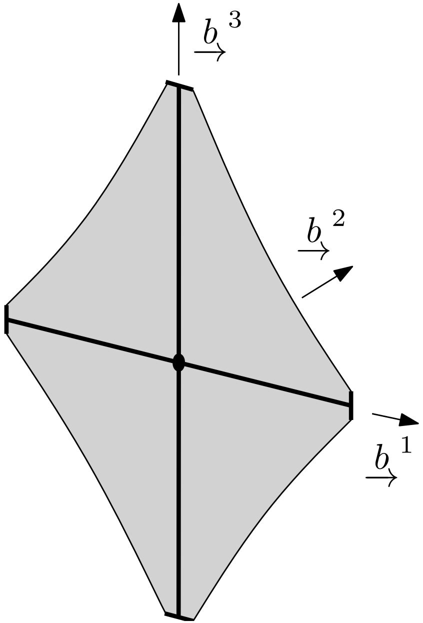
CABLESSail: Cable-Actuated Bio-Inspired Lightweight Elastic Solar Sail

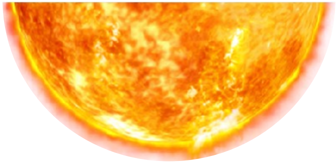


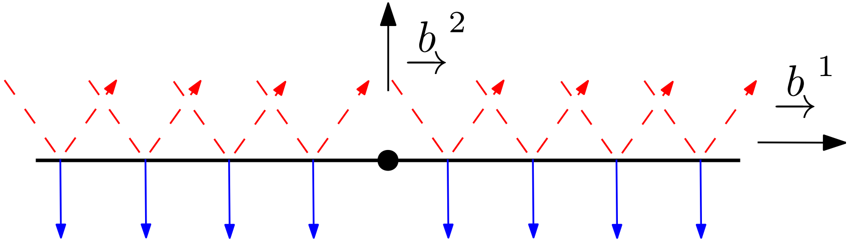
Winches in Bus Actuate T_1, T_2, T_3, T_4:
T_1 and T_4 Bend the Boom/Sail
T_2 and T_3 Twist the Boom/Sail

Bending Induces Torque About $\underrightarrow{b}^{3}$ (Yaw)

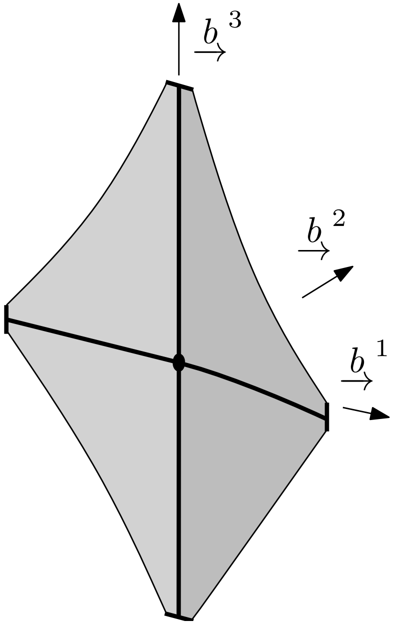
CABLESSail Concept - In-Plane (Pitch/Yaw) Torques

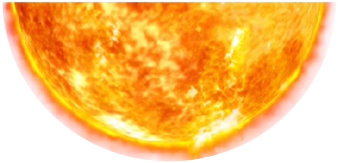




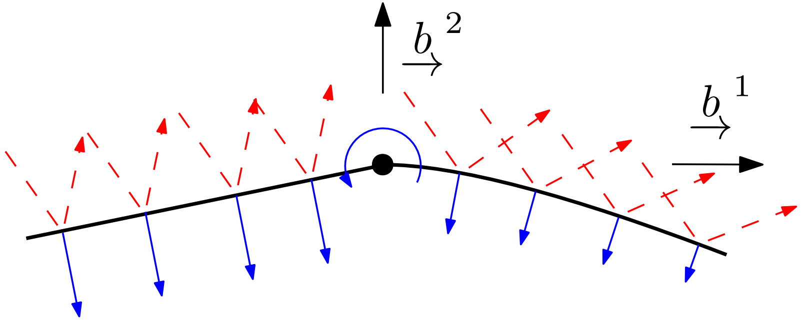


CABLESSail Concept - In-Plane (Pitch/Yaw) Torques

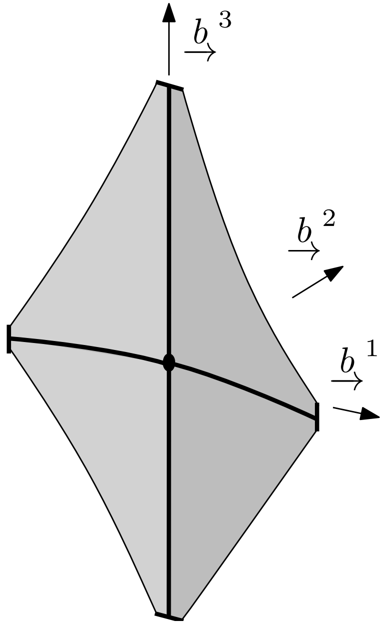


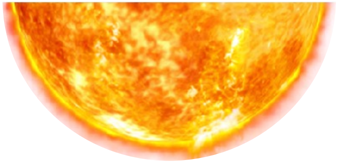


- Increase tension in cable to induce bending of right-hand-side of sail.
- Obtain control torque in CCW direction.

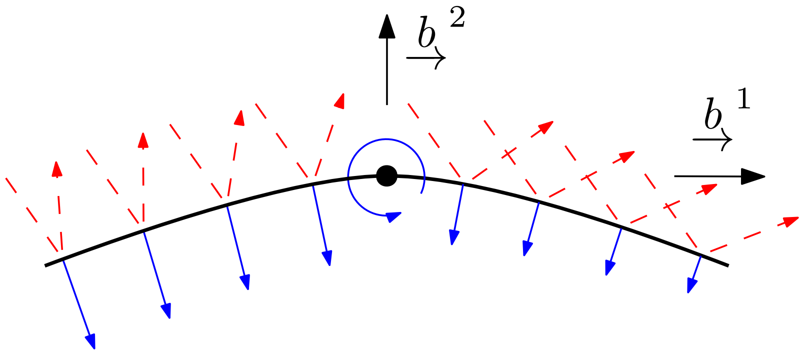


CABLESSail Concept - In-Plane (Pitch/Yaw) Torques

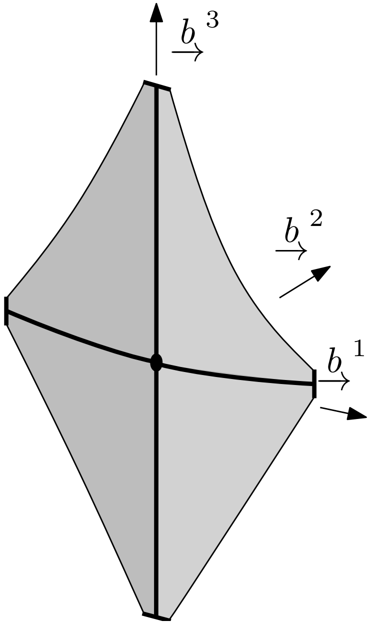


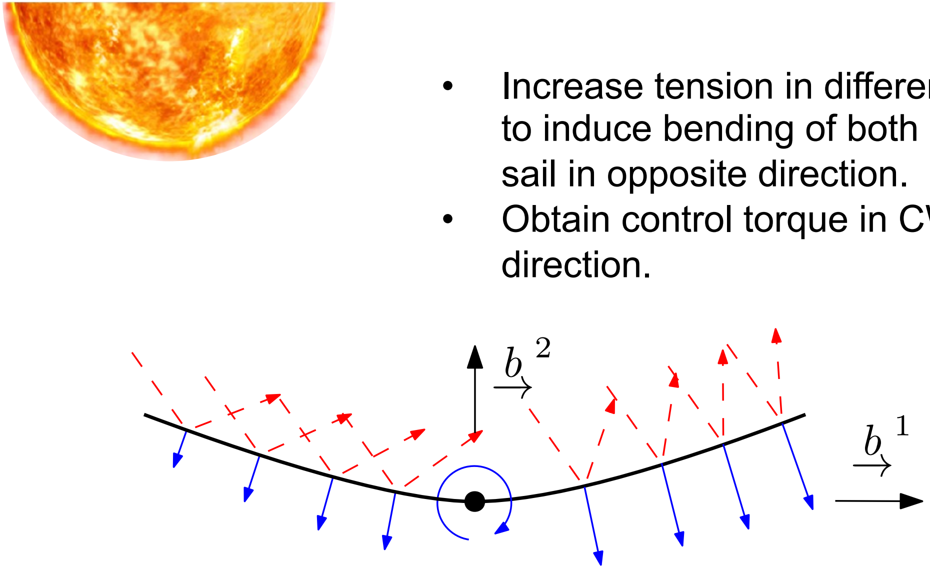


- Increase tension in cables to induce bending of both sides of sail.
- Obtain larger control torque in CCW direction.



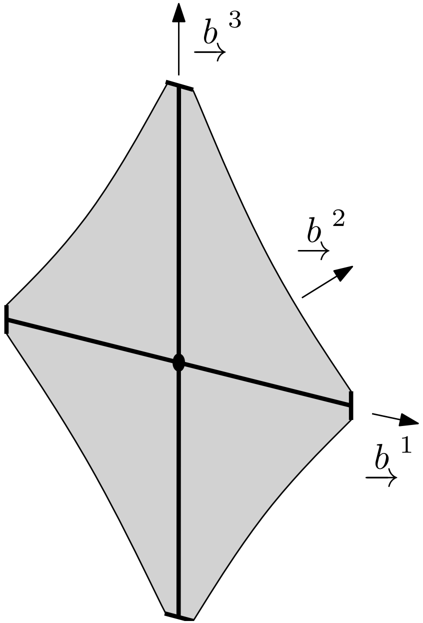
CABLESSail Concept - In-Plane (Pitch/Yaw) Torques

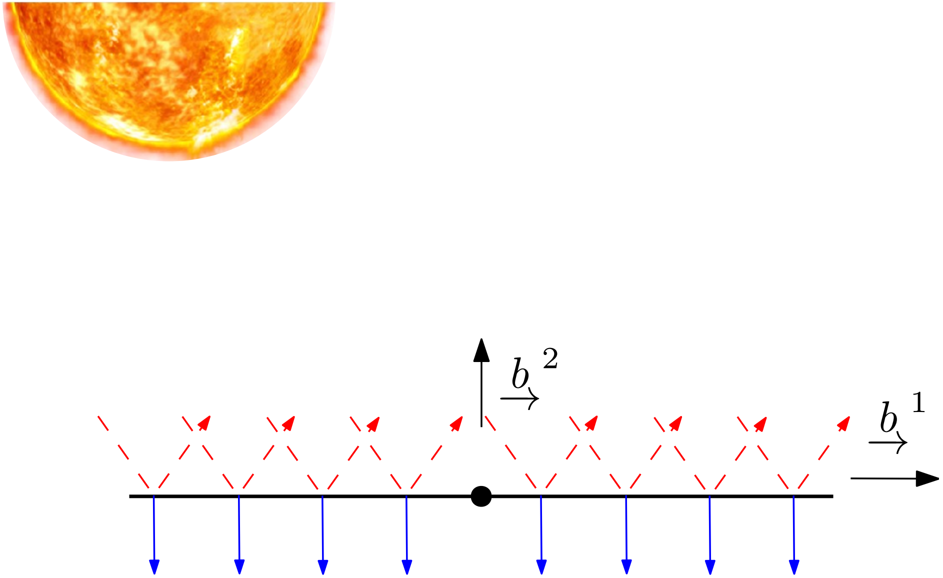




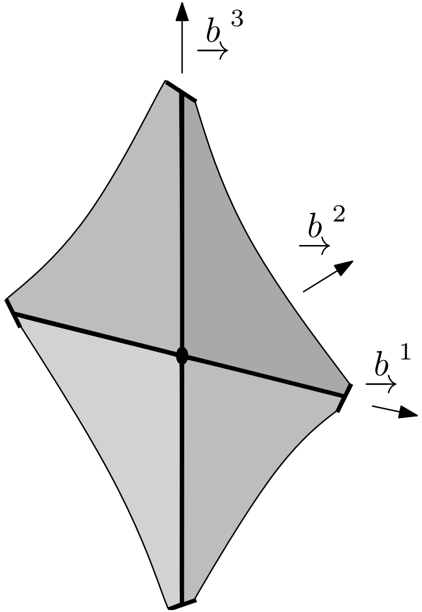
- Increase tension in different cables to induce bending of both sides of sail in opposite direction.
- Obtain control torque in CW direction.

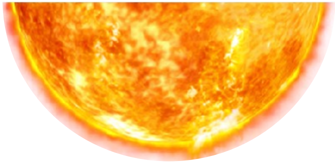
CABLESSail Concept – Out-of-Plane (Roll) Torques



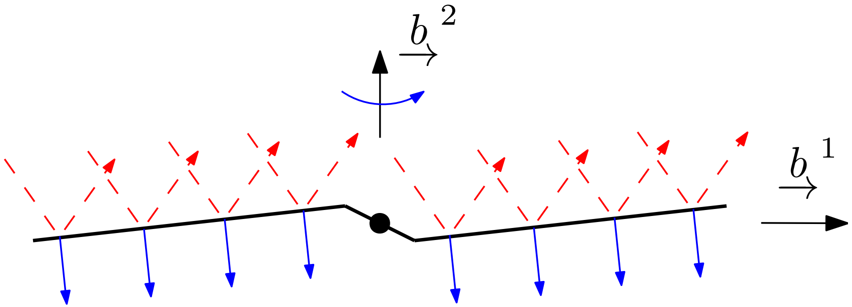


CABLESSail Concept – Out-of-Plane (Roll) Torques





- Increase tension in helical cables to induce twisting of sails.
- Obtain control torque about the out-of-plane axis.



CABLESSail Design Considerations

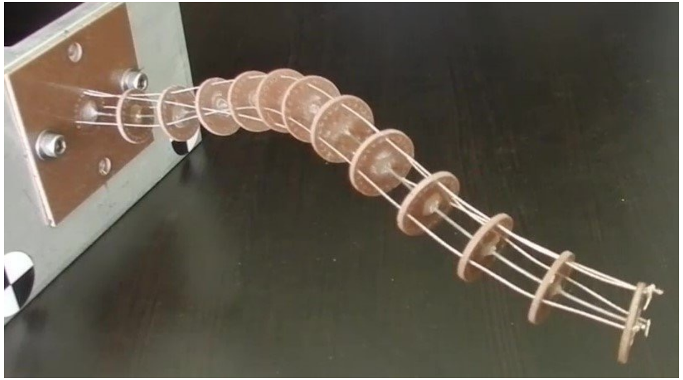


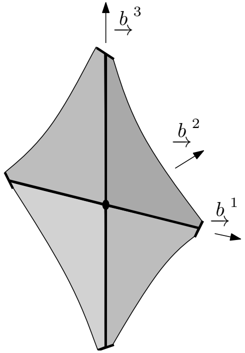
Image Credit: Dr. Rucker, University of Tennessee.

Which Boom Geometry/Type?

- Cable-Driven Robotics-Inspired.
- TRAC boom.
- NASA Langley/DLR's ACS3 boom.
- Coilable boom (ATK Space Systems).

How Many/Which Actuating Cables?

- More cables result in greater redundancy, but with additional size, weight, and power (SWaP).
- Is "pinwheel" deformation achievable?



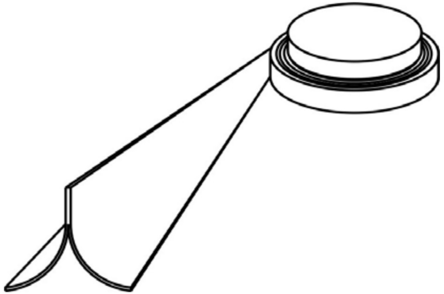


Image Credit: The Planetary Society

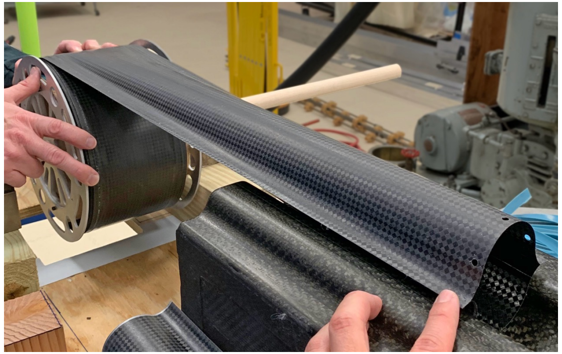


Image Credit: NASA

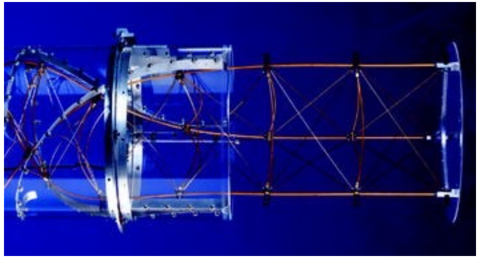


Image Credit: ATK Space Systems

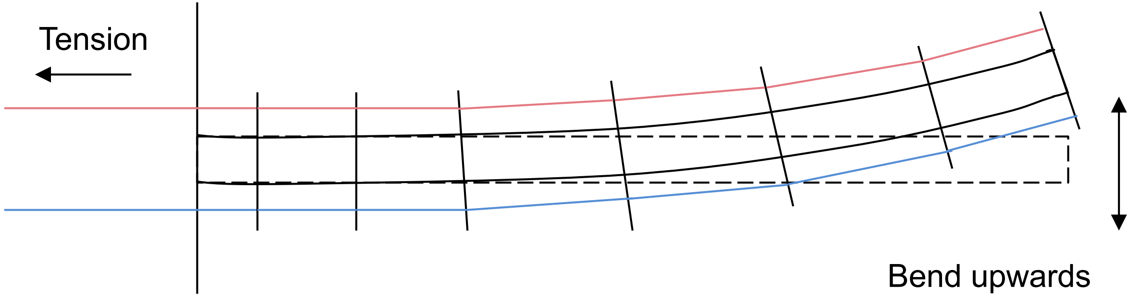
CABLESSail Concept – Cable-Driven Robotics-Inspired Booms

Operation

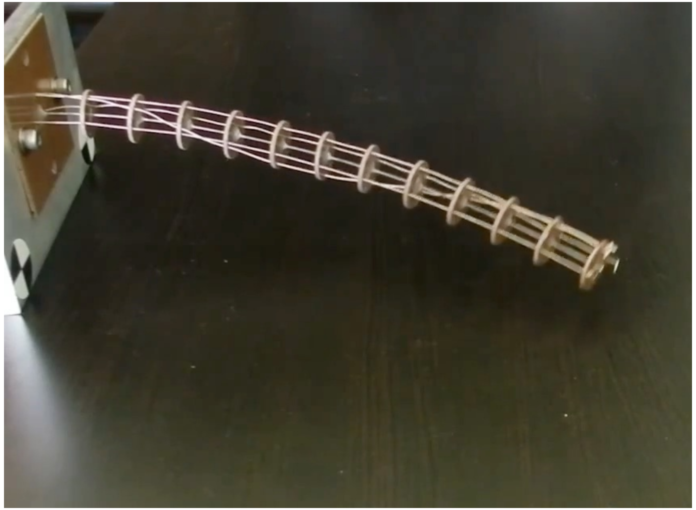
- Bending (pitch/yaw) induced by tension in cable above and/or below.
- Twisting (roll) induced by tension in helically-routed cables.

Remarks

- Greater control authority with wider spacing.
- Concerns with storage and deployment.



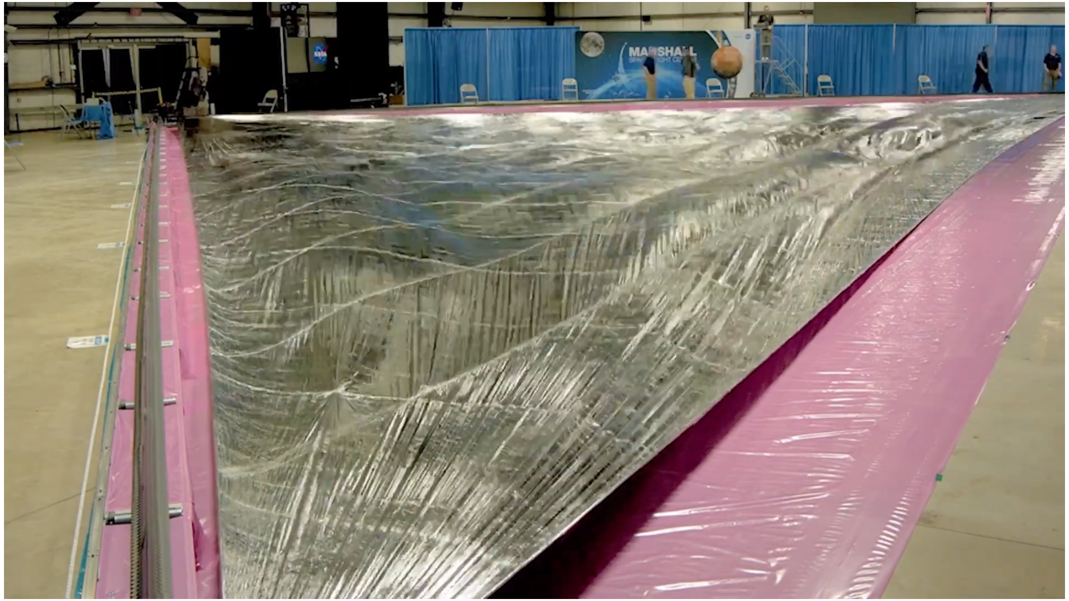
Bend upwards and downwards



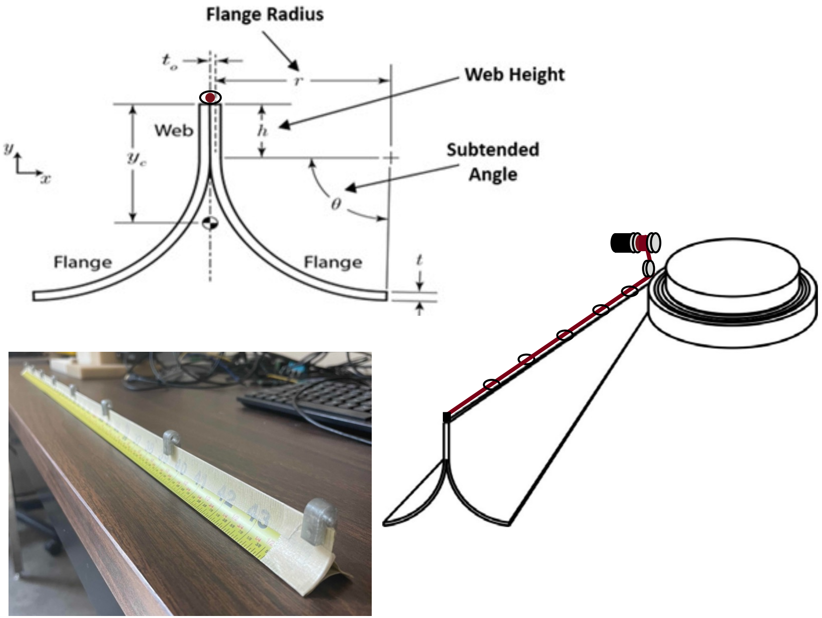
Video Credit: Dr. Rucker, University of Tennessee.

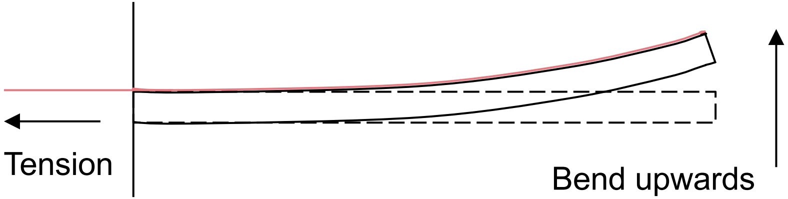
CABLESSail Concept – Connection to TRAC Booms

TRAC Boom Deployment Test

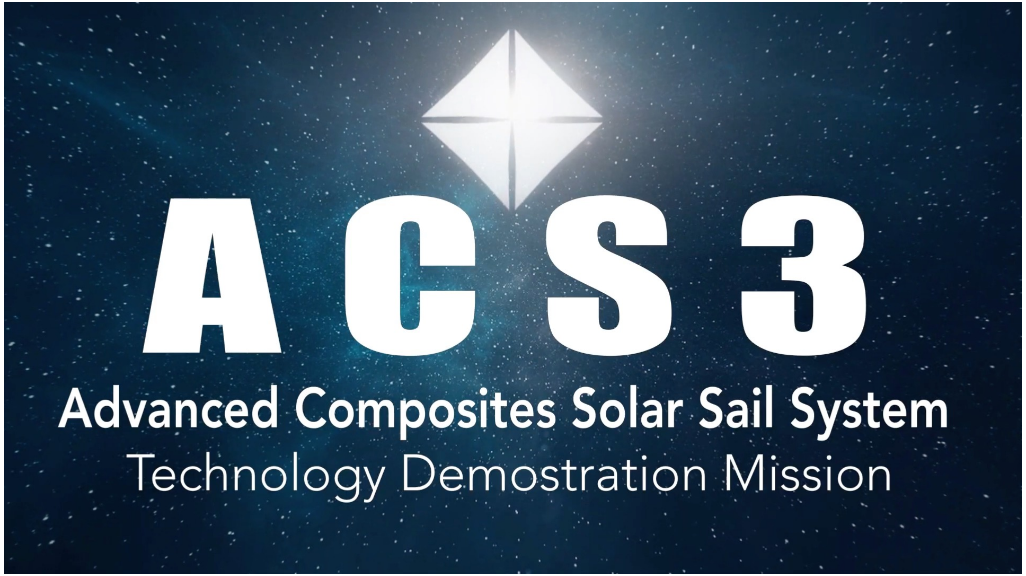


Video Credit: NASA

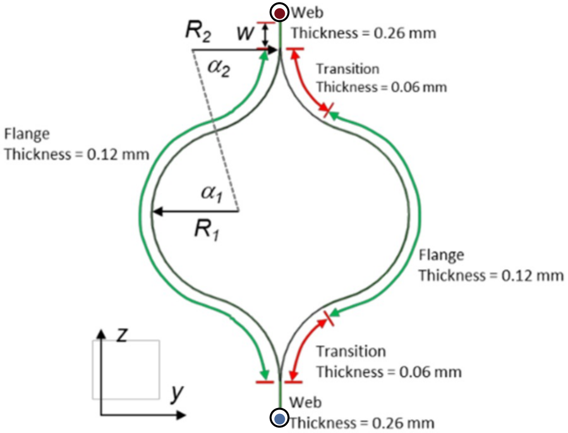




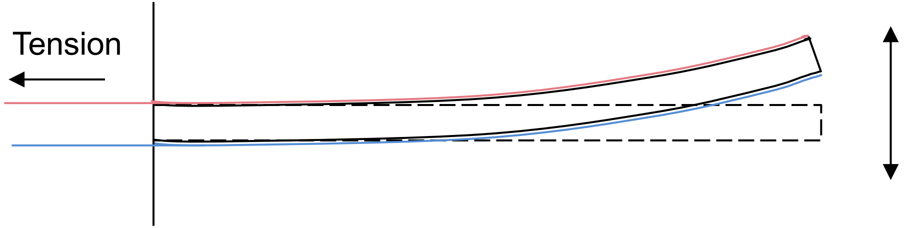
CABLESSail Concept – Connection to ACS3 Booms



Video Credit: NASA



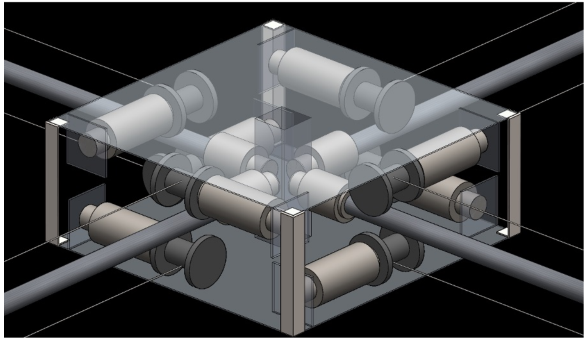
Bend upwards and downwards

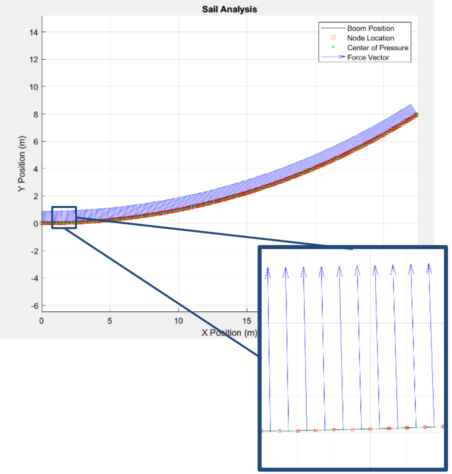


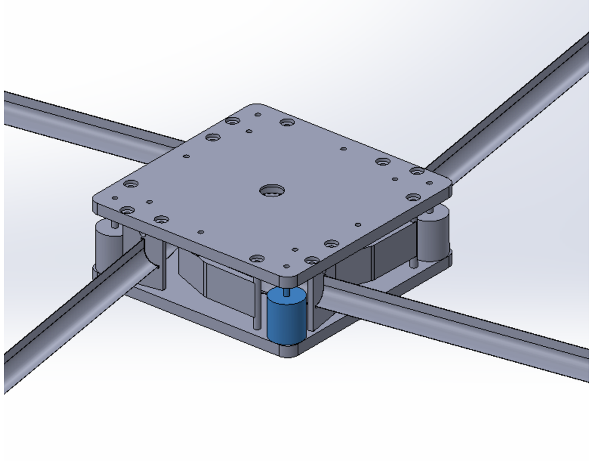
Preliminary CABLESSail Design

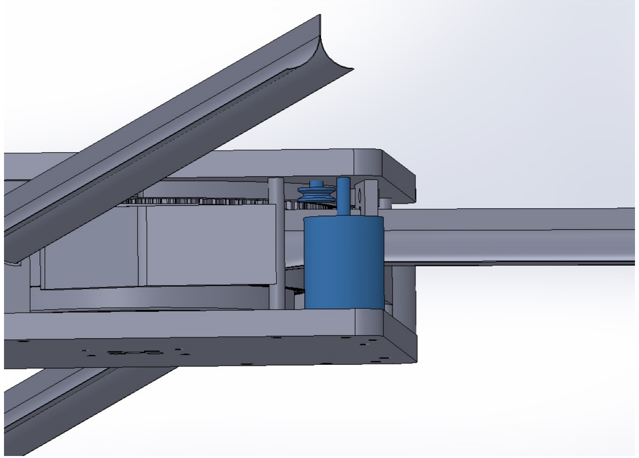
Fall 2022 Undergraduate Senior Design Team

- Magnitudes of torques that can be generated through boom bending in deployed configuration.
- Modified code University of Toronto code designed for continuum robots to assess deformed boom shapes.
- “Panel code” computes attitude torques from boom/sail deformations.





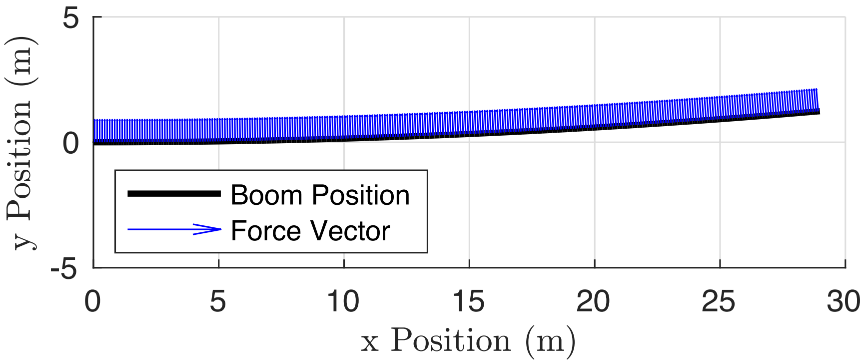


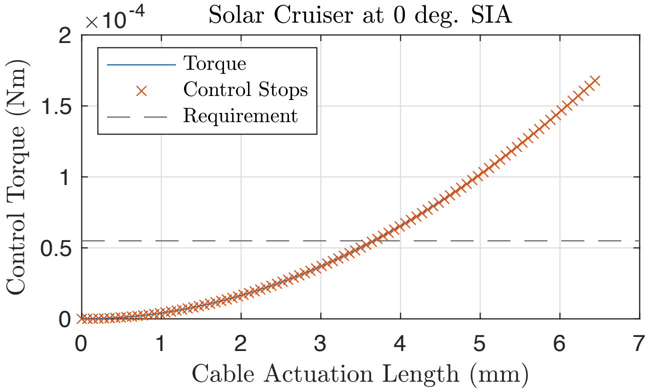


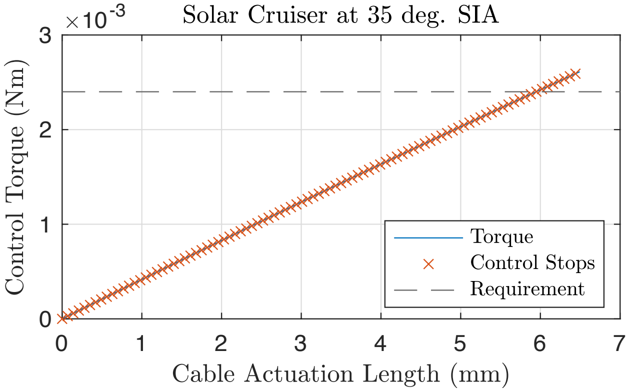
Preliminary CABLESSail Design

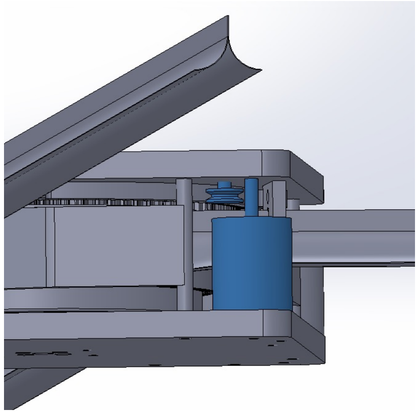
Solar Cruiser-Class Design Analysis

- Total mass of 3.1 kg:
  - Motors: 1.6 kg
  - Cables: 1 kg
  - Supporting Hardware: 0.5 kg
- Cable routings with 7.5 cm radius.
- Requirements met with 63 N of cable tension and less than 7 mm change in cable length.



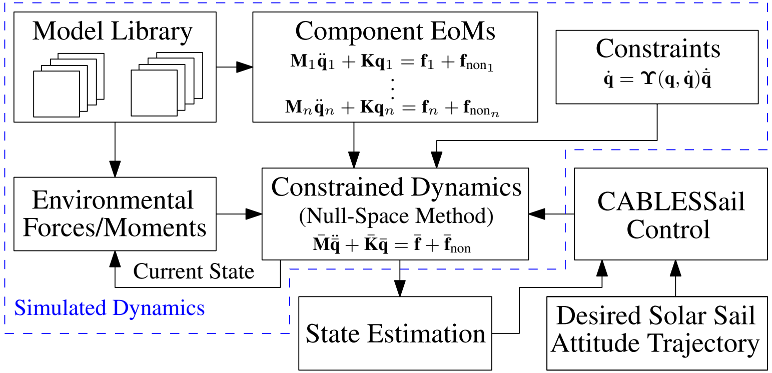






CABLESSail Dynamic Modeling and Simulation

- Developing modular dynamic simulation code that is amenable to the evaluation of different designs (null-space method).
- Dynamic simulation code will allow for in-the-loop testing of control and estimation algorithms.



Model Library

Component EoMs

$\mathbf{M}_1\ddot{\mathbf{q}}_1 + \mathbf{K}\mathbf{q}_1 = \mathbf{f}_1 + \mathbf{f}_{\text{non}_1}$

$\vdots$

$\mathbf{M}_n\ddot{\mathbf{q}}_n + \mathbf{K}\mathbf{q}_n = \mathbf{f}_n + \mathbf{f}_{\text{non}_n}$

Constraints

$\dot{\mathbf{q}} = \boldsymbol{\Upsilon}(\mathbf{q},\dot{\mathbf{q}})\dot{\bar{\mathbf{q}}}$

Environmental Forces/Moments

Constrained Dynamics (Null-Space Method)

$\bar{\mathbf{M}}\ddot{\bar{\mathbf{q}}} + \bar{\mathbf{K}}\bar{\mathbf{q}} = \bar{\mathbf{f}} + \bar{\mathbf{f}}_{\text{non}}$

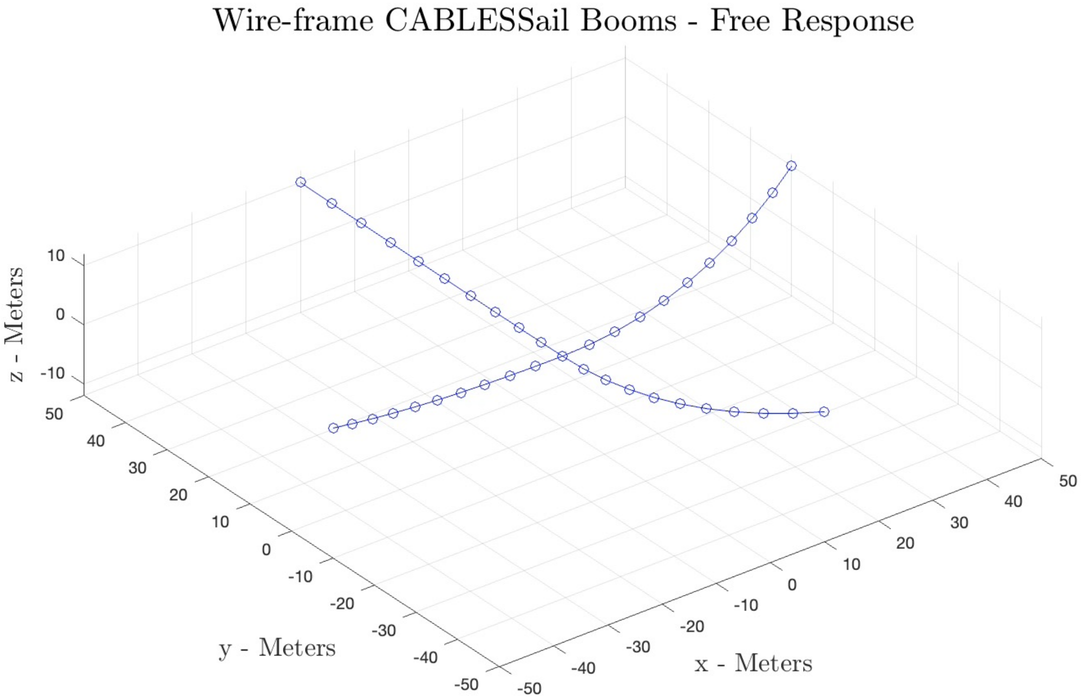
CABLESSail Control

Current State

Simulated Dynamics

State Estimation

Desired Solar Sail Attitude Trajectory

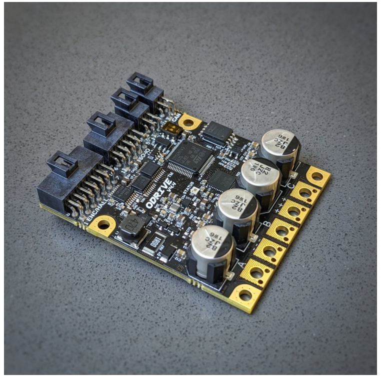


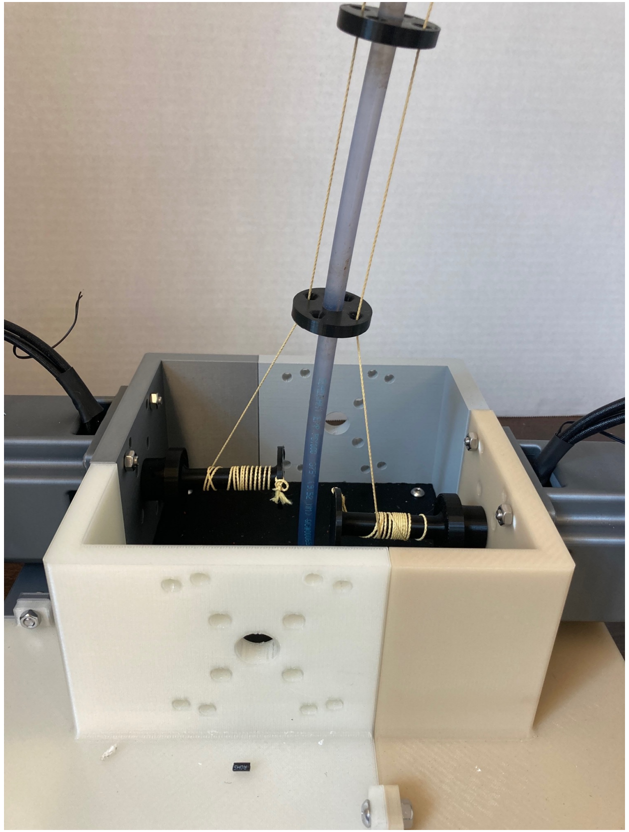
Wire-frame CABLESSail Booms - Free Response

CABLESSail Prototyping

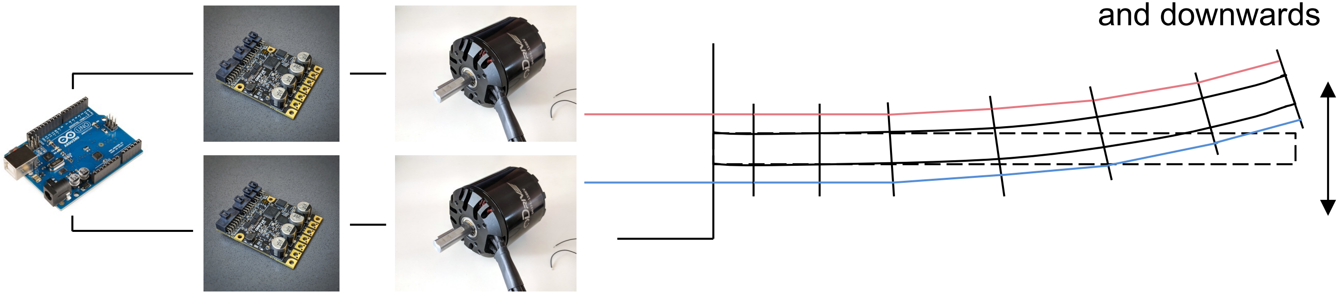
Small-Scale Prototypes

- Assess effects such as friction, boom deployment, measurement noise and delays.
- Using open-source motor controllers (ODrive).

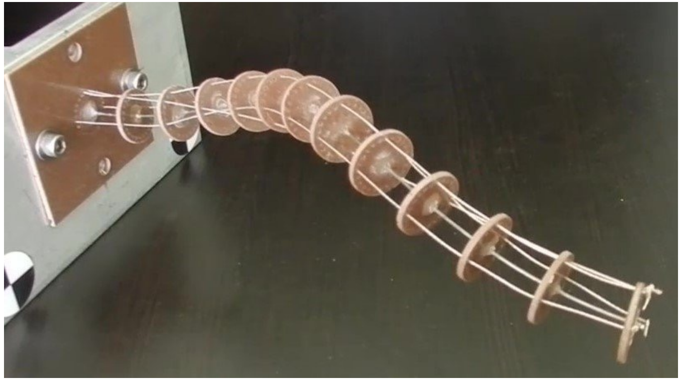




Prototype 1: Starting Point / Standalone Design



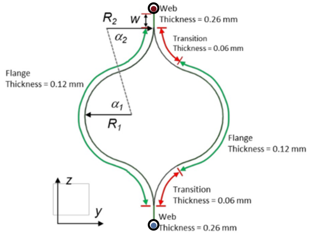
Bend upwards and downwards

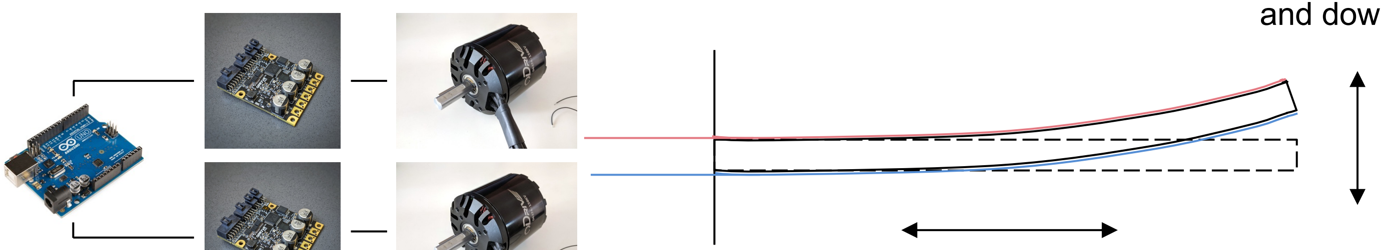


Prototype 2a/2b: ACS3 and TRAC Booms

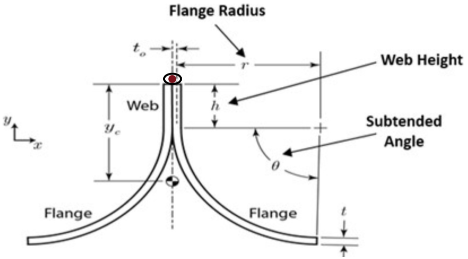
Prototype 2a (Integrated with ACS3 Boom Design)

Bend upwards and downwards



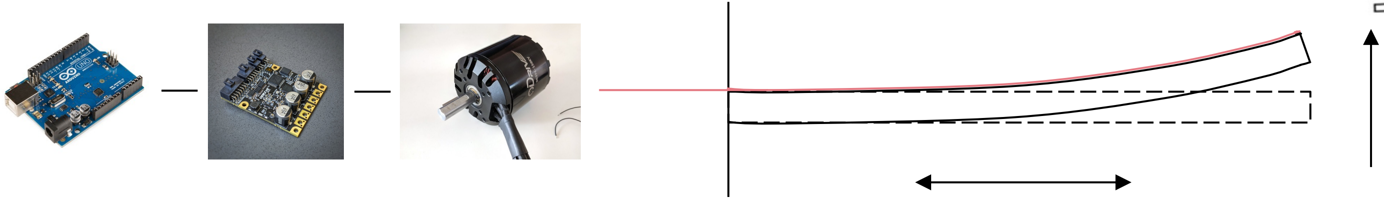


Possibly incorporate deployment and twisting in prototype

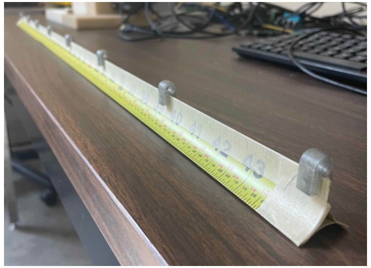


Prototype 2b (Integrated with TRAC Boom Design)

Bend upwards



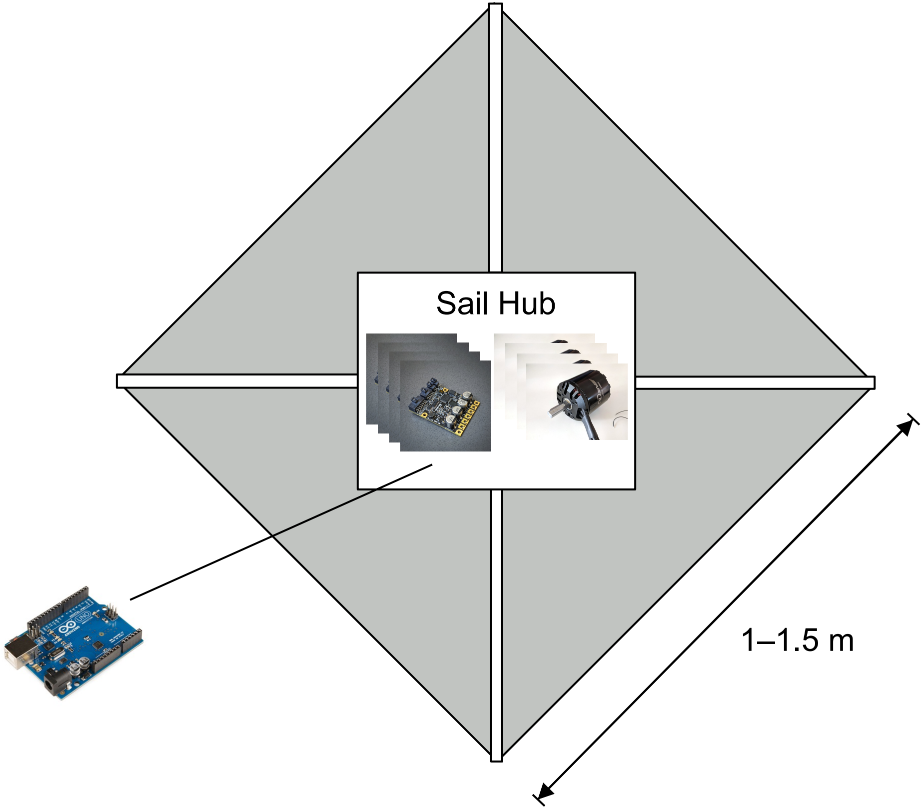
Possibly incorporate deployment and twisting in prototype



Prototype 3: Small-Scale 4-Boom Solar Sail

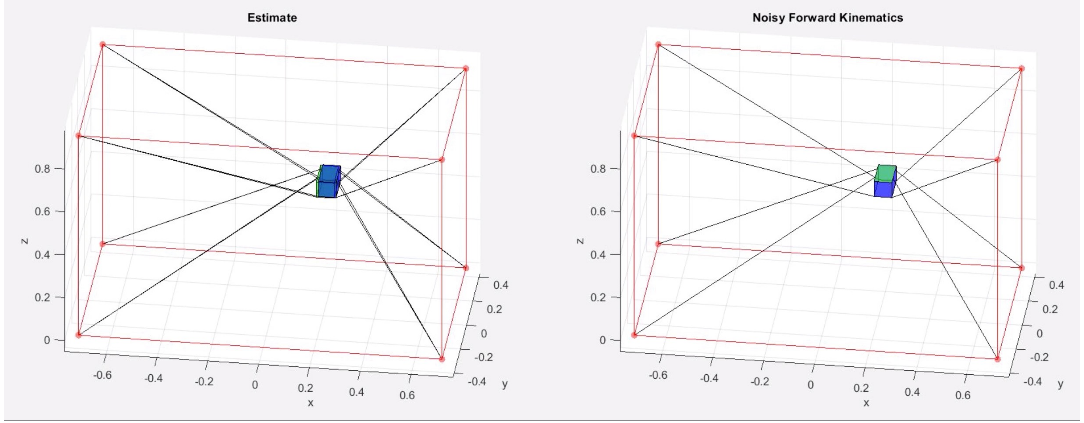
Prototype 3 (Small Scale 4-Boom Solar Sail)

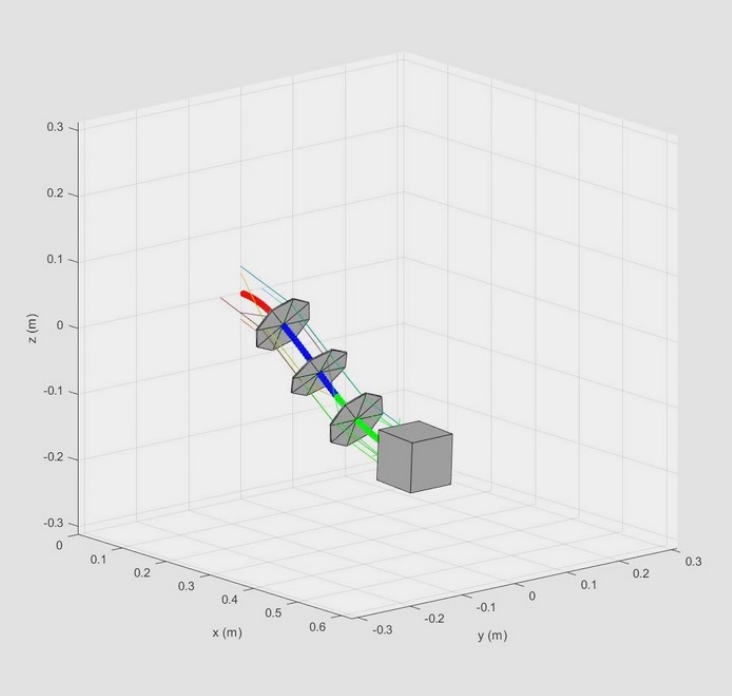
- Small-scale testing of most promising design (ACS3 vs TRAC booms)
- Test practical aspects of design:
    - Real sensors/actuators in the loop.
    - Data transmission.
    - Unmodeled dynamics.
- VICON motion capture system available to validate control/estimation performance
- Publish build procedure and code on GitHub.



CABLESSail Feedback Control & State Estimation

- Focus on precise, robust, and reliable deformation of the booms (feedback control).
  - Robust control techniques.
- Requires knowledge of elastic boom deflection (state estimation).
  - Sensors: winch encoders, IMUs, fiber optics.





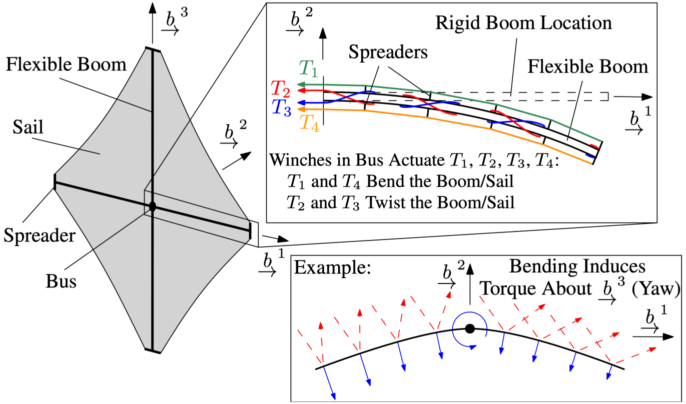
Conclusions and Future Work

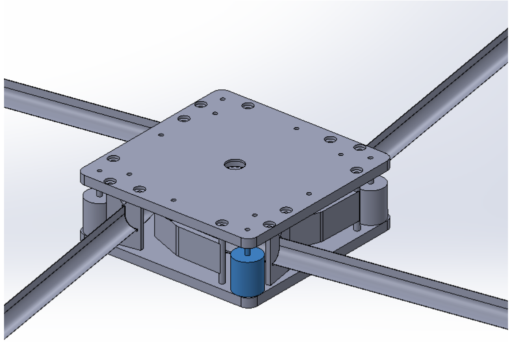
Conclusions

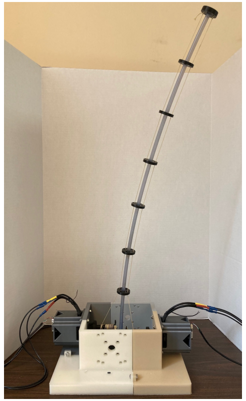
- Feasibility of preliminary CABLESSail concept design.
  - Design surpasses control torque requirements.
- Pushing the boundaries of cable-driven robotics modeling, control, and state estimation.

Future Work

- Concept Design
  - Detailed design with deployable booms.
  - Trade study on number/configuration of cables.
- Numerical Simulation
  - Open-source 3D simulation integrated with sail model.
- Prototyping
  - Test actuation with deployable booms.
  - Full 4-boom prototype.
- Control & State Estimation
  - Develop robust control and state estimation algorithms in simulation & experiments.



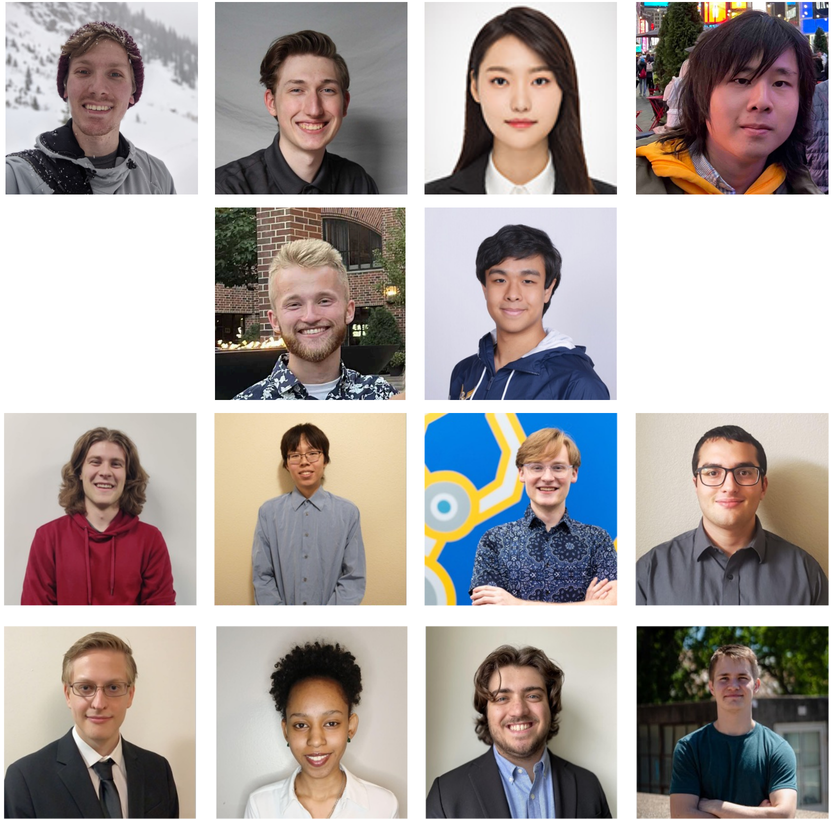




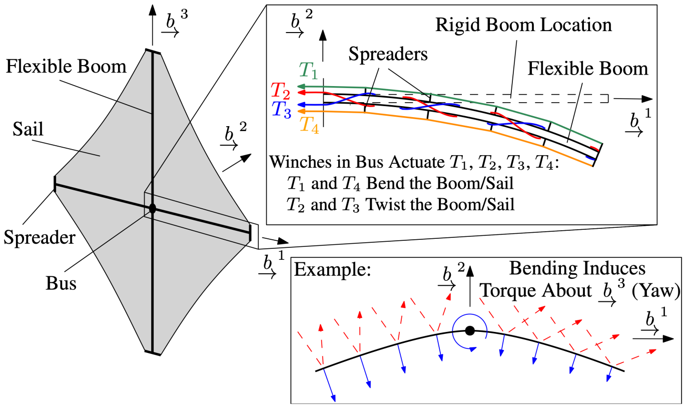
Acknowledgements

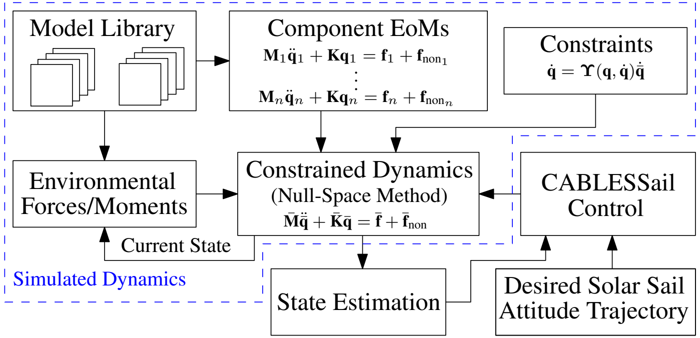
- CABLESSail Team
  - Grad Students: Keegan Bunker, Nathan Raab, Soojeong Lee, Vinh Nguyen.
  - Undergrads: Austin Bodin, Michael Dallalah, Michael States.
  - Undergrad Senior Design Team
- MSFC Collaborators
  - Danny Tyler
  - Andy Heaton
- Funding:
  - This work was supported by an Early Career Faculty grant from NASA's Space Technology Research Grants Program.
  - Vinh Nguyen's work supported by NSF GRFP.

Partner



CABLESSail





Model Library

Component EoMs
$\mathbf{M}_1\ddot{\mathbf{q}}_1 + \mathbf{K}\mathbf{q}_1 = \mathbf{f}_1 + \mathbf{f}_{\text{non}_1}$
$\vdots$
$\mathbf{M}_n\ddot{\mathbf{q}}_n + \mathbf{K}\mathbf{q}_n = \mathbf{f}_n + \mathbf{f}_{\text{non}_n}$

Constraints
$\dot{\mathbf{q}} = \boldsymbol{\Upsilon}(\mathbf{q},\dot{\mathbf{q}})\dot{\bar{\mathbf{q}}}$

Environmental Forces/Moments

Constrained Dynamics (Null-Space Method)
$\bar{\mathbf{M}}\ddot{\bar{\mathbf{q}}} + \bar{\mathbf{K}}\bar{\mathbf{q}} = \bar{\mathbf{f}} + \bar{\mathbf{f}}_{\text{non}}$

CABLESSail Control

Current State

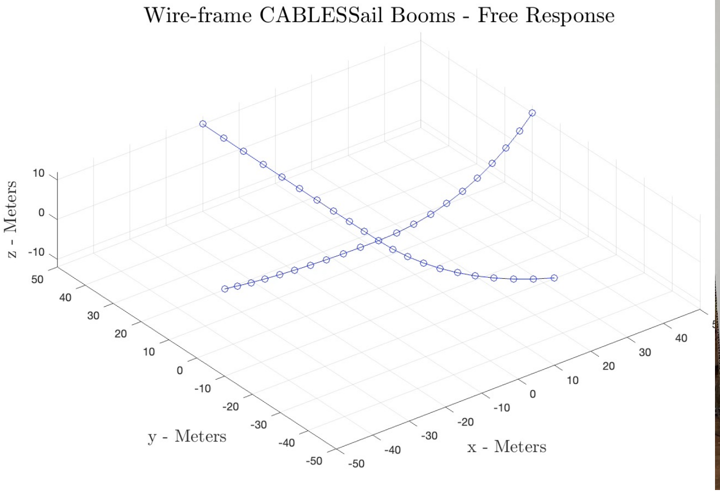
Simulated Dynamics

State Estimation

Desired Solar Sail Attitude Trajectory

Thanks for Your Attention!

Contact: rcaverly@umn.edu



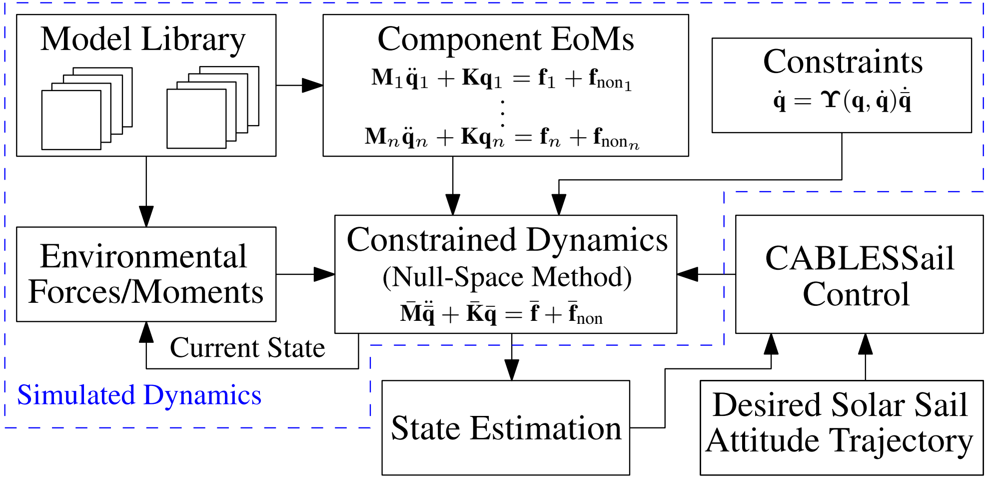
Wire-frame CABLESSail Booms - Free Response

Additional Slides

Task 2.A: CABLESSail Static and Dynamic Modeling

Null-Space Method

- Allows for the modeling of multi-body systems by kinematically constraining individually modeled components.
- Simple to swap out different components by adjusting constraints.



Library of Component Equations of Motion

$$\mathbf{M}_i\ddot{\mathbf{q}}_i + \mathbf{K}_i\mathbf{q}_i = \mathbf{f}_i + \mathbf{f}_{\text{non}_i}$$

Constraints at Rate Level

For example:

$$\underset{\rightarrow}{v}^{y_1 w}(\dot{\mathbf{q}}_1) = \underset{\rightarrow}{v}^{y_2 w}(\dot{\mathbf{q}}_2) \text{ or } \underset{\rightarrow}{\omega}^{b_1 a}(\dot{\mathbf{q}}_1) = \underset{\rightarrow}{\omega}^{b_2 a}(\dot{\mathbf{q}}_2)$$

$$\boldsymbol{\Xi}_1\dot{\mathbf{q}}_1 + \boldsymbol{\Xi}_2\dot{\mathbf{q}}_2 \cdots + \boldsymbol{\Xi}_n\dot{\mathbf{q}}_n = \mathbf{0}$$

$$\underbrace{\begin{bmatrix}\boldsymbol{\Xi}_1 & \boldsymbol{\Xi}_2 & \cdots & \boldsymbol{\Xi}_n\end{bmatrix}}_{\boldsymbol{\Xi}}\underbrace{\begin{bmatrix}\dot{\mathbf{q}}_1\\ \dot{\mathbf{q}}_2\\ \vdots \\ \dot{\mathbf{q}}_n\end{bmatrix}}_{\dot{\mathbf{q}}} = \mathbf{0}$$

Task 2.A: CABLESSail Static and Dynamic Modeling

Constrained Equations of Motion

$$\underbrace{\begin{bmatrix} \mathbf{M}_1 & \cdots & \mathbf{0} \\ \vdots & \ddots & \vdots \\ \mathbf{0} & \cdots & \mathbf{M}_n \end{bmatrix}}_{\mathbf{M}} \underbrace{\begin{bmatrix} \ddot{\mathbf{q}}_1 \\ \vdots \\ \ddot{\mathbf{q}}_n \end{bmatrix}}_{\ddot{\mathbf{q}}} + \underbrace{\begin{bmatrix} \mathbf{K}_1 & \cdots & \mathbf{0} \\ \vdots & \ddots & \vdots \\ \mathbf{0} & \cdots & \mathbf{K}_n \end{bmatrix}}_{\mathbf{K}} \underbrace{\begin{bmatrix} \mathbf{q}_1 \\ \vdots \\ \mathbf{q}_n \end{bmatrix}}_{\mathbf{q}} = \underbrace{\begin{bmatrix} \mathbf{f}_1 \\ \vdots \\ \mathbf{f}_n \end{bmatrix}}_{\mathbf{f}} + \underbrace{\begin{bmatrix} \mathbf{f}_{\mathrm{non},1} \\ \vdots \\ \mathbf{f}_{\mathrm{non},n} \end{bmatrix}}_{\mathbf{f}_{\mathrm{non}}} + \underbrace{\begin{bmatrix} \mathbf{\Xi}_1^{\mathsf{T}} \\ \vdots \\ \mathbf{\Xi}_n^{\mathsf{T}} \end{bmatrix}}_{\mathbf{\Xi}^{\mathsf{T}}} \boldsymbol{\lambda}$$

$$\mathbf{M}\ddot{\mathbf{q}} + \mathbf{K}\mathbf{q} = \mathbf{f} + \mathbf{f}_{\mathrm{non}} + \mathbf{\Xi}^{\mathsf{T}}\boldsymbol{\lambda}$$

Task 2.A: CABLESSail Static and Dynamic Modeling

Constrained Equations of Motion

$$\mathbf{M}\ddot{\mathbf{q}} + \mathbf{K}\mathbf{q} = \mathbf{f} + \mathbf{f}_{\text{non}} + \boldsymbol{\Xi}^{\mathsf{T}}\boldsymbol{\lambda}$$

Choose Independent Coordinates

For example:

$$\dot{\bar{\mathbf{q}}} = \begin{bmatrix} \dot{\mathbf{r}} \\ \boldsymbol{\omega} \\ \dot{\mathbf{q}}_e \end{bmatrix}$$

Determine Mapping from Dependent to Independent Coordinates

$$\dot{\mathbf{q}} = \boldsymbol{\Upsilon}\dot{\bar{\mathbf{q}}}$$

where

$$\boldsymbol{\Xi}\boldsymbol{\Upsilon} = \mathbf{0}$$

since

$$\boldsymbol{\Xi}\dot{\mathbf{q}} = \mathbf{0}$$

$$\boldsymbol{\Xi}\boldsymbol{\Upsilon}\dot{\bar{\mathbf{q}}} = \mathbf{0}$$

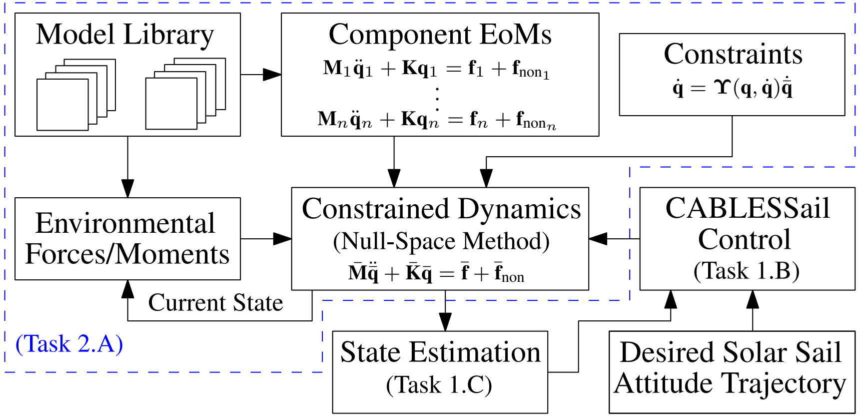
Task 2.A: CABLESSail Static and Dynamic Modeling

Substitute Independent Coordinates into Constrained Equations of Motion

$$\underbrace{\boldsymbol{\Upsilon}^{\mathsf{T}}\mathbf{M}\boldsymbol{\Upsilon}}_{\bar{\mathbf{M}}}\ddot{\bar{\mathbf{q}}} + \underbrace{\boldsymbol{\Upsilon}^{\mathsf{T}}\mathbf{K}\mathbf{q}}_{\bar{\mathbf{K}}\bar{\mathbf{q}}} = \underbrace{\boldsymbol{\Upsilon}^{\mathsf{T}}\mathbf{f}}_{\bar{\mathbf{f}}} + \underbrace{\boldsymbol{\Upsilon}^{\mathsf{T}}\left(\mathbf{f}_{\text{non}} - \mathbf{M}\dot{\boldsymbol{\Upsilon}}\dot{\bar{\mathbf{q}}}\right)}_{\bar{\mathbf{f}}_{\text{non}}} + \cancelto{\mathbf{0}}{\boldsymbol{\Upsilon}^{\mathsf{T}}\boldsymbol{\Xi}^{\mathsf{T}}\boldsymbol{\lambda}}$$

Constrained Equations of Motion Without Lagrange Multipliers

$$\bar{\mathbf{M}}\ddot{\bar{\mathbf{q}}} + \bar{\mathbf{K}}\bar{\mathbf{q}} = \bar{\mathbf{f}} + \bar{\mathbf{f}}_{\text{non}}$$



Model Library

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$\vdots$

$\mathbf{M}_n\ddot{\mathbf{q}}_n + \mathbf{K}\mathbf{q}_n = \mathbf{f}_n + \mathbf{f}_{\text{non}_n}$

Constraints

$\dot{\mathbf{q}} = \boldsymbol{\Upsilon}(\mathbf{q}, \dot{\mathbf{q}})\dot{\bar{\mathbf{q}}}$

Environmental Forces/Moments

Constrained Dynamics (Null-Space Method)

$\bar{\mathbf{M}}\ddot{\bar{\mathbf{q}}} + \bar{\mathbf{K}}\bar{\mathbf{q}} = \bar{\mathbf{f}} + \bar{\mathbf{f}}_{\text{non}}$

CABLESSail Control (Task 1.B)

Current State

(Task 2.A)

State Estimation (Task 1.C)

Desired Solar Sail Attitude Trajectory

Validation & Mission Scenario Testing

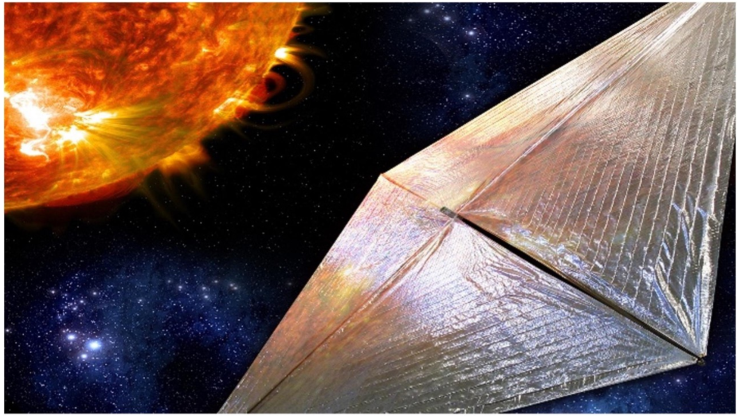
Validate Dynamic Model

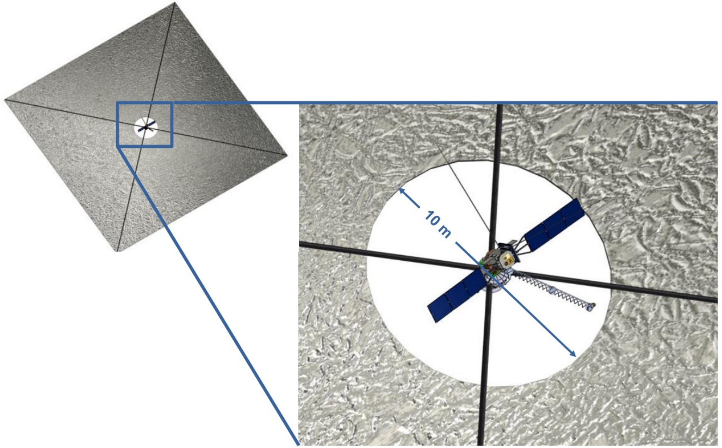
- Perform checks on simulation code (energy & momentum conservation).
- Compare to models in the literature and MSFC code.

Mission Scenario Testing

- Test attitude control maneuvers within Solar Cruiser and SPI mission scenarios.
- Obtain benchmark results.

Case	Out-of-Plane (Roll) Torque (N-m)	In-Plane (Pitch/Yaw) Torque (N-m)
Solar Cruiser (1684 m^2) 0^0 SIA	$4.7x10^{-6}$	$5.5x10^{-5}$
Solar Cruiser (1684 m^2) 35^0 SIA	$4.9x10^{-5}$	$2.4x10^{-3}$
SPI (7000 m^2) 0^0 SIA	$7.7x10^{-5}$	$4.6x10^{-3}$
SPI (7000 m^2) 35^0 SIA	$6.4x10^{-4}$	$4.7x10^{-2}$

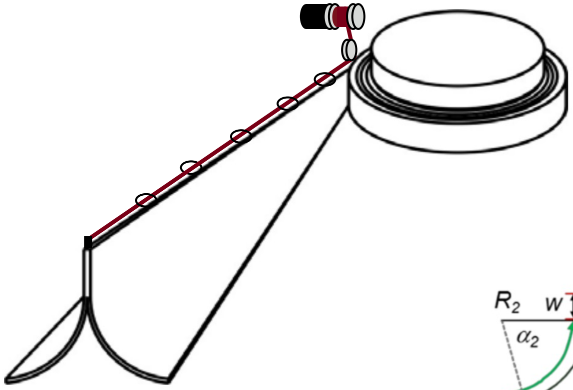


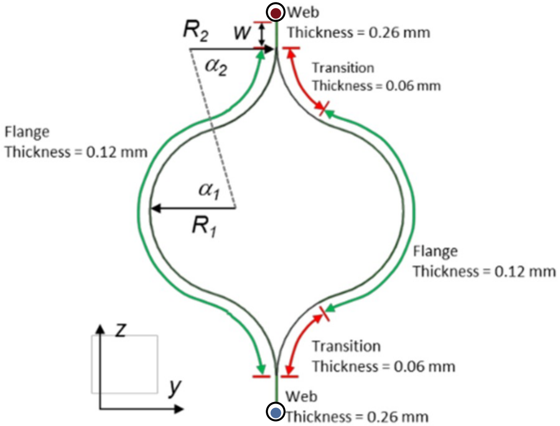


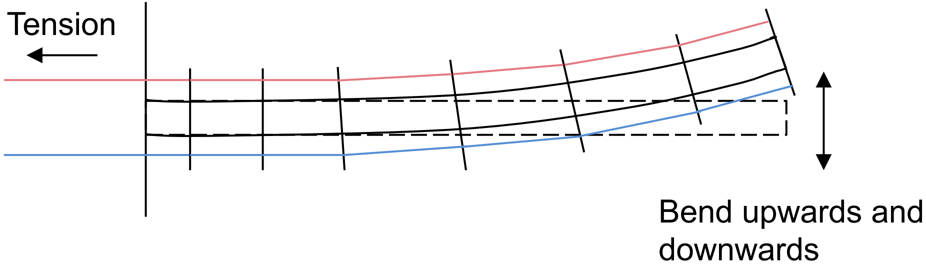
CABLESSail Hardware/Configuration Design

Hardware/Configuration

- Continue investigating 3 possible boom designs:
  - Continuum cable robotics design
    - Deployability?
  - TRAC boom and ACS3
    - Ease of integration?
    - Twist capability?
- New Undergrad Senior Design Team in Fall 2023 will develop detailed deployable design.
- Will iterate on design once testing begins in simulation and on prototypes.

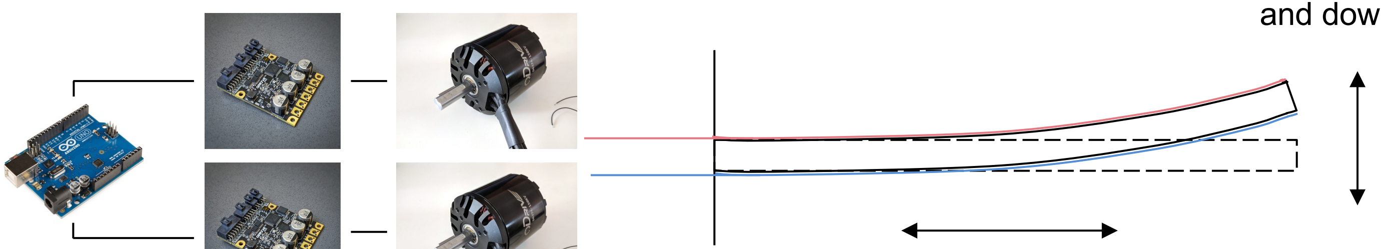






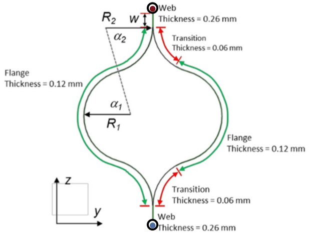
Prototype 2a/2b: ACS3 and TRAC Booms

Prototype 2a (Integrated with ACS3 Boom Design)

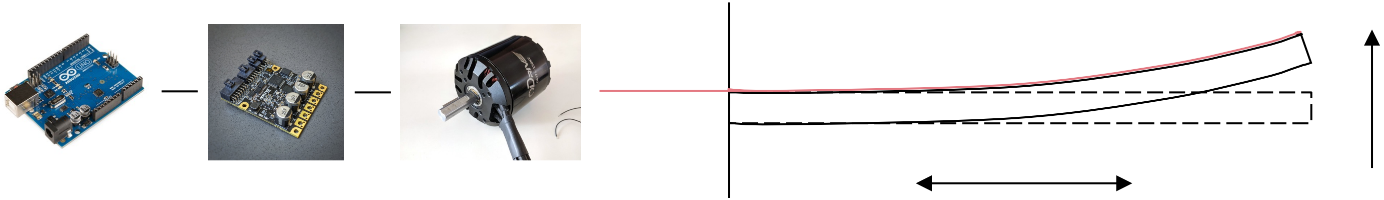


Bend upwards and downwards

Possibly incorporate deployment and twisting in prototype

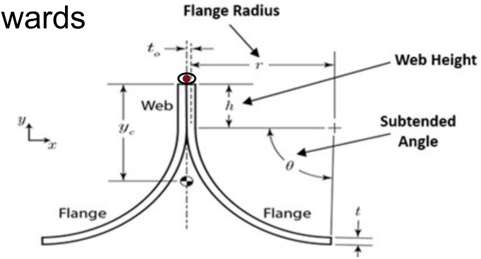


Prototype 2b (Integrated with TRAC Boom Design)



Bend upwards

Possibly incorporate deployment and twisting in prototype



Project Milestones

Milestone I (Year 1, Q4)

- Initial design complete.

Milestone II (Year 2, Q2)

- Simulation code complete/validated (TRL 2).

Milestone III (Year 2, Q3)

- Prototype built.

Milestone IV (Year 3, Q3)

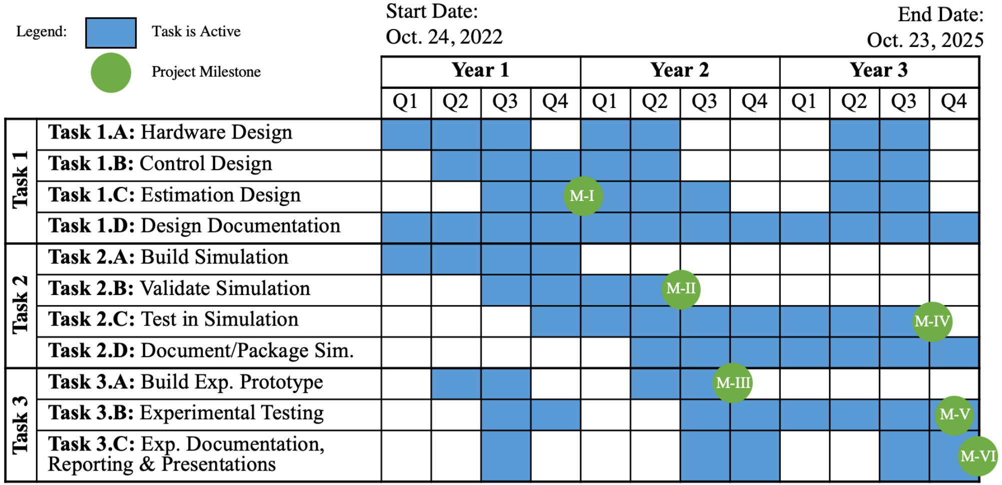
- Simulation of mission scenarios tested/benchmarked.

Milestone V (Year 3, Q4)

- Prototype testing complete **(TRL 3)**.

Milestone VI (Year 3, Q4)

- Documentation, final report, sharing of open-source code.



Legend: 🟦 Task is Active

● Project Milestone

Start Date:
Oct. 24, 2022

End Date:
Oct. 23, 2025

		Year 1				Year 2				Year 3			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1	**Task 1.A:** Hardware Design	🟦	🟦	🟦		🟦	🟦				🟦	🟦	
	Task 1.B: Control Design		🟦	🟦	🟦	🟦	🟦				🟦	🟦	
	Task 1.C: Estimation Design			🟦	🟦 M-I	🟦	🟦	🟦			🟦	🟦	
	Task 1.D: Design Documentation	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Task 2	**Task 2.A:** Build Simulation	🟦	🟦	🟦	🟦								
	Task 2.B: Validate Simulation			🟦	🟦	🟦	🟦 M-II						
	Task 2.C: Test in Simulation				🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦 M-IV	
	Task 2.D: Document/Package Sim.						🟦	🟦	🟦	🟦	🟦	🟦	🟦
Task 3	**Task 3.A:** Build Exp. Prototype		🟦	🟦			🟦	🟦 M-III					
	Task 3.B: Experimental Testing			🟦	🟦			🟦	🟦	🟦	🟦	🟦	🟦 M-V
	Task 3.C: Exp. Documentation, Reporting & Presentations			🟦				🟦	🟦			🟦	🟦 M-VI