ARGO
SPACE CORP

Navigator Radiators

Radiator Testing Tag-Up

Presenter: Jonathan Vollrath

5 – 16 - 2025

Jonathan Vollrath [jonathan@argospace.com]

Overview

Motivations

- Successful deployment of radiators essential to mission success
- Inability to test mechanism before Navigator mission

Approach

- Combine kinematics model and deployment rig to ensure maximum confidence of successful deployment
- Deployment rig -> gravity offloading

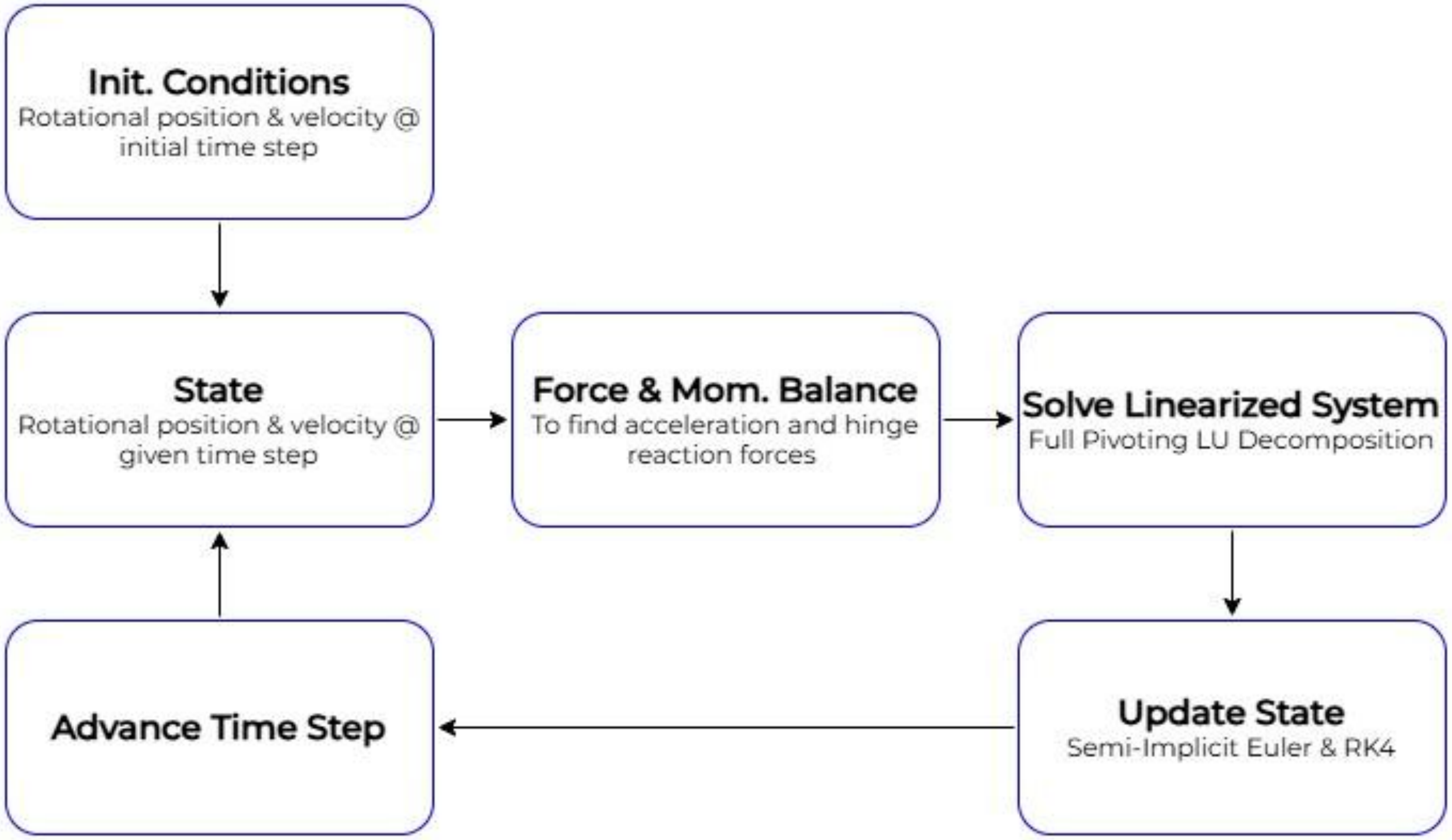
Model - Overview

Approach

- System boils down to 5 DOF coupled system (Inherent non-linearity from coupled dynamics, rotational kinematics, and hard-stops resulting in DAE system)
    - Pseudo-linearization via time discretization
        - For a given rotational position and velocity, sum forces and moments to solve for accelerations and reaction forces
        - Numerically approximate next step given these values
- Newtonian method over Lagrangian (energy based) to preserve reaction forces
- Include static and viscous hinge friction terms to correlate to hardware

Model – Overview

Block Diagram



Model – A Bit of the Weeds

Terminology

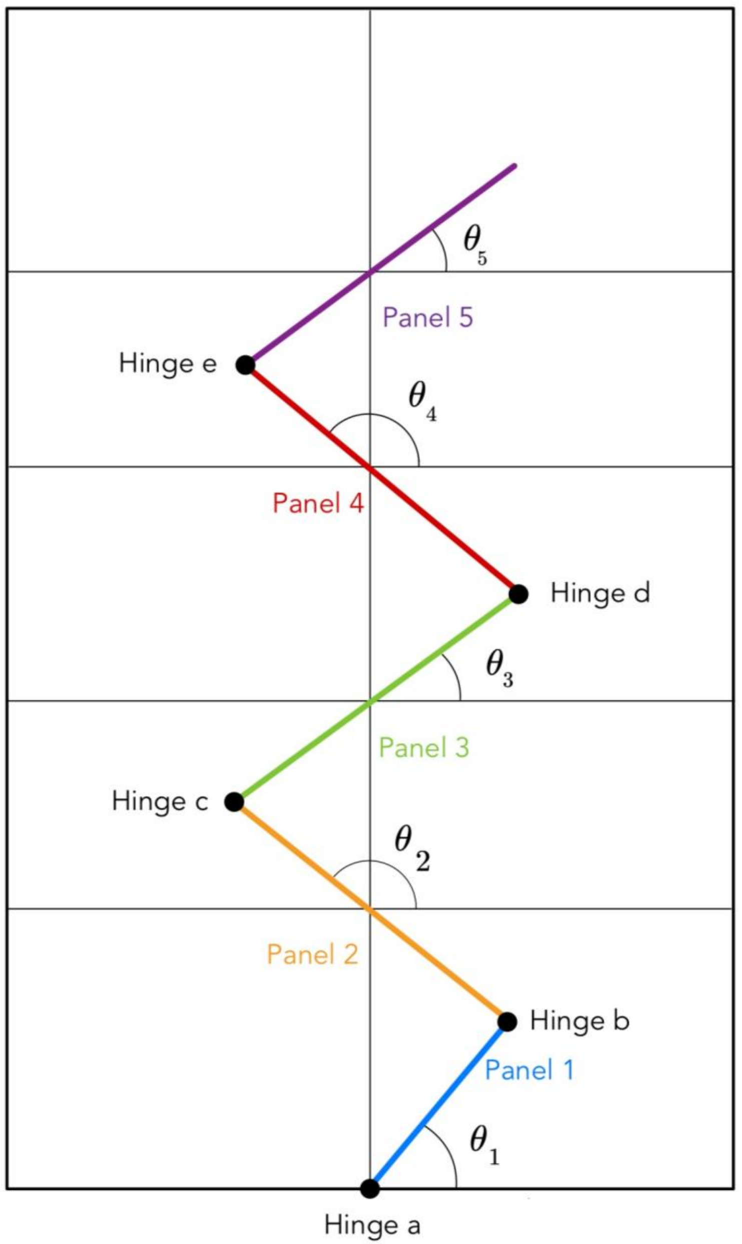
- Hinges referred to with letters, panels numbers
- Forces referred to by root hinge

General Approach

- Summation of moments done about root hinge

$$\Sigma F = m_1 \vec{a}_1 = m_1 \begin{bmatrix} -\ddot{\theta}_1 \frac{w_1}{2} \sin(\theta_1) - \frac{w_1}{2} \dot{\theta}_1^{\,2} \cos(\theta_1) \\ \ddot{\theta}_1 \frac{w_1}{2} \cos(\theta_1) - \frac{w_1}{2} \dot{\theta}_1^{\,2} \sin(\theta_1) \end{bmatrix} = \vec{F}_a - \vec{F}_b$$

$$\Sigma \tau_1 = I_1 \ddot{\theta}_1 = 4\, k_a \left(\frac{3\pi}{2} - \theta_1\right) - 4\, k_b \left(\pi - \theta_1 + \theta_2\right) + \vec{r}_{a \to b} \times (-\vec{F}_b)$$



Model – A Bit of the Weeds

System Setup (System Matrix)

$$
\begin{bmatrix}
-m_1\frac{w_1}{2}\sin(\theta_1) & 0 & 0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-m_1 w_1\sin(\theta_1) & -m_2\frac{w_2}{2}\sin(\theta_2) & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
-m_1 w_1\sin(\theta_1) & -m_2 w_2\sin(\theta_2) & -m_3\frac{w_3}{2}\sin(\theta_3) & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 & 0 \\
-m_1 w_1\sin(\theta_1) & -m_2 w_2\sin(\theta_2) & -m_3 w_3\sin(\theta_3) & -m_4\frac{w_4}{2}\sin(\theta_4) & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 1 & 0 \\
-m_1 w_1\sin(\theta_1) & -m_2 w_2\sin(\theta_2) & -m_3 w_3\sin(\theta_3) & -m_4 w_4\sin(\theta_4) & -m_5\frac{w_5}{2}\sin(\theta_5) & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 \\
\frac{w_1}{2}\cos(\theta_1) & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
w_1\cos(\theta_1) & \frac{w_2}{2}\cos(\theta_2) & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 & 0 & 0 \\
w_1\cos(\theta_1) & w_2\cos(\theta_2) & \frac{w_3}{2}\cos(\theta_3) & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 \\
w_1\cos(\theta_1) & w_2\cos(\theta_2) & w_3\cos(\theta_3) & \frac{w_4}{2}\cos(\theta_4) & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 1 \\
w_1\cos(\theta_1) & w_2\cos(\theta_2) & w_3\cos(\theta_3) & w_4\cos(\theta_4) & \frac{w_5}{2}\cos(\theta_5) & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 \\
\frac{1}{3}m_1 w_1^2 & 0 & 0 & 0 & 0 & 0 & 0 & -w_1\sin(\theta_1) & w_1\cos(\theta_1) & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{1}{3}m_2 w_2^2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -w_2\sin(\theta_2) & w_2\cos(\theta_2) & 0 & 0 & 0 & 0 \\
0 & 0 & \frac{1}{3}m_3 w_3^2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -w_3\sin(\theta_3) & w_3\cos(\theta_3) & 0 & 0 \\
0 & 0 & 0 & \frac{1}{3}m_4 w_4^2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -w_4\sin(\theta_4) & w_4\cos(\theta_4) \\
0 & 0 & 0 & 0 & \frac{1}{3}m_5 w_5^2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\ddot{\theta}_1 \\ \ddot{\theta}_2 \\ \ddot{\theta}_3 \\ \ddot{\theta}_4 \\ \ddot{\theta}_5 \\ F_{ax} \\ F_{ay} \\ F_{bx} \\ F_{by} \\ F_{cx} \\ F_{cy} \\ F_{dx} \\ F_{dy} \\ F_{ex} \\ F_{ey}
\end{bmatrix}
$$

Model – A Bit of the Weeds

System Matrix Setup (RHS Vector)

$$
\begin{bmatrix}
\frac{w_1}{2}\dot{\theta}_1^2\cos(\theta_1) \\
w_1\dot{\theta}_1^2\cos(\theta_1) + \frac{w_2}{2}\dot{\theta}_2^2\cos(\theta_2) \\
w_1\dot{\theta}_1^2\cos(\theta_1) + w_2\dot{\theta}_2^2\cos(\theta_2) + \frac{w_3}{2}\dot{\theta}_3^2\cos(\theta_3) \\
w_1\dot{\theta}_1^2\cos(\theta_1) + w_2\dot{\theta}_2^2\cos(\theta_2) + w_3\dot{\theta}_3^2\cos(\theta_3) + \frac{w_4}{2}\dot{\theta}_4^2\cos(\theta_4) \\
w_1\dot{\theta}_1^2\cos(\theta_1) + w_2\dot{\theta}_2^2\cos(\theta_2) + w_3\dot{\theta}_3^2\cos(\theta_3) + w_5\dot{\theta}_4^2\cos(\theta_4) + \frac{w_5}{2}\dot{\theta}_5^2\cos(\theta_5) \\
\frac{w_1}{2}\dot{\theta}_1^2\sin(\theta_1) \\
w_1\dot{\theta}_1^2\sin(\theta_1) + \frac{w_2}{2}\dot{\theta}_2^2\sin(\theta_2) \\
w_1\dot{\theta}_1^2\sin(\theta_1) + w_2\dot{\theta}_2^2\sin(\theta_2) + \frac{w_3}{2}\dot{\theta}_3^2\sin(\theta_3) \\
w_1\dot{\theta}_1^2\sin(\theta_1) + w_2\dot{\theta}_2^2\sin(\theta_2) + w_3\dot{\theta}_3^2\sin(\theta_3) + \frac{w_4}{2}\dot{\theta}_4^2\sin(\theta_4) \\
w_1\dot{\theta}_1^2\sin(\theta_1) + w_2\dot{\theta}_2^2\sin(\theta_2) + w_3\dot{\theta}_3^2\sin(\theta_3) + w_5\dot{\theta}_4^2\sin(\theta_4) + \frac{w_5}{2}\dot{\theta}_5^2\sin(\theta_5) \\
4k_a(\frac{3\pi}{2} - \theta_1) + 4k_b(\pi - \theta_1 + \theta_2) \\
-4k_b(\pi - \theta_1 + \theta_2) - 4k_c(\pi + \theta_2 - \theta_3) \\
4k_c(\pi + \theta_2 - \theta_3) + 4k_d(\pi - \theta_3 + \theta_4) \\
-4k_d(\pi - \theta_3 + \theta_4) - 4k_e(\pi + \theta_4 - \theta_5) \\
4k_e(\pi + \theta_4 - \theta_5)
\end{bmatrix}
$$

Model – A Bit of the Weeds

System Matrix Setup (Coulomb & Viscous Friction)

- Each moment summation gets additional friction terms on RHS Vector
- Hyperbolic tan present to prevent numerical instability near zero velocity
- Coefficient of friction approx. 0.1 (PTFE Impregnated Aluminum on PEEK)
- Damping coefficient 0.05 (based on designed fit)
- Both root and branch frictions apply to given panel
- Root radial forces for coulomb friction use radial forces from previous time step

$$\tau_{Coulomb} = -\mu||\vec{F}_{root}||tanh(100\dot{\theta}_{root})$$

$$\tau_{viscous} = -b\dot{\theta}_i$$

Model – A Bit of the Weeds

System Matrix Setup (Hard Stop Kinematics)

- Hard stops affect only moment summations (equations 11 – 15)

- Hard stops modelled as unidirectionally damped spring-damper (k = 50, b = 20)

$$\tau_{hardstop-a1} = -k(\theta_1 - \frac{\pi}{2}) - b\dot{\theta}_1, \text{ for } \theta_1 > \frac{\pi}{2}$$

$$\tau_{hardstop-b2} = k(\theta_1 - \theta_2) + b(\dot{\theta}_1 - \dot{\theta}_2), \text{ for } \theta_1 > \theta_2$$

$$\tau_{hardstop-c3} = -k(\theta_3 - \theta_2) - b(\dot{\theta}_3 - \dot{\theta}_2), \text{ for } \theta_3 > \theta_2$$

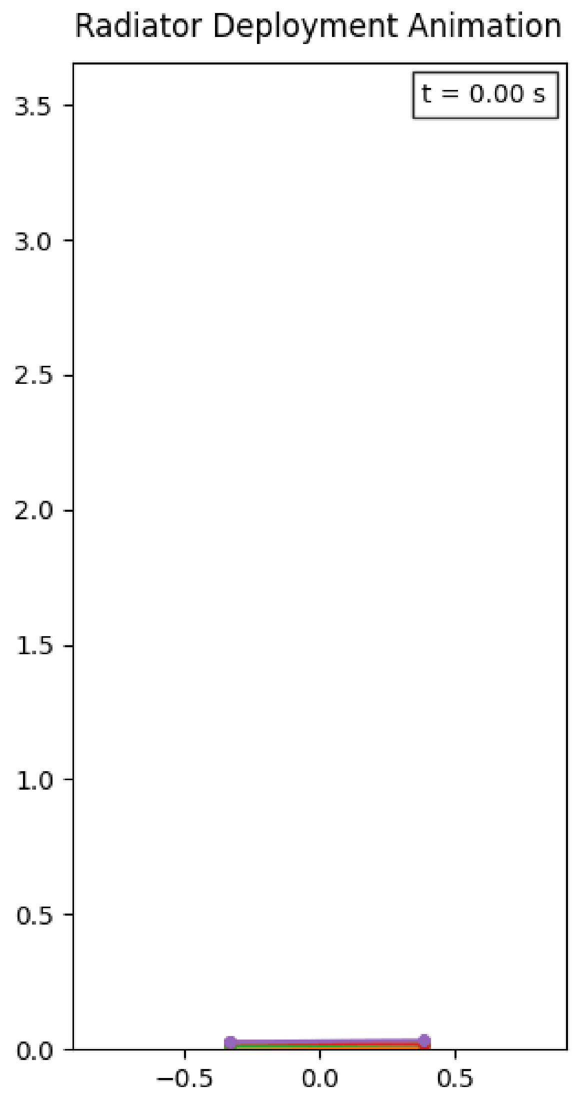
$$\tau_{hardstop-d4} = k(\theta_3 - \theta_4) + b(\dot{\theta}_3 - \dot{\theta}_4), \text{ for } \theta_3 > \theta_4$$

$$\tau_{hardstop-e5} = -k(\theta_5 - \theta_4) - b(\dot{\theta}_5 - \dot{\theta}_4), \text{ for } \theta_5 > \theta_4$$

Model – Optimization

Model Optimizes for 10s Deployment

- This is NOT a hard requirement, and can/will be adjusted throughout testing
- Does NOT include hard stop mechanics to minimize number of solutions
- A bit finicky – optimizer can get stuck on critical points
- Optimizes for 10 sec, “perfect” deployment
  - Each panel reaches hard stop at same time
  - Inherently minimizes lateral cg displacement



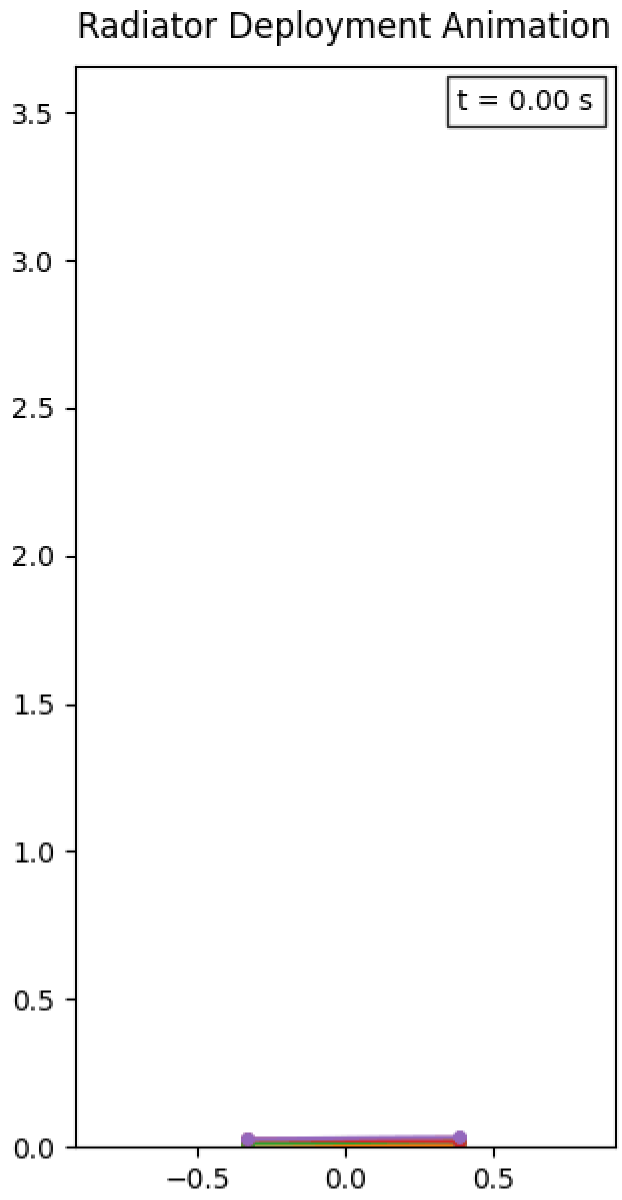

```
Optimized stiffness values:
0.000458354 0.00272724 0.00194915 0.00212127 0.000776445
Final cost: 0.0254341
Number of Optimization Iterations: 179
```

Model – Input

Model takes Input Torsional Stiffnesses

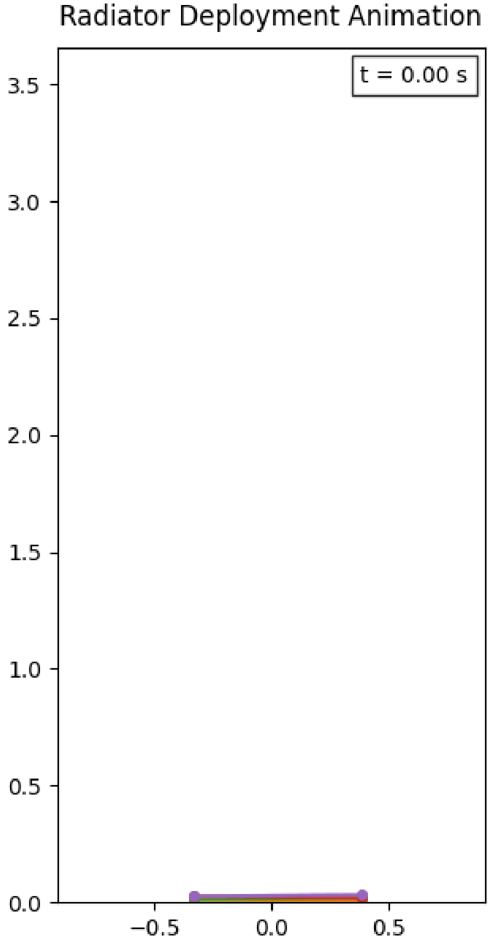
- Primarily for testing effects of different choices
    - Allows for use of stock springs, though flight will likely have custom
- Includes hard stop mechanics
- Optimization gives good first “guess”, but needs to be iterated on to allow for good steady state behavior
- Great for off-nominal deployment testing

```
System simulated with spring constants:
0.000458354  0.00272724  0.00194915  0.00212127 0.000776445
```

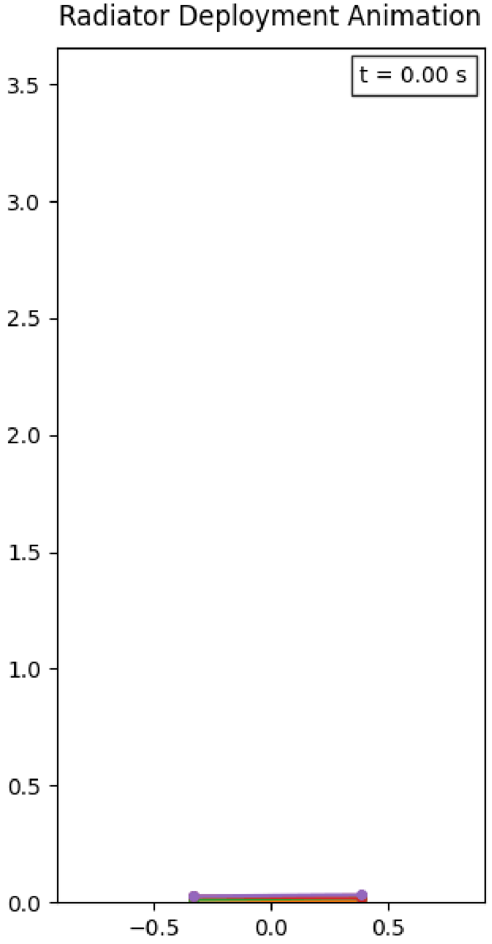


Model – Input

Testing Different Inputs (All Stock)




```
System simulated with spring constants:
0.00312298 0.00495003 0.00312298 0.00312298 0.00156149
```




```
System simulated with spring constants:
0.00312298 0.00312298 0.00312298 0.00312298 0.00156149
```

Deployment Rig - Overview

Approach

- Radiators deploy in microgravity of orbit therefore deployment needs to be tested in similar conditions
- Obviously, this is a problem that is not singular to our radiators
  - Narrowing down viable options
- <u>Minimize inertial contribution of system suspension mechanism (5% → 150g)</u>
- Minimize cost and complexity
- Deployment rig will be large, will draw eyes of visitors/investors, we want it to be solid and look professionally made

Deployment Rig – Approach

Different Options

Horizontal Systems

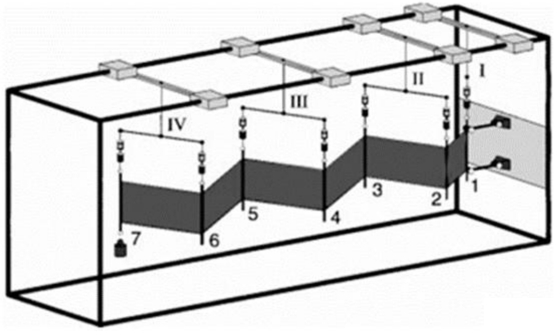
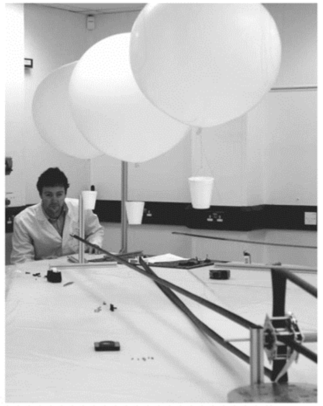


Fig. 3 Solar array deployment test setup, [1



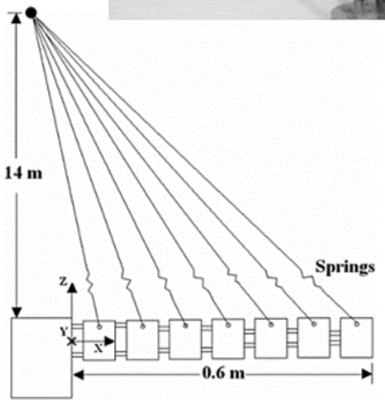


Fig. 3.11 Suspension scheme [47, Fig. 4] for the CubeSat solar array deployment test shown in Fig. 3.10.

Vertical Systems

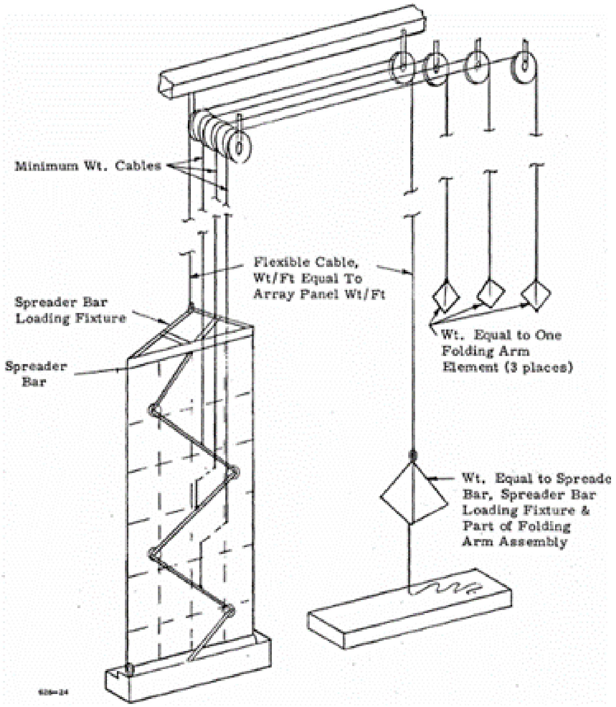


Fig. 3.5 Vertical deployment test schematic with multiple suspension points [37, Fig. 2.5.2-1].

Deployment Rig – Approach

Different Options

Passive Suspension (Rollers)

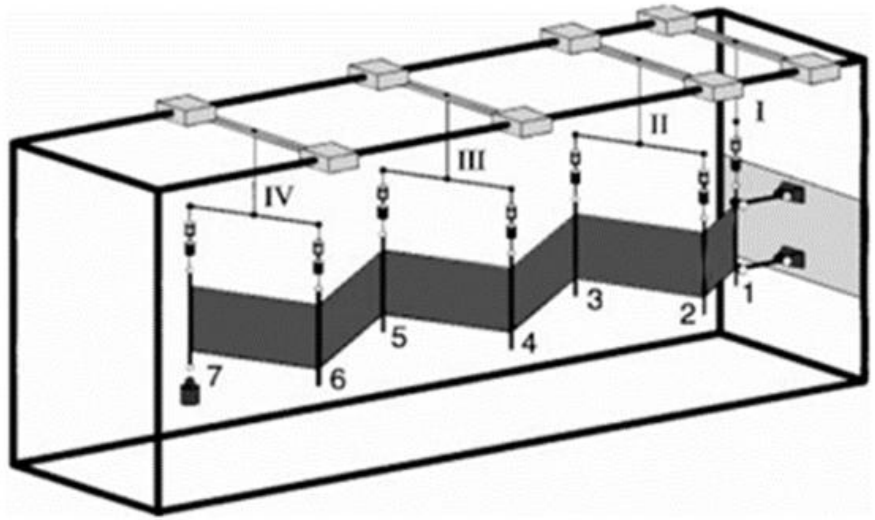
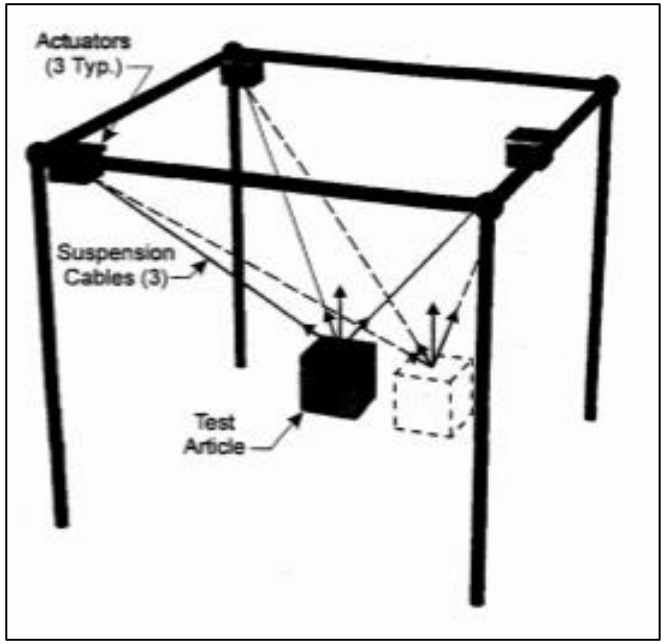


Fig. 3 Solar array deployment test setup, [1].

Active Suspension



Deployment Rig – Design

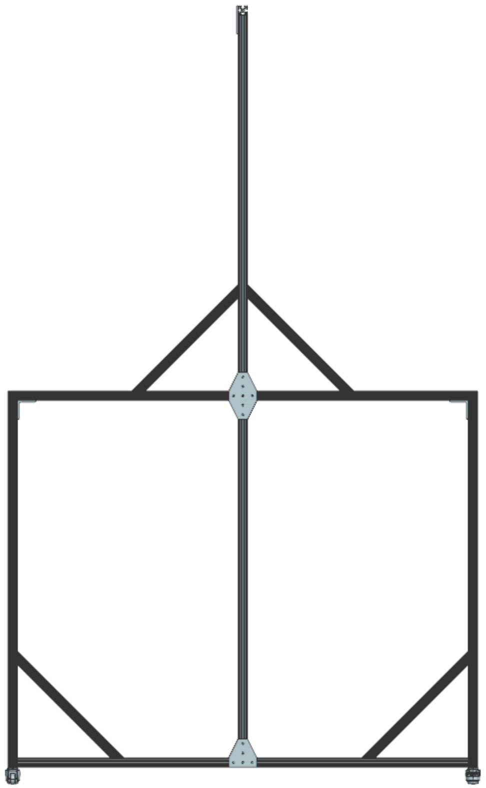
Considerations

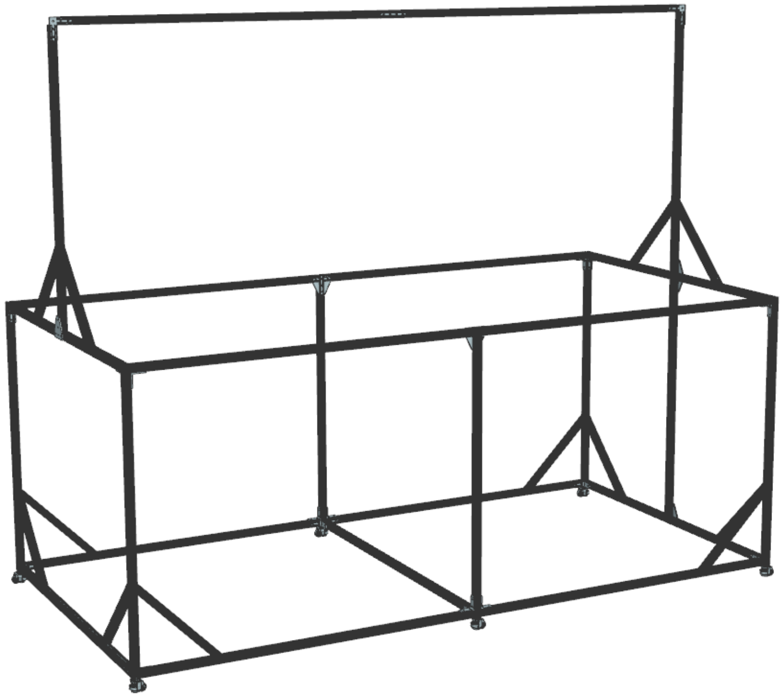
- Max torque of hinges on the order of 0.15
- To limit effect of rig on deployment:
  - Increase height of rig as much as possible within reasonable limits
  - Limit lateral CG displacement → aiming for "perfect" deployment

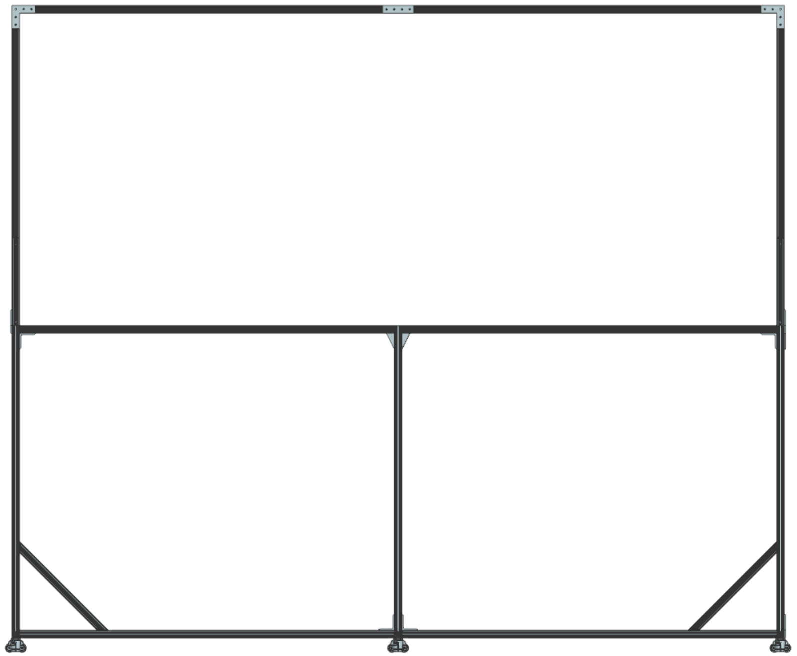
Maximum CG Displacement (m)	Rig Height (m)	Panel Height (m)	Correcting Force (N)	Restoring Torque (N-m)
0.10	1.524	0.515	0.386	0.139
0.18	1.524	0.515	0.694	0.250
0.50	1.524	0.515	1.928	0.694
0.10	3.048	0.515	0.218	0.079
0.18	3.048	0.515	0.393	0.142
0.50	3.048	0.515	1.092	0.393
0.10	3.658	0.515	0.186	0.067
0.18	3.658	0.515	0.335	0.121
0.50	3.658	0.515	0.930	0.335

Deployment Rig – Design

Primary Structure Design



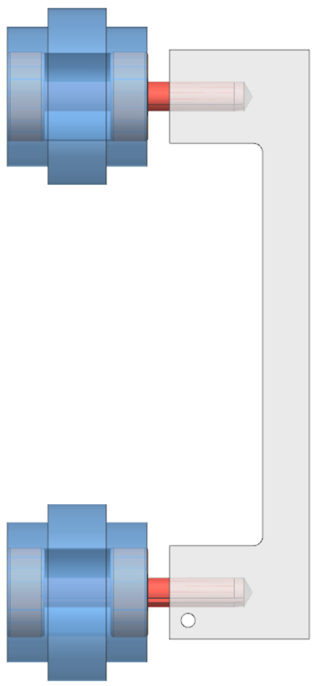


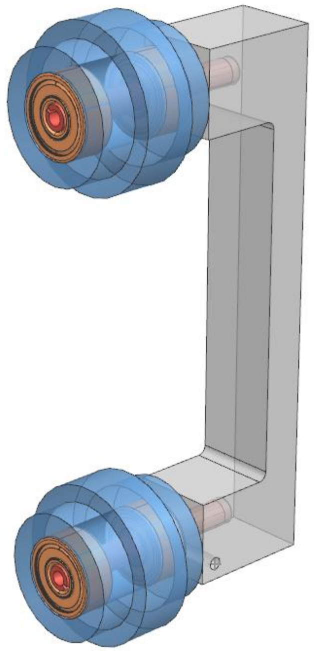


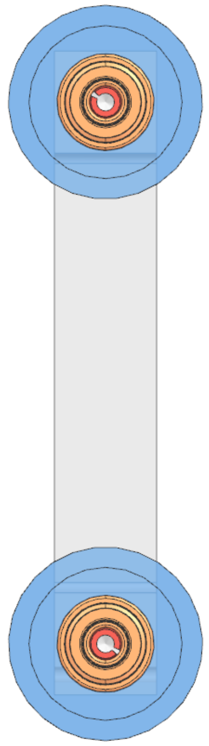
Deployment Rig – Design

Roller Design (0.0354 kg ≈ 4.7%)

- COTS options more expensive ($117 each) and weigh too much (300 g each)







Deployment Rig – Design

Bill of Materials

Name	Description	Vendor (or Part #)	Quantity	Cost/item	Total Cost
Threaded Single T-Slot Framing (5ft)	With threaded hole (3/8 - 16) on one end for casters - 1 1/2	4601N37	6	$ 52.08	$ 312.48
Single T-Slot Solid (6ft)	Solid for base - 1 1/2	47065T103	7	$ 64.73	$ 453.11
Single T-Slot Hollow (6ft)	Second levels - 1 1/2	47065T102	6	$ 46.50	$ 279.00
Threaded Stem Leveling Casters	Stem casters for mobility with 3/8 - 16 stem	2445T51	6	$ 25.52	$ 153.12
T-Slot Diagonal Bracket (24")	For support at base and at lateral support - 1 1/2	47065T704	12	$ 40.77	$ 489.24
Single T-Slot Hollow (8ft)	For cross beam - 1 1/2	47065T102	2	$ 60.49	$ 120.98
T-Slot Corner Bracket (Extended)	For support throughout structure - 1 1/2	47065T241	20	$ 9.54	$ 190.80
Single T-Slot Hollow (5ft)	For second floor vertical supports & radiator mounting - 1 1/2	47065T102	3	$ 43.06	$ 129.18
T-Slot Surface Bracket Tee	For radiator mounting - 1 1/2	47065T279	4	$ 13.93	$ 55.72
T-Slot Surface Straight Bracket (Extended)	To support cross beam in middle - 1 1/2	47065T261	1	$ 13.46	$ 13.46
Roller Housing	In house design - 1 1/2	Xometry	6	$ 39.58	$ 237.48
Roller Wheel	In house design - 1 1/2	Xometry	12	$ 15.49	$ 185.88
Radiator Attachment Piece	In house design	SendCutSend	1	$ 36.91	$ 36.91
T-Slot Framing End-Feed Fastener	To secure radiator attachment piece to t-slot framing	6000N202	1	$ 6.67	$ 6.67
Ball Bearings	For rollers	60355K209	24	$ 7.45	$ 178.80
Total			111		$ 2,842.83

Radiator Testing – Primary Worries

Effect of Suspension not Correctable

- Current plan is to add correcting forces of suspension to new model to tune sim, then plug same springs back into original model
  - New sim needs: moments across panels & correcting forces
  - Plan requires overlap of deployable on rig and deployable in flight
  - Springs on suspension cables may help, ultra-low friction bearings (expensive), motor driven track for rollers
  - If all else fails: Active 2 DOF Suspension
- Reliability of radiator deployment depends on accuracy of sim (both flight and rig)

Radiator Testing – Data Gathering/Processing

Data Gathering

- Camera for data collection
  - Will take some time to learn/implement computer vision aspect, will starting build before
  - Definitely exists already, may only require adaptation to our setup
- Will need to trade stand-alone system vs. some connectivity to computers

Data Processing

- Will need to convert gathered data on rig to “equivalent” flight deployment
  - Will start this while waiting for parts

Failure Modes

- Golf Club Failure:
  - Bending moments caused by deployment or hard stops
- Hinge Sticking Failure:
  - Hinges become stuck due to galling, thermal expansion, etc.
- Launch Lock Mechanism Sticking Failure:
  - Non-axial Launch Lock Mechanism release preventing hinges from deploying
- Asymmetric Deployment:
  - Deployment outside bounding box interfering with solar panels/forcing CONOPs

Radiator Testing – Successful Testing

Type	Name	Necessity	Primary Text, "The system shall...":	Source/Rationale
Requirement	Succesful flight deployment	5	Over the course of 10 tests, predict successful deployment of radiators given flight parameters with an FOS of at least 1.5 on all stresses experienced during deployment.	Radiators flight critical.
Requirement	Non-interference flight deployment	4	Over the course of 10 tests, predict a deployment that does not interfere with solar panels or other subsystems in such a way that forces CONOPs decisions. (Needs more details)	Forcing CONOPs decisions this early, generally considered bad.
Requirement	No deflection under flight loads	4	Over the course of 10 tests, predict a steady state that, under flight loads, does not deflect in such a way that causes interference with solar panels or other subsystems. (Needs more details)	Though flight loads are minimal, steady state of radiators needs to be such that they don't interfere with other subsystems, see above.
Requirement	Rig-Flight Correction	3	For tests on the rig, lateral cg displacement shall be minimized such that it can be corrected for in the flight model	Presence of gravity means we cannot run full system test until in flight, combination of simulation and rig gives highest assurance of success.