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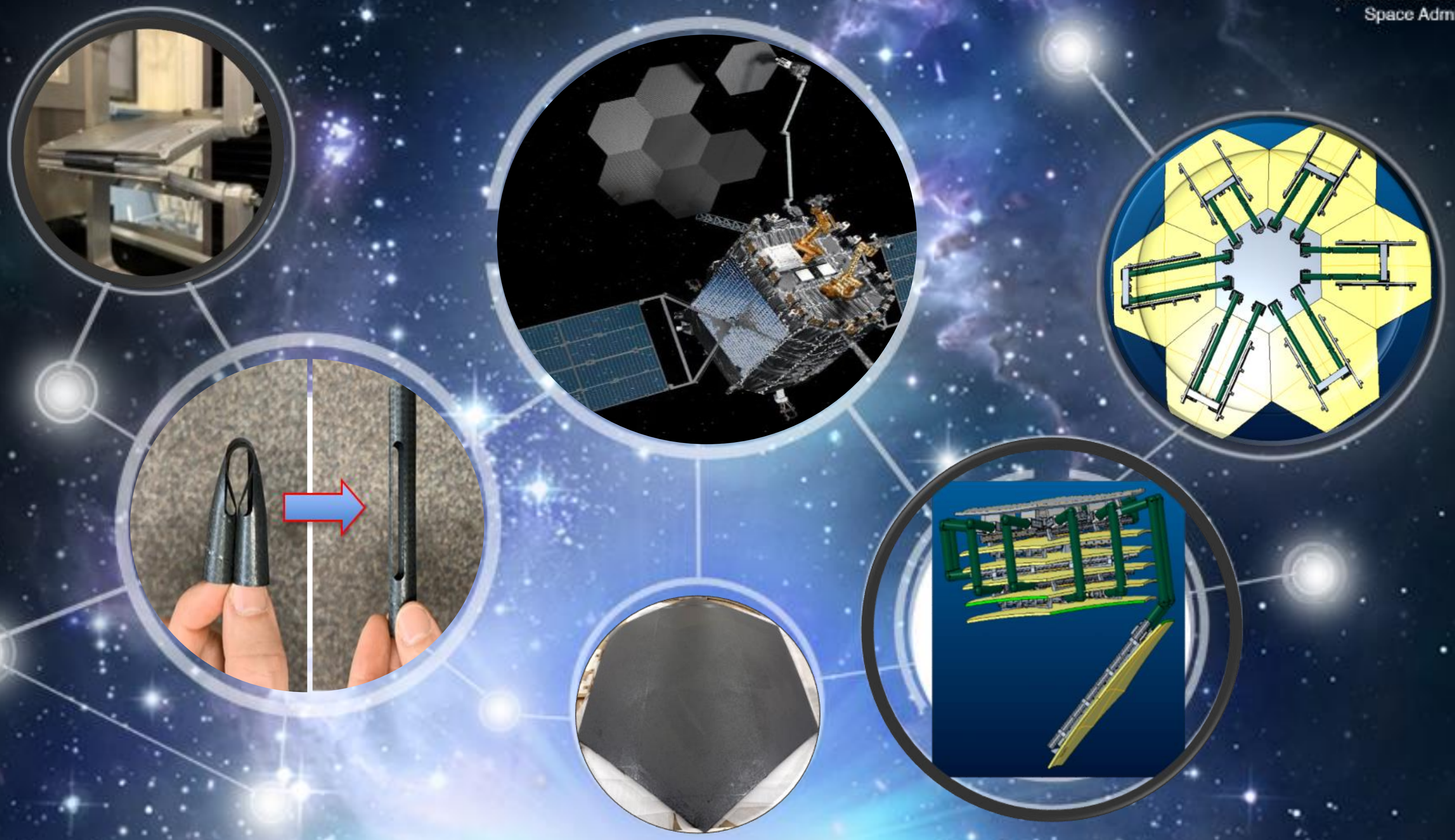
National Aeronautics and Space Administration



Segmented Hexagonal Antenna Reflector Concentrically Stacked Using Shape Memory Composite Tubular Hinges

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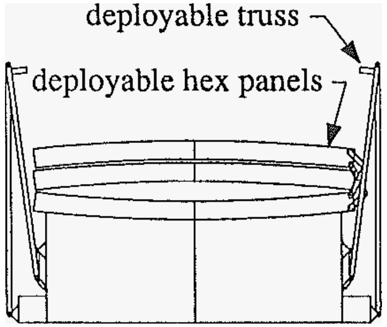
Introduction

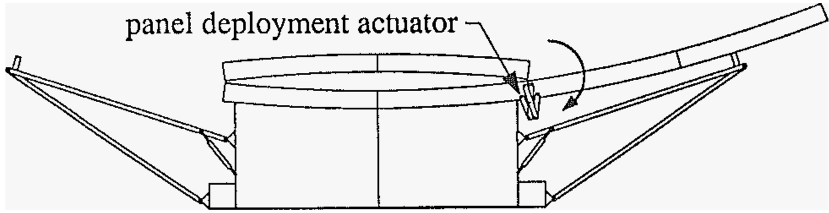
➢ Background and State-of-the-art

- Fixed solid surface antenna radiofrequency (RF) reflectors up to 4-m size and can target > Ka-Band RF. Deployable versions with rigid panels target up to 10-m class due to mechanical complexity to stow/deploy, volume, and mass.

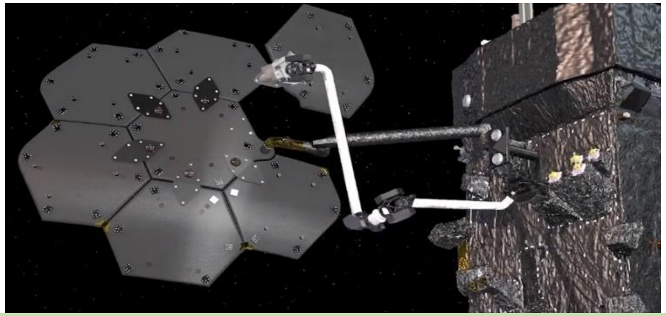
- Deformable versions using mesh or thin-shell composite reflective surface construction are possible but have size limitation due to surface accuracy requiring deep backbones.

- In-space assembly (ISA) viewed as alternative approach for > 10 m scale. Current concepts like the Space Infrastructure Dexterous Robot (SPIDER) rely on robotic arm to assemble many individual panels that do not package well and require complicated techniques for joining and multiple operations, increasing cost and risk.





Space Construction Operations Performance Experiment (SCOPE) stowed and with one panel and support truss member deployed



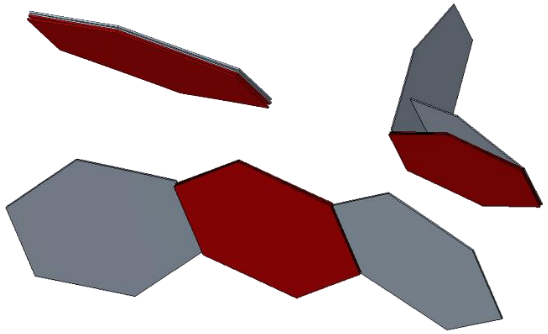
SPIDER experiment by Maxar on NASA On-orbit Servicing, Assembly and Manufacturing (OSAM-1) mission will robotically assemble in space a 3-m scale reflector from seven 1-m rigid segments fixed to the spacecraft

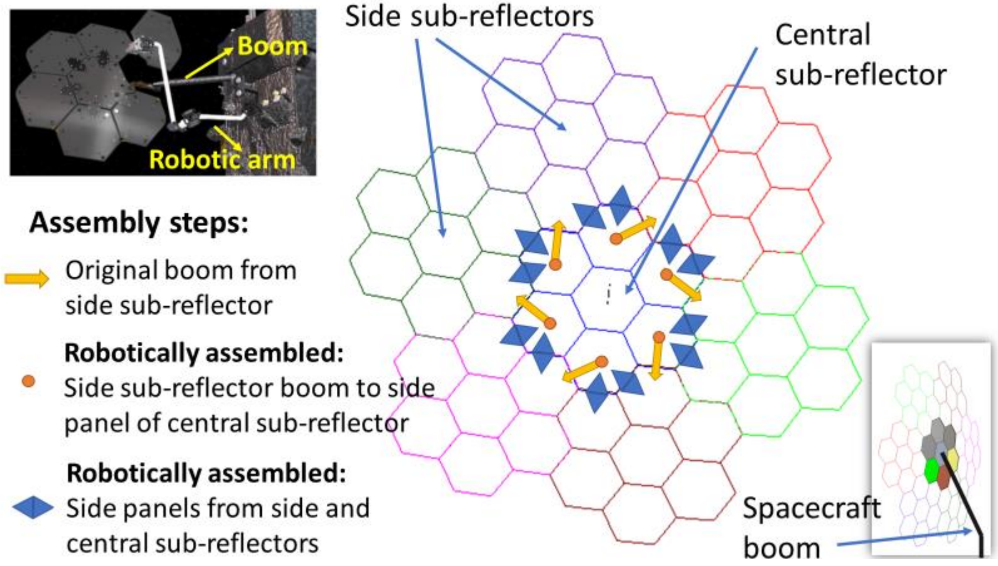
Introduction

➢ Technical capability goals

- Develop dimensionally and thermally stable and deformable (yet stiff) composite substrate material that enables efficient packaging of solid surface segmented antenna reflectors.
- Create a folding scheme and architecture that enables deployment of up to 10-m size sub-reflectors that are still compatible with in-space robotic assembly for larger versions.
- Investigated thin-shell construction of the foldable substrate using High Strain Composites (HSC) and Shape Memory Composites (SMC) to enable a solution that has high packaging efficiency and low mass, while simplifying stowage/deployment via low part count.

One alternative simple stowage approach proposed by NASA using HSC Flexures

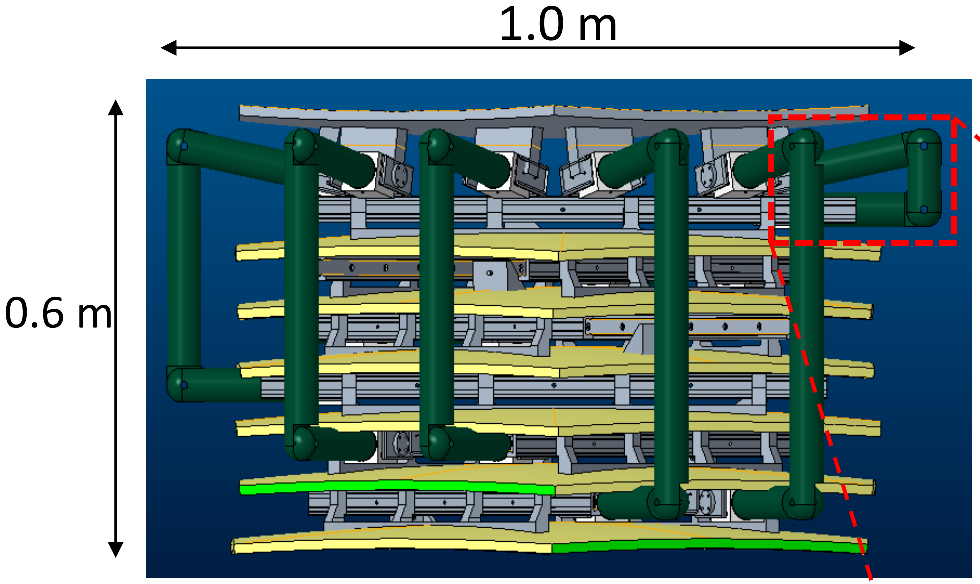


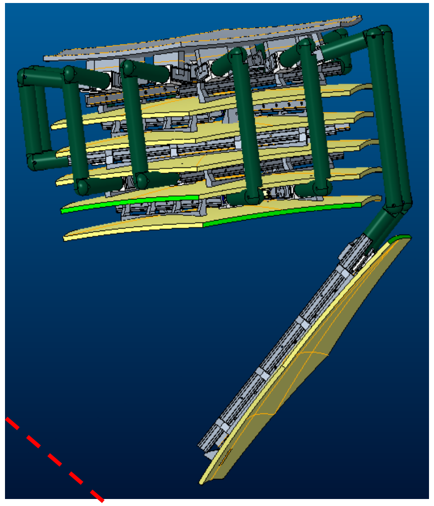


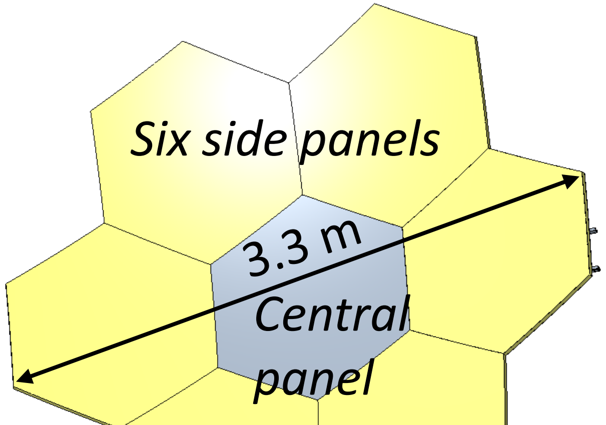
ISA of large reflector by robotic arm from smaller deployable sub-reflectors

Reflector Architecture

- **Six rigid reflector panels stacked under the central one and deployed one by one by composite tubular hinges to form a sub-reflector**

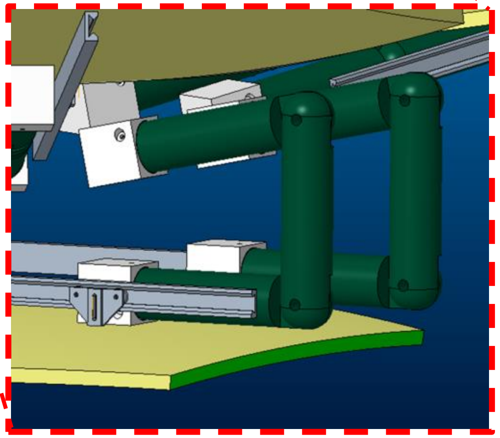




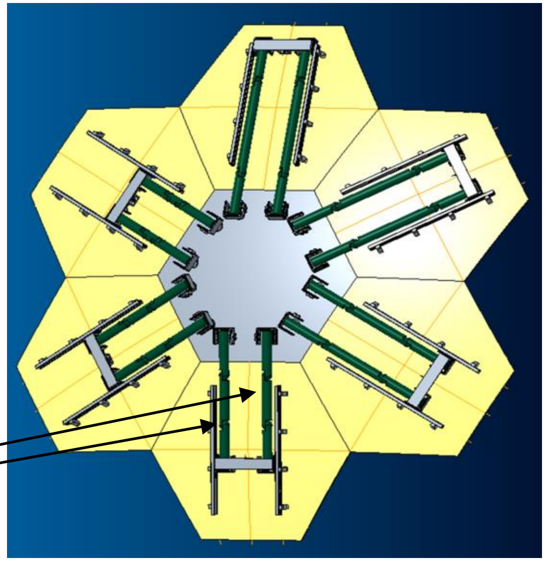


Hexagonal Seven-Panel Reflector Deployed

Composite tubular hinge substrate enables efficient side panel stacking

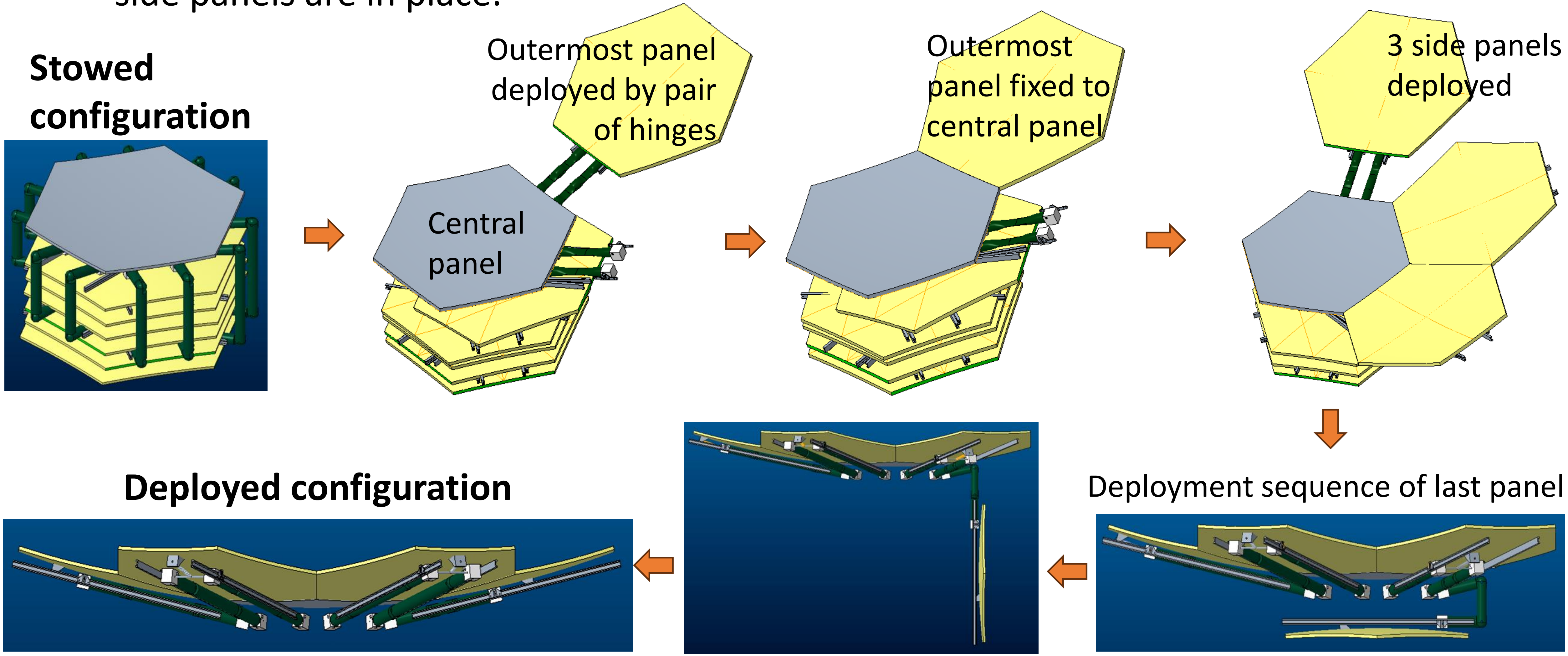


Pairs of tubular hinges on the back side



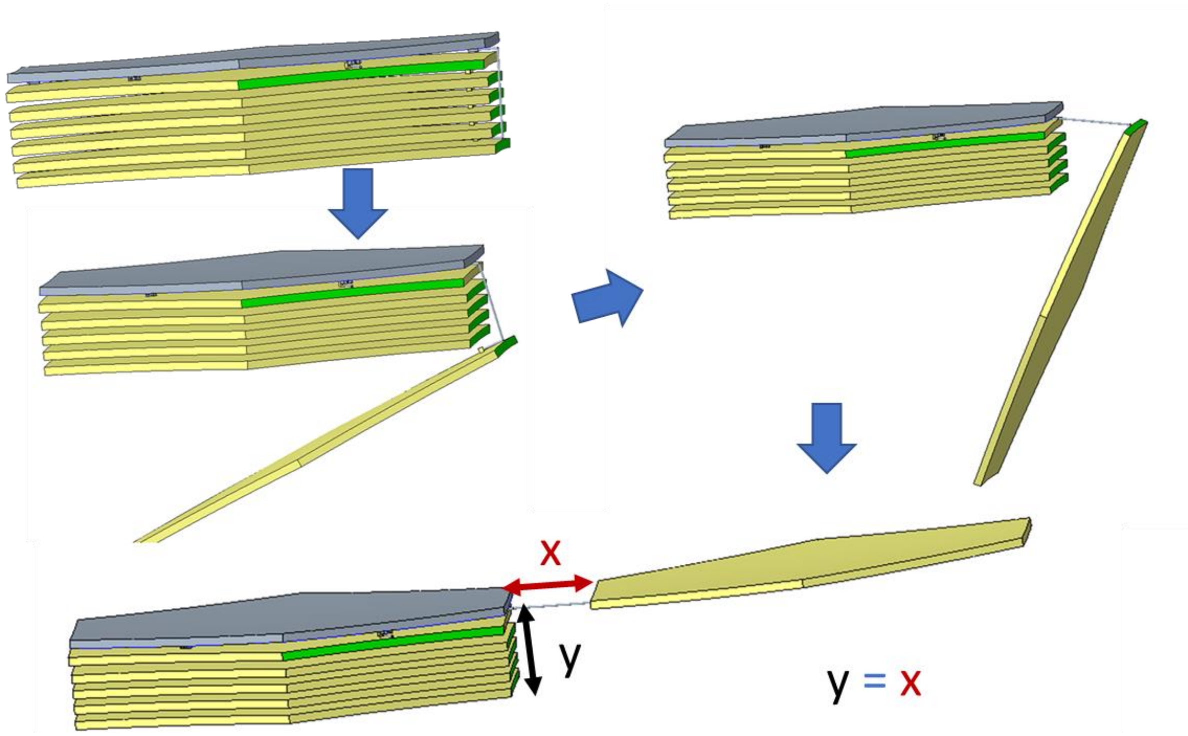
Reflector Deployment Sequence

- Deployment occurs one panel at a time starting from the outermost panel until all six side panels are in place.



Concentric vs Staggered Panel Stacking

Concentric Panel Stacking **(Down-selected)**



For optimal panel stacking, the initial gap between panels when deployed needs to be closed by a secondary mechanism

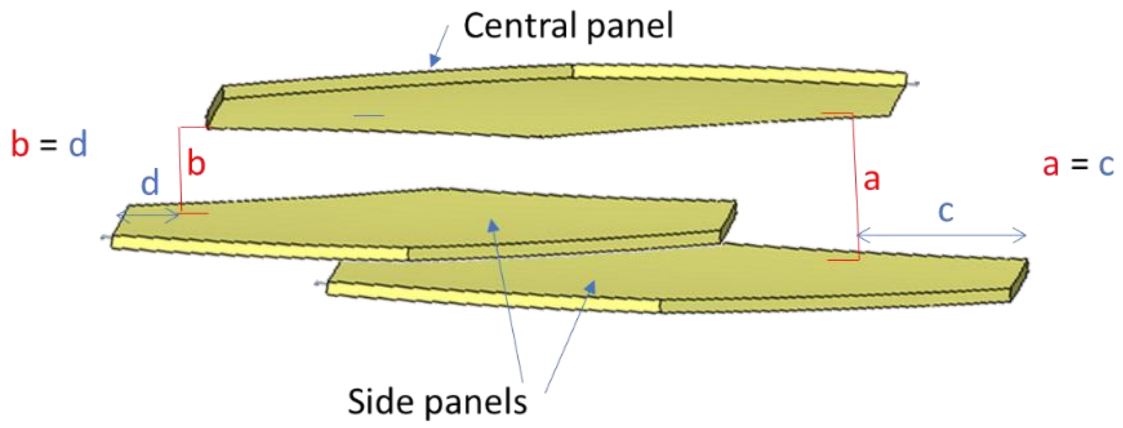
y = initial vertical offset of panel stacked

x = amount of travel needed to close panel gap

Staggered Panel Stacking

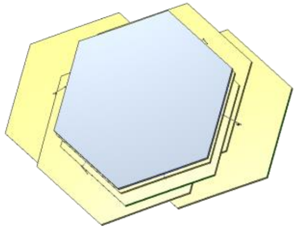
a and b are the vertical offset

c and d are the horizontal offset (edge distance to the side panel)

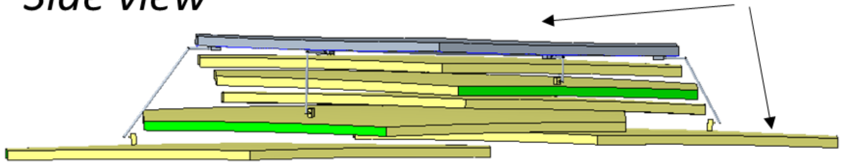


For simple hinge and no gap between panels when deployed, the side panel stacking needs to be initially offset

Top view



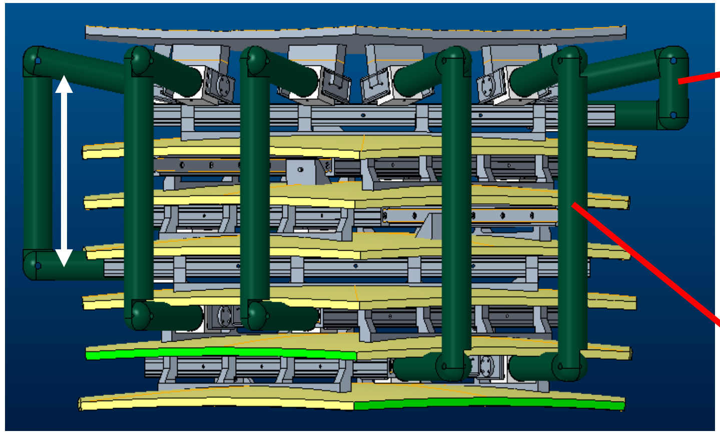
Side view



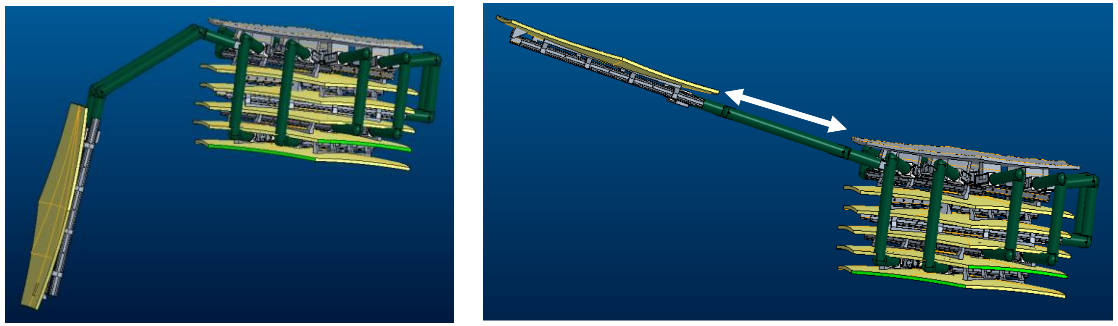
Some panels could be stowed on top of central panel for better packaging

Composite Tubular Hinge Substrate

Stowed configuration

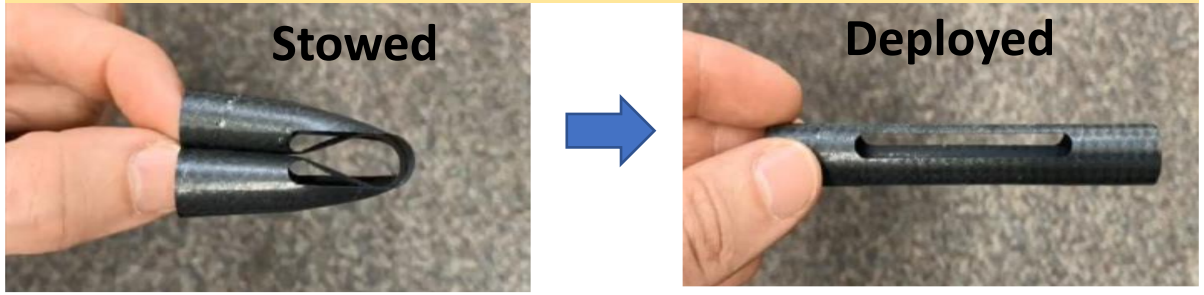


Outermost panel deployment

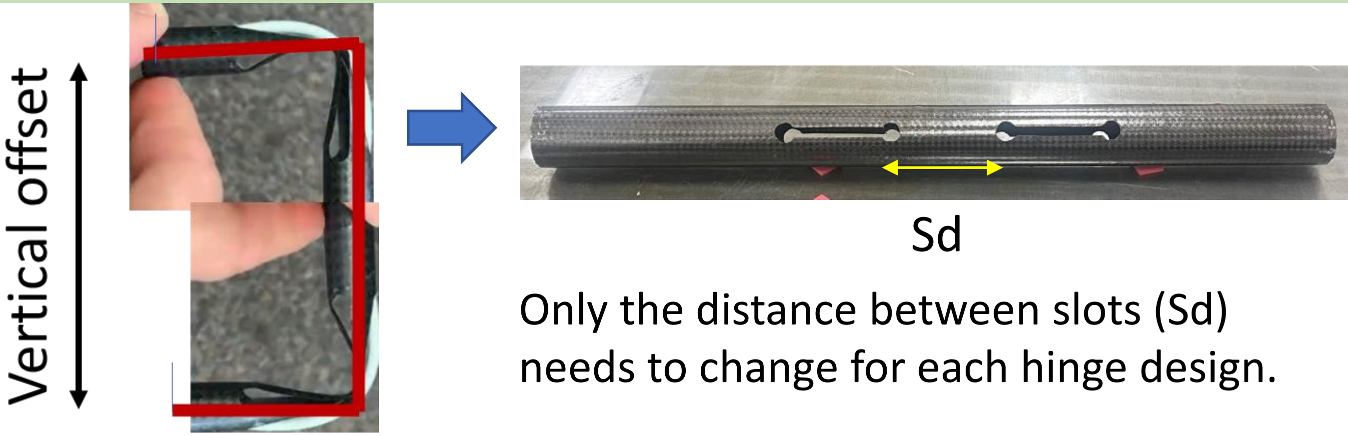


Since the offset of each of the six side panels to the central one is different, six unique sets of tubular hinges will be required to bridge this gap.

Single slot tubular hinge for ~180º bend. Can only be used for side panel closest to the central one.



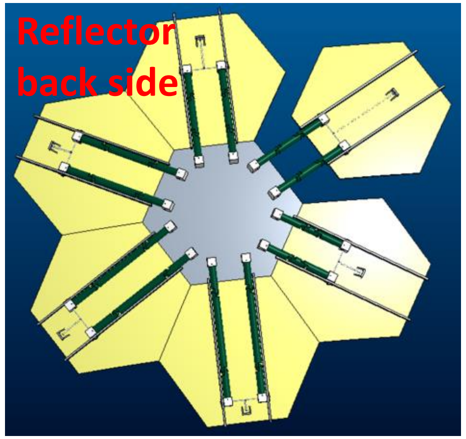
Two-slot tubular hinge for ~180º bend with offset. To be used for the rest of the five side panels.

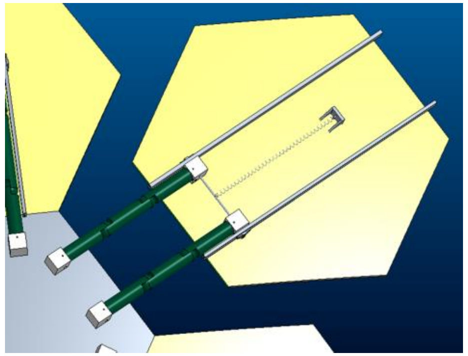


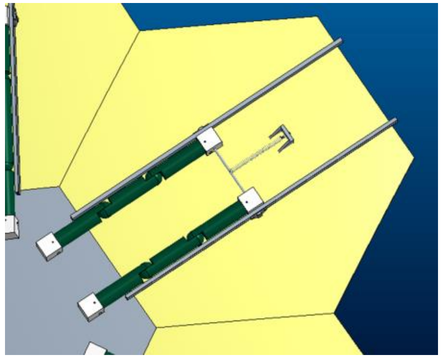
Only the distance between slots (Sd) needs to change for each hinge design.

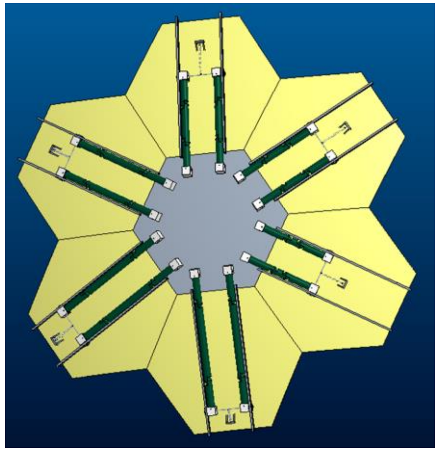
Inter-Panel Gap Secondary Closing Mechanism

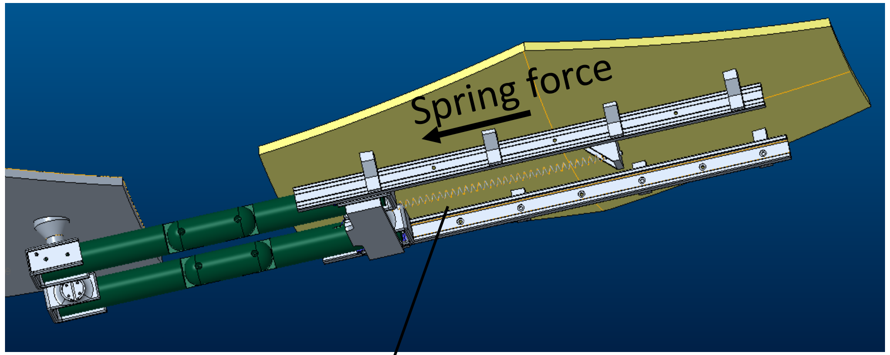
Secondary locking mechanism to close the initial panel-to-panel gap



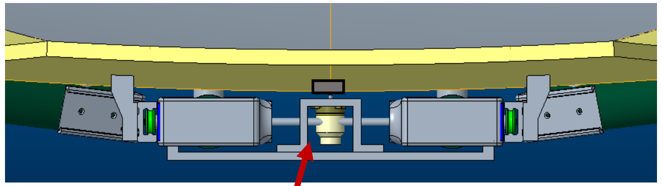




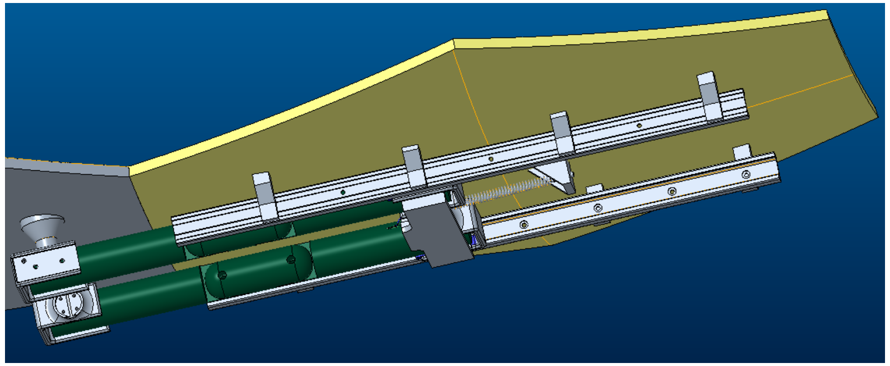


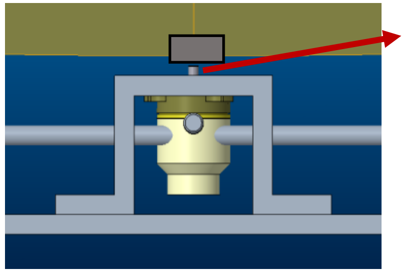


Spring (tension or constant force) acting along tubular hinge axis when the hinges are deployed.

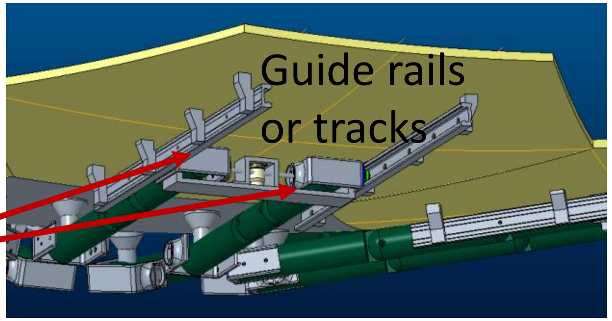


Hold-down release mechanism for launch fixes hinge end fittings to the side hex panel.





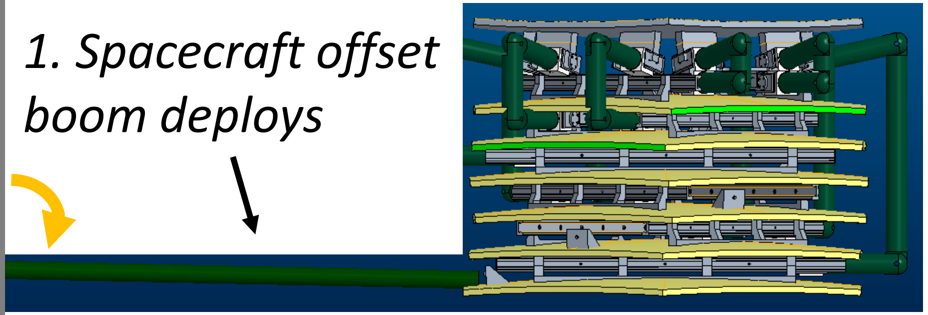
Upon release, the spring force closes the panel gap by translating the hinge end fittings along the straight tracks



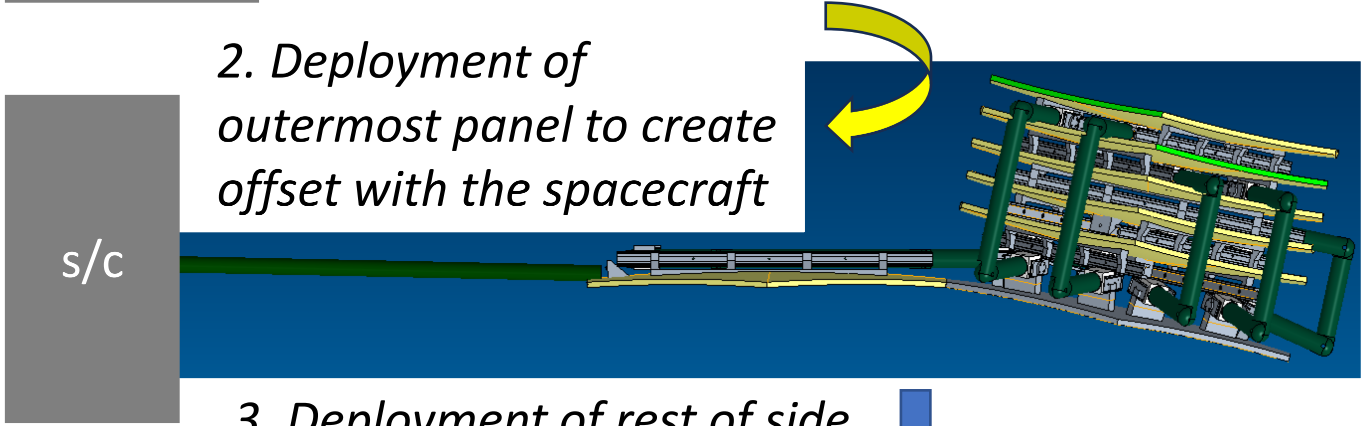
Scalable architecture using robotic in-space assembly

Spacecraft (s/c) - Not to scale

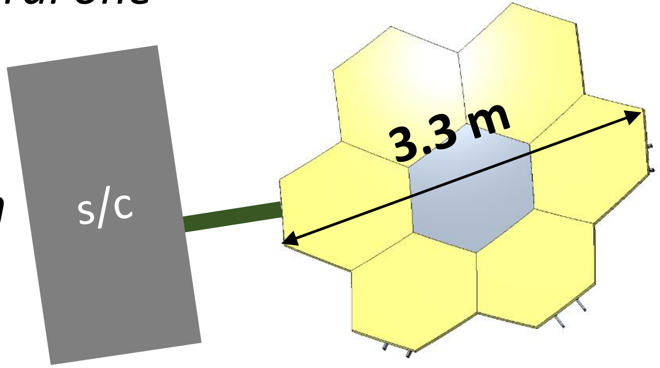
1. Spacecraft offset boom deploys



2. Deployment of outermost panel to create offset with the spacecraft

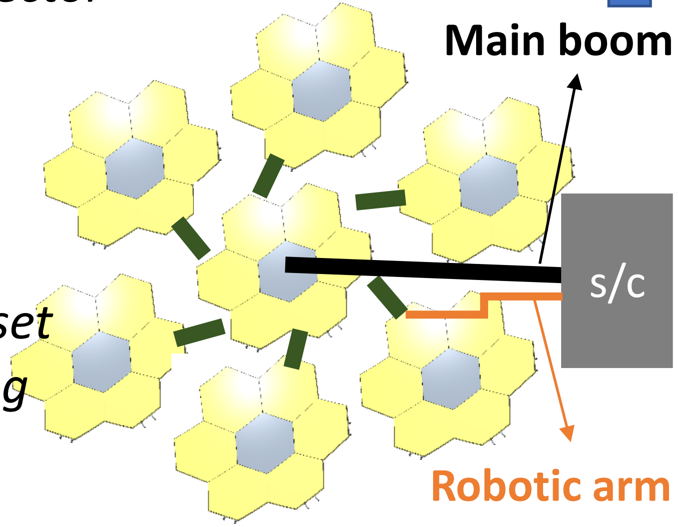


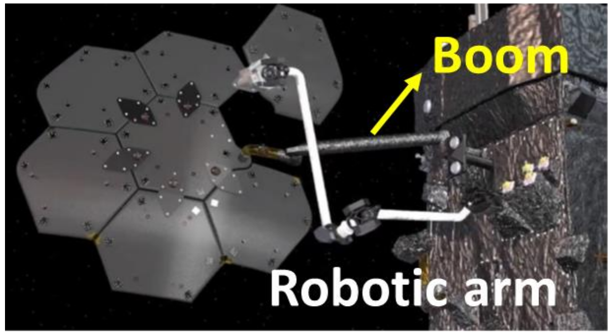
3. Deployment of rest of side panels from central one

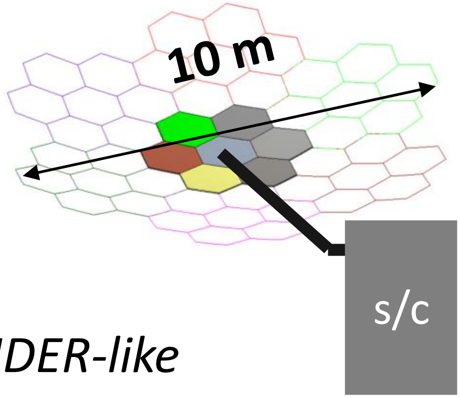


4. Deployed 3.3 m sub-reflector with offset boom ready to be robotically assembled to the rest

5. Robotic arm uses offset booms to initiate mating of side sub-reflectors to central one



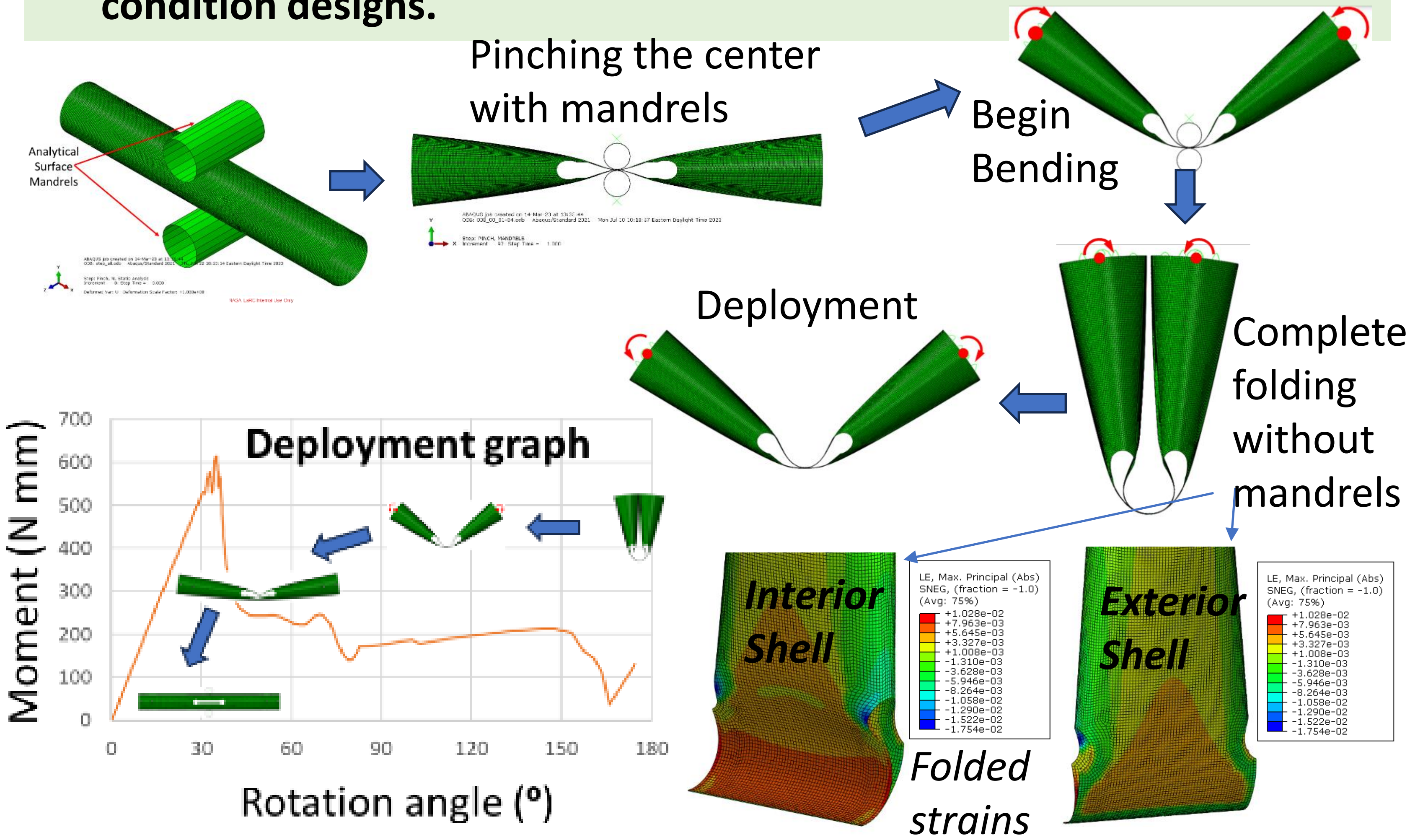




6. Robotic arm uses SPIDER-like Interconnect Assembly plates to fix certain hexagonal side panels for additional global stiffness of the 10 m reflector

Tubular Hinge Analysis and Test Fixture

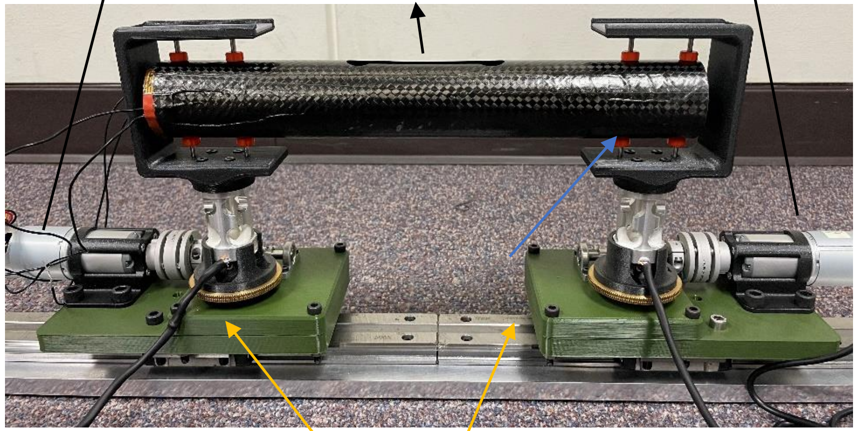
➢ **Quasi-static folding and deployment of composite hinge with different end fitting designs to assess hinge stiffness, moment vs rotation deployment graph, and folding strains to drive boundary condition designs.**



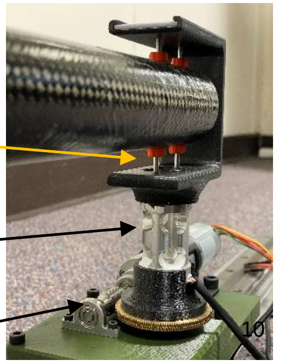
➢ **Tubular Hinge Bending Fixture.**
- **Measure Moment vs Rotation during hinge deployment to correlated with analysis.**

Motors at ends for rotation angle actuation

SMC Tubular hinge



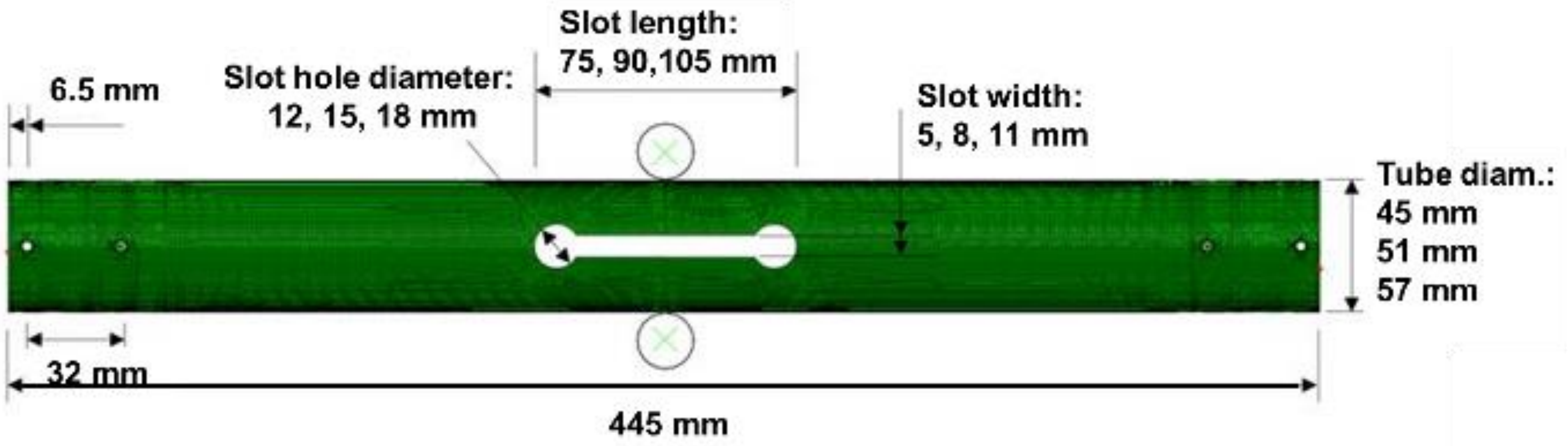
- Mounting plates on linear bearings
- Hinge fixed to flight-like end fitting
- Torque sensor
- Gear and lead screw



Tubular Hinge Parametric Study

➢ Parametric study for a single-slot hinge with representative boundary conditions (BC) to assess how design features affect critical performance metrics for design down-selection:
  1) Composite laminate strains in the folded state of the hinge.
  2) The deployment moment-rotation relationship to determined steady-state and peak deployment moment, as well as hinge deployed stiffness.
  3) Whether the hinge snaps back at end of deployment once an inertial tip mass equivalent to the side panel assembly is attached. The higher the dynamic peak moment the higher the locking moment.

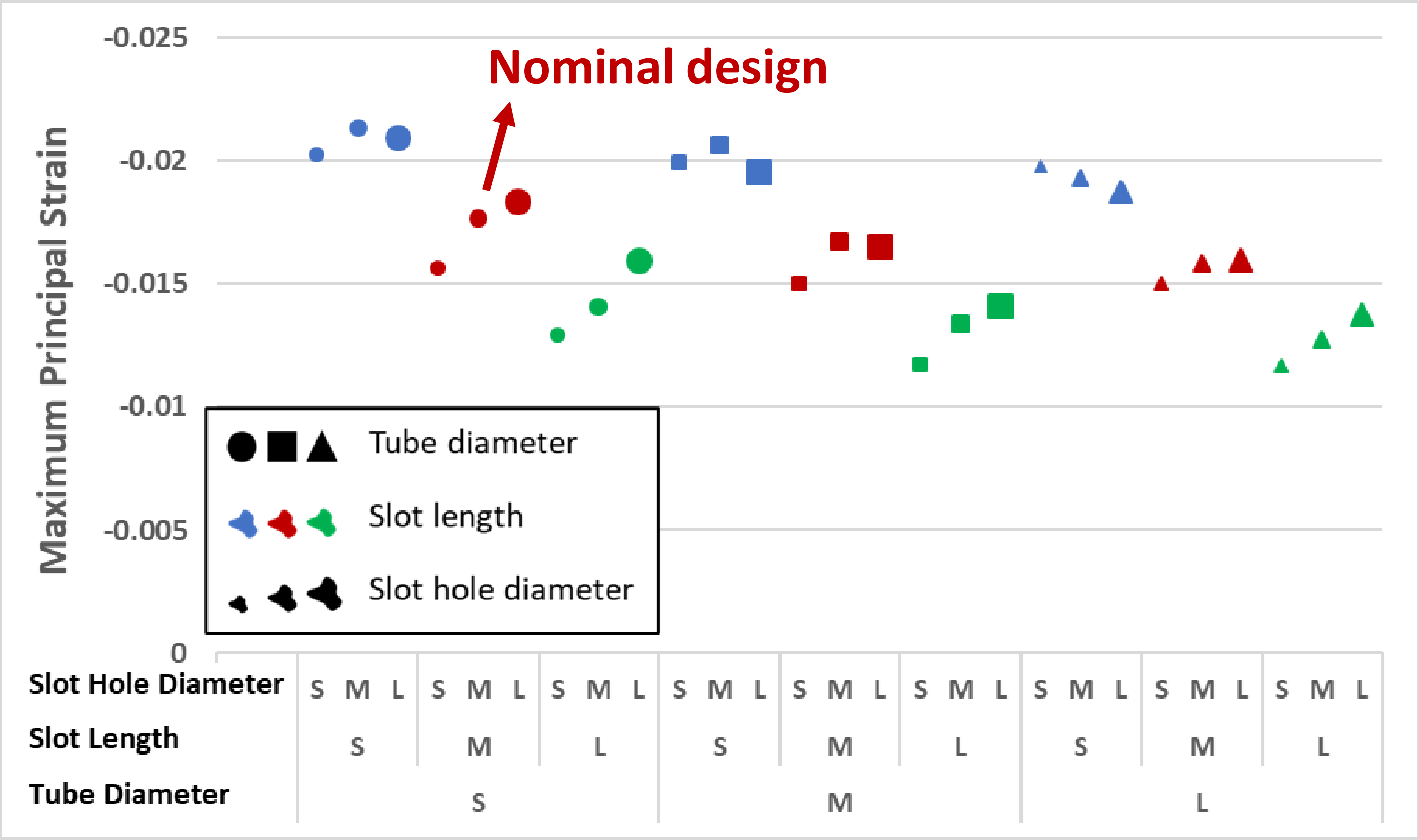
- Three independent parameters: tube diameter, hinge slot length, and the diameter at the end of the dogbone slot (with the slot width being proportional to it) with three different dimensions (small, medium and large) generated a total of 27 analysis cases.



Tubular Hinge Parametric Study Results (1/2)

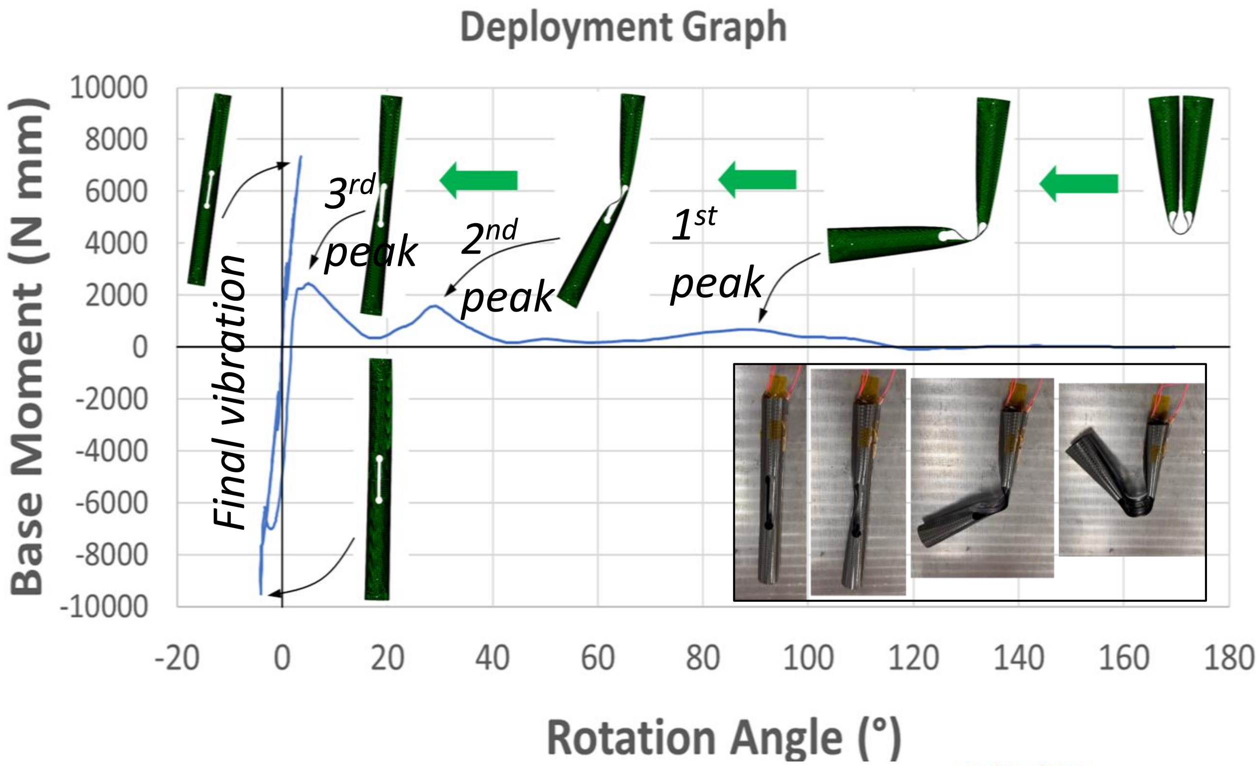
- The peak compressive strains after quasi-static folding are normally located around the slot hole diameter.
- Diameter hole size inversely proportional to the maximum compressive strain, except for cases with a small slot length.
- Removing more material at slot ends is effective if it does not impact the arc length needed to fold the tube.
- Folded strains diminish with both the tube diameter size and the slot length.
- Folded strains between 1.2% to 2.2% are expected, suggesting the use of intermediate modulus carbon fiber laminates with high strain to failure or elastomeric-like resin.

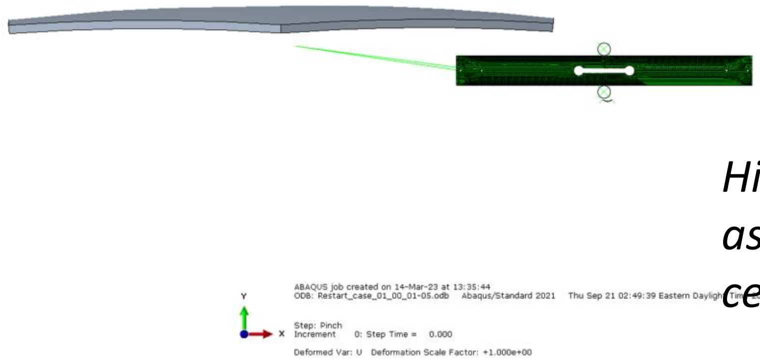
Maximum strains obtained in the folded state of the hinge for all 27 design cases analyzed.



Tubular Hinge Parametric Study Results (2/2)

- Implicit dynamic analyses in Abaqus captures the deployment path and shapes of experimental hinges with one end fixed and the other free.
- Dynamic deployment moment-rotation graph shows three peak moments of increasing value:
  1. Traveling folded region of hinge at ~90° rotation.
  2. Unfolding of outer ligament at ~ 30° remaining.
  3. Snap-through of inner ligament at ~ 6° angle.
- Large peak moments after hinges reaches final straight configuration at 0° angle. Hinge vibrates back and forth until the kinetic energy dissipates.
- Only the three cases with a large tube size and a small slot width and diameter fail to reach straight configuration and snapped back.
- Dynamic analysis of hinge with a 4.15-kg tip mass attached at one end (½ of side panel assembly) show sufficient stiffness to react final shock from inertia.

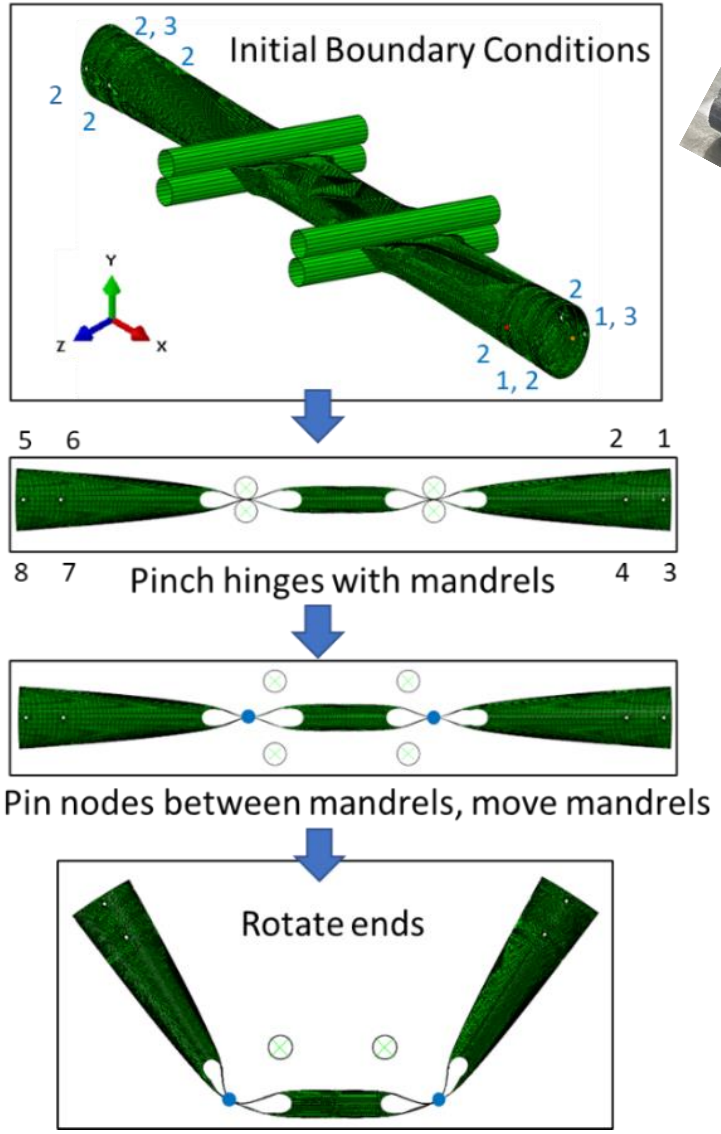




Hinge with ½ of side panel assembly mass attached at center of gravity

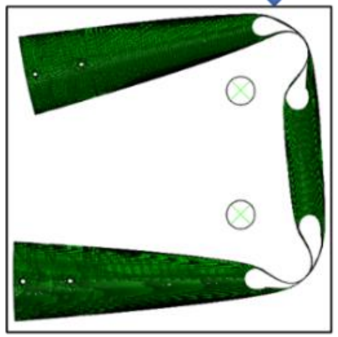
Two-slot Tubular Hinge Analysis

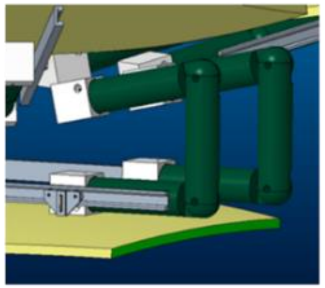
- Down-selected tube size, slot design and end BCs were used in the two-slot tubular hinge model.
- Multiple steps to achieve folded state that matches the desired configuration of the panel stack:
  - Rotation angle of 92º for one end and 100º for the other end.
  - Hinge section between pinched ligaments is unstable and tends to twist requiring artificial control.
- The dynamic deployment study with and without a tip mass under is ongoing, as well as a configuration with a pair of hinges coupled.



Single two-slot hinge from Side Panel #2

After several cycles of restraining hinge – partial fold – releasing hinge, a folded tube into the final desired state is possible

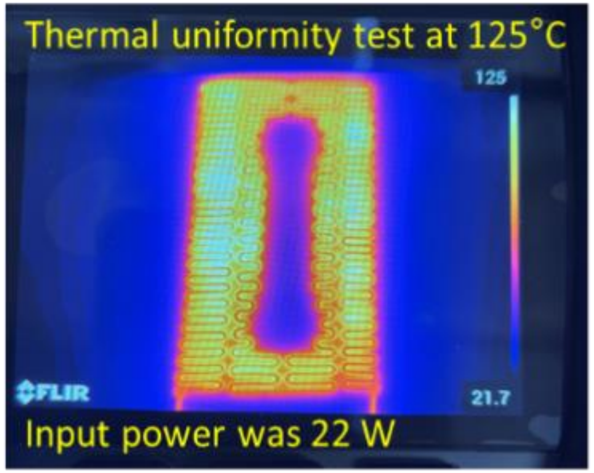


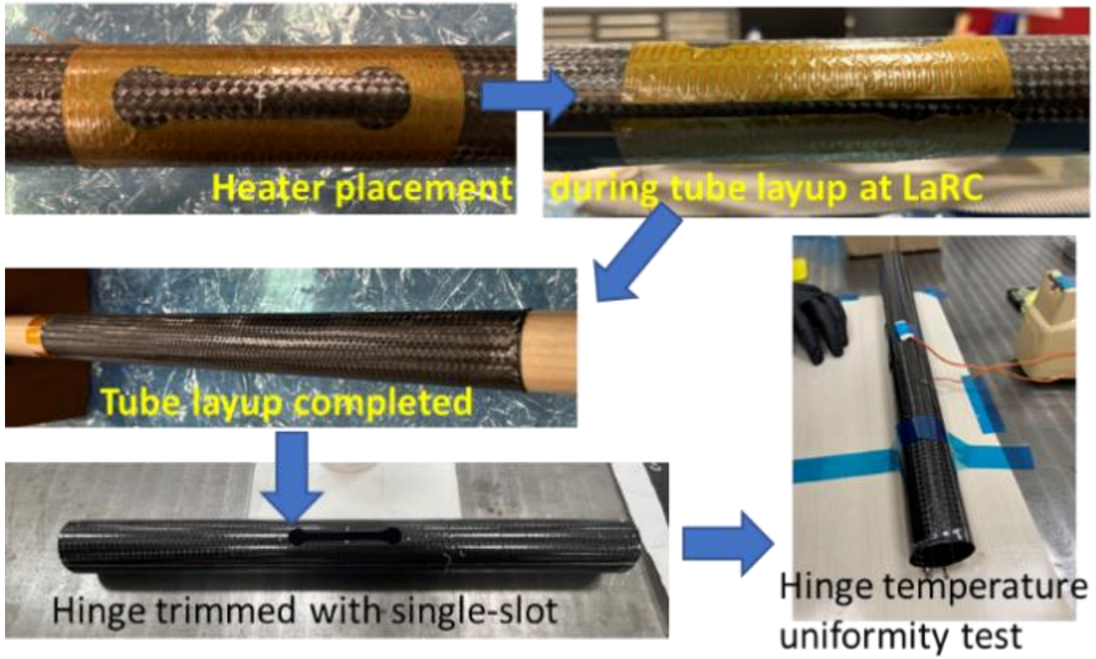


Simple kinematic representation of hinge for CAD model

Breadboard Component Fabrication and Testing: Tubular Hinges

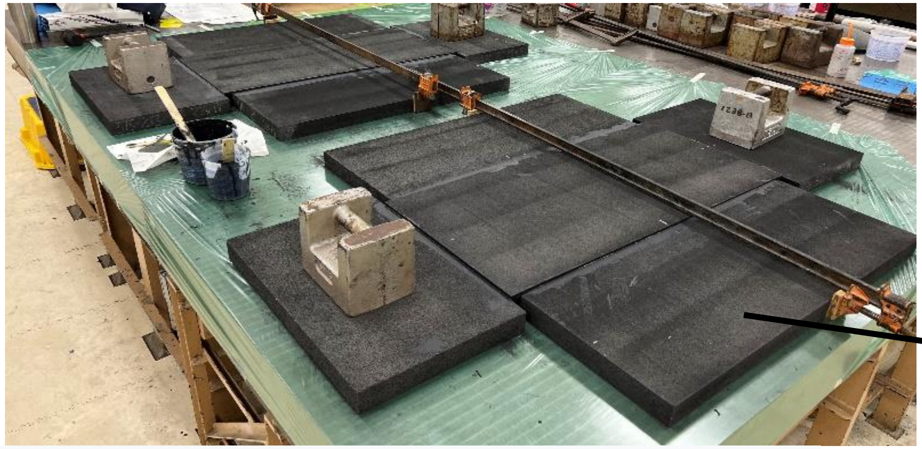
- Ultra-thin custom heaters and temperature and strain sensors developed by Pennsylvania State University in collaboration with NASA.
- 26-µm thick heaters have a serpentine shape to increase flexibility without yielding the conductive Copper layer.
- The components are embedded into the tubular hinge along the neutral axis of the laminate to minimize bending strains.
- New shape memory composite material developed at NASA produces self-actuation of hinge under thermal input of heaters and sensor control.
- Low power actuation of < 100 W per SMC hinge or < 200 W per panel.
- Controlled self-deployment of hinge over 10 – 15 s without final shock.

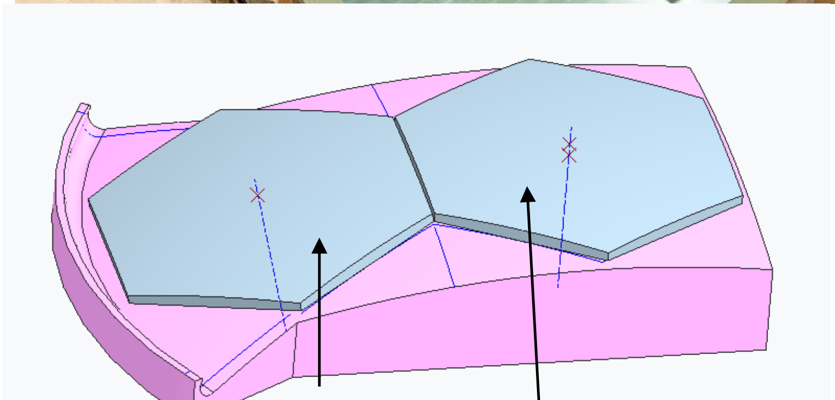




Breadboard Component Fabrication: Hexagonal Panels

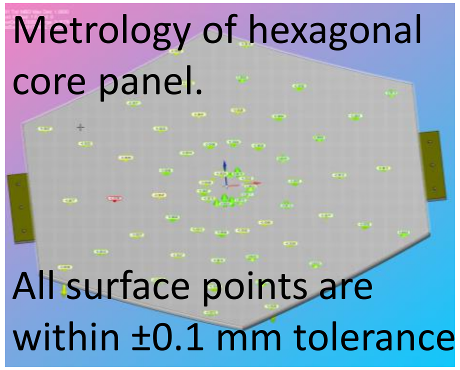
- **Carbon foam (CFOAM 30®) board assembly for machining the core panels.**





Side and central hexagonal panels on top of 3-m diameter reflector tool

- **1-m wide hexagonal panels with sandwich construction from:**
  - **Machined 12.7-mm thick CFOAM 30® core sealed with ES-215 epoxy resin.**
  - **Two 0.16-mm four-ply thick carbon fiber laminates skins co-cured and bonded with thin EA9696 film adhesive against the (pink color) reflector tool shown.**



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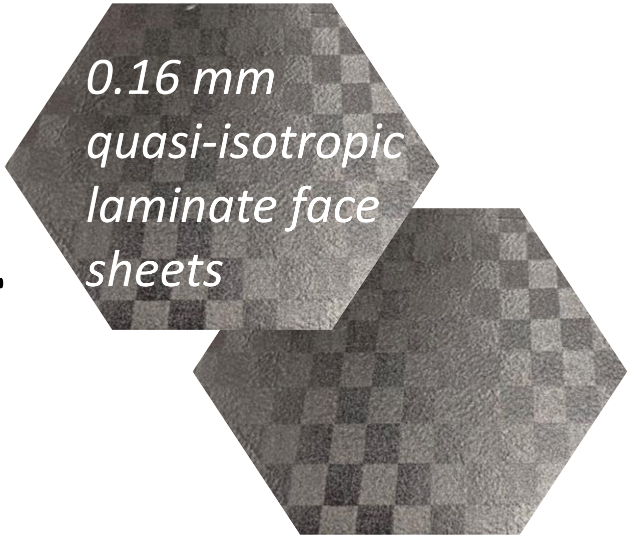
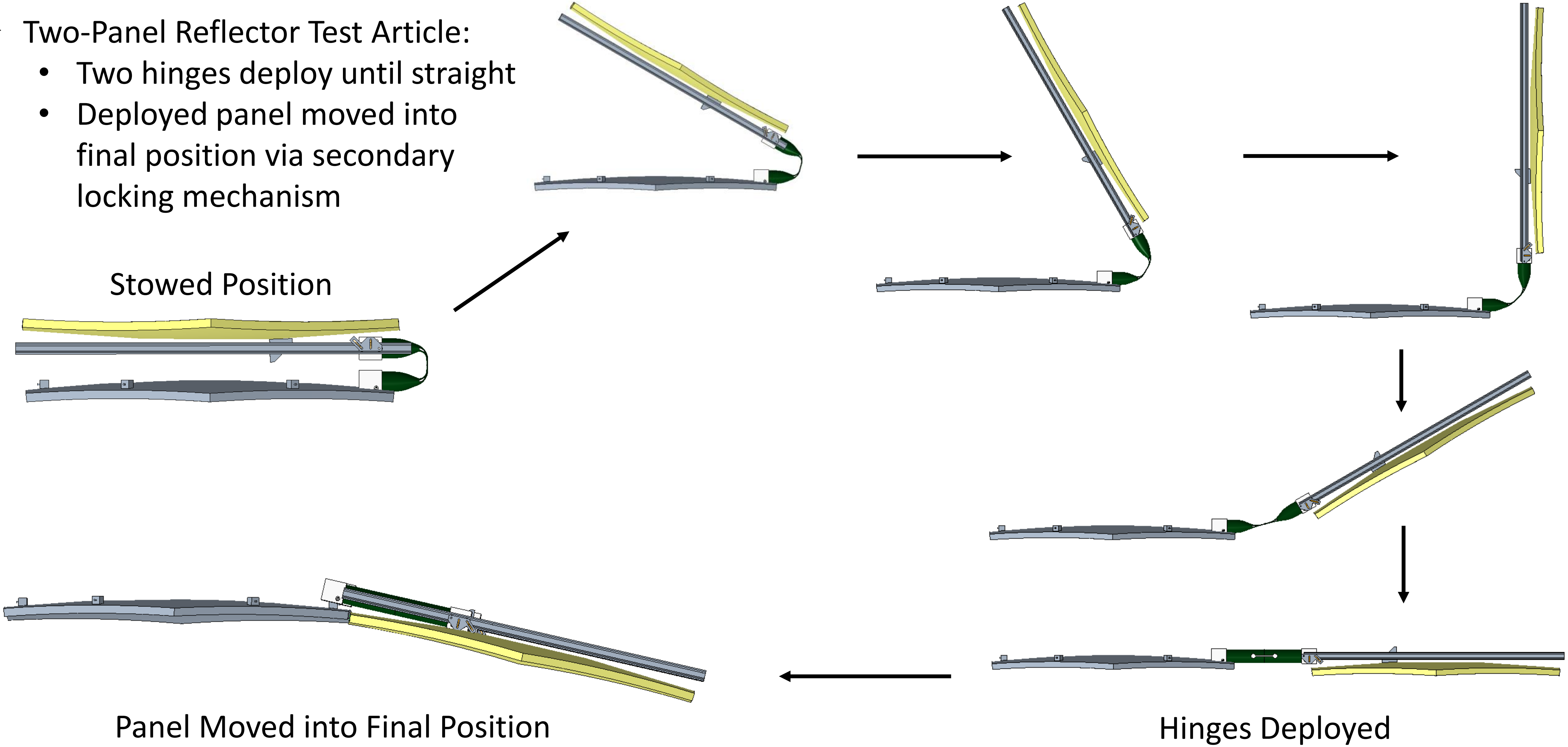


Dimensionally and thermally stable for high RF applications. Each panel mass = 6.4 kg (could be halved in next iteration)

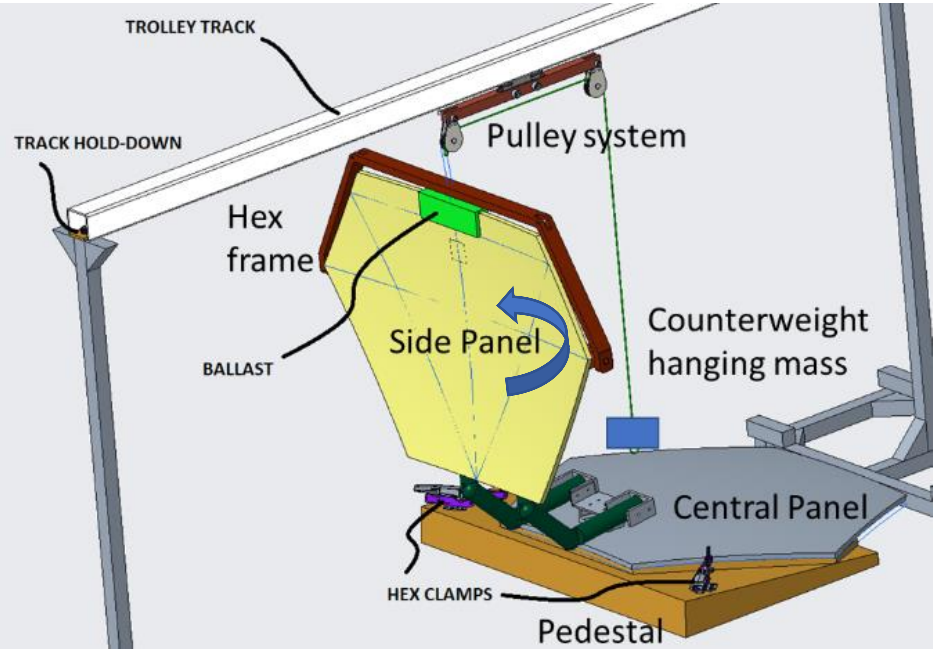
Two-Hinged Panel Deployment Sequence

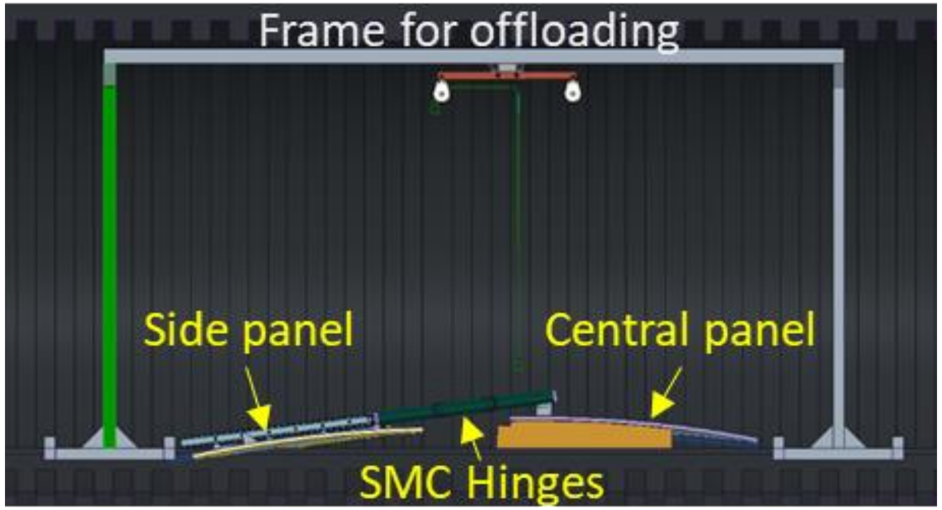
- Two-Panel Reflector Test Article:
  - Two hinges deploy until straight
  - Deployed panel moved into final position via secondary locking mechanism



Final Test for Concept Validation

- Concept validation via functional test of two-panel assembly of 3-m diameter scale reflector.
- Deployment testing of both the SMC hinge self-deployment and secondary locking mechanism inside thermal chamber at 80ºC.
- Gravity offloading of side panel via pulley system with hanging mass traveling along chamber axis on overhead conveyor track.
- Side panel can swing on hexagonal frame that allows panel rotation on bearings about axis connecting two opposing corners.
- Shape measurement scans of the reflective surface pre-and-post deployment used to assess feasibility to support S-band and above RF (≥ 4 GHz) for antennas.





Conclusions

- New architecture for solid surface antenna reflector that combines deployment of unit cells of vertically-stacked, seven-hexagonal panel sub-reflectors compatible with robotic assembly into larger version.
- Project goal is to develop and asses new features to be used in designs at ≥ 10-m scale.
- Focus has been on design, analysis and manufacturing of SMC hinges with embedded actuators and sensing, and other backbone hardware used to secure panel assembly.
- Parametric study helped in SMC hinge design with baseline case showing acceptable folding strains, sufficient stiffness and low deployment dynamics.
- Reflector panel manufacturing process with new dimensionally and thermally stable sandwich construction shown.
- Final 3-m scale test article and test configuration presented will be used to demonstrate efficient stowage with minimal constrains, controlled deployment, and maintain necessary shape accuracy of < 3 mm root mean square (RMS) error in relevant environment.

Questions

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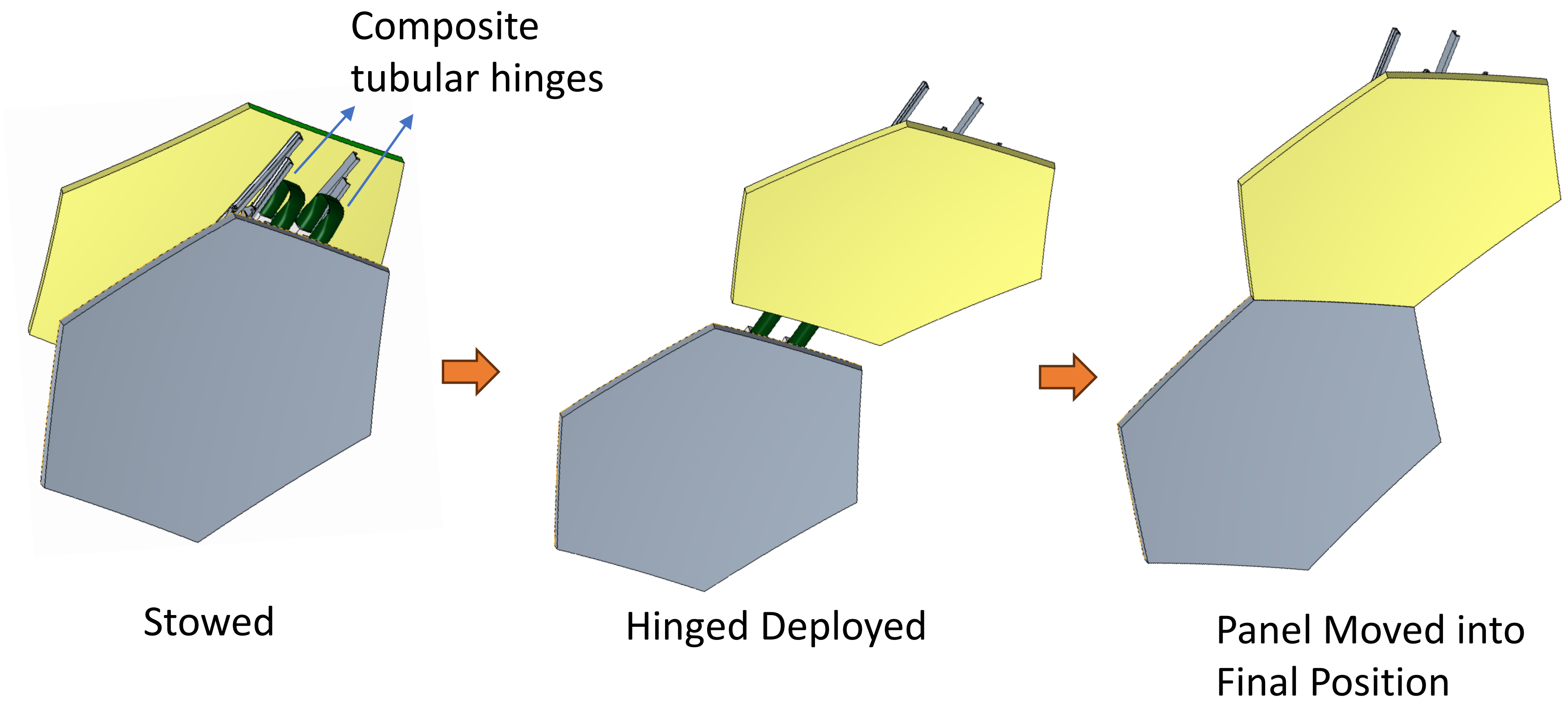
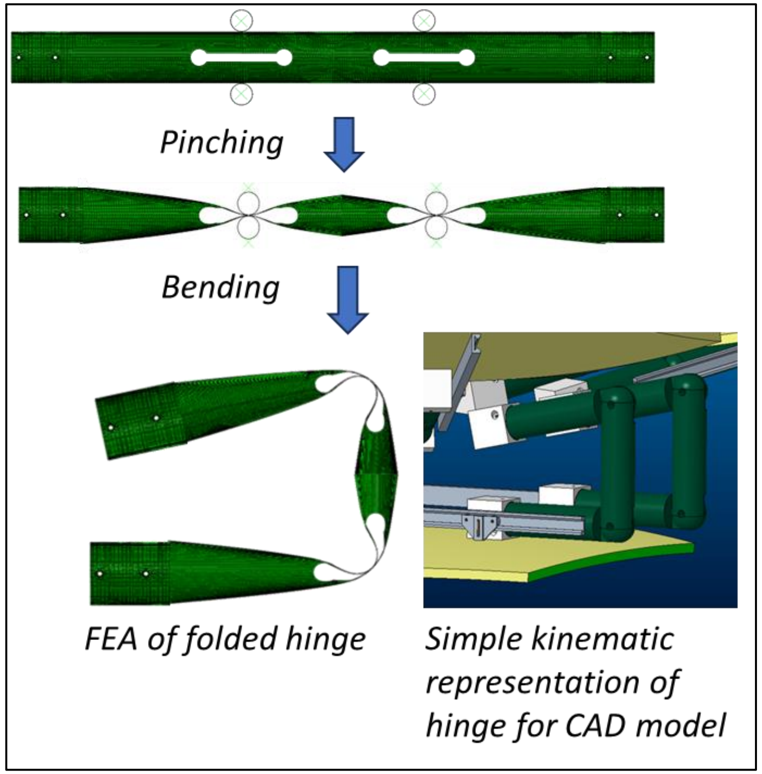
Backup Slides

Test article to be produced for final test campaign

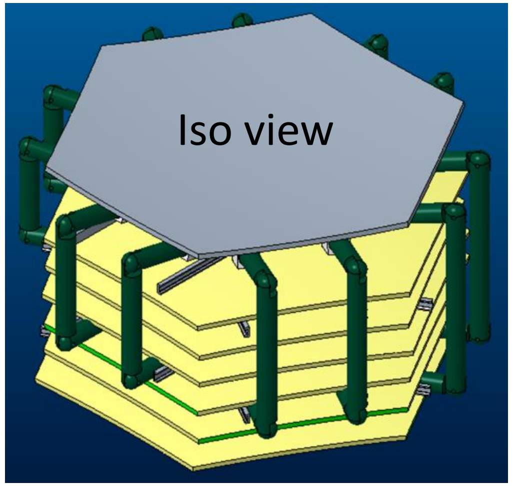
- For the final test campaign, a two-panel hinged reflector test article will be used for demonstration purposes.
- Hinge pairs designed for the second side panel closes to the central panel in the stack will be fabricated.
- The secondary panel gap closing mechanism will also be included.



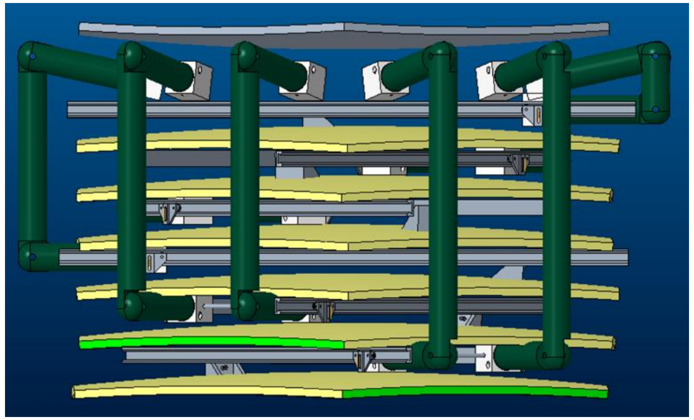


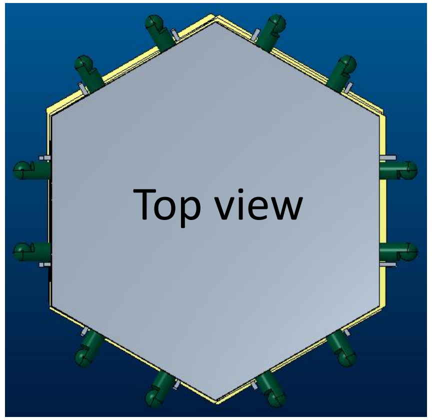
Monthly Highlight: Final Design of Rigid Hex Panel with SMC Hinges

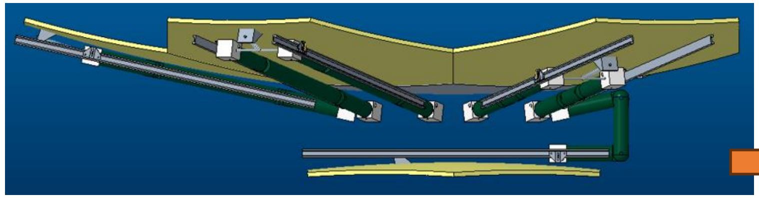
Reflector Stowed Configuration

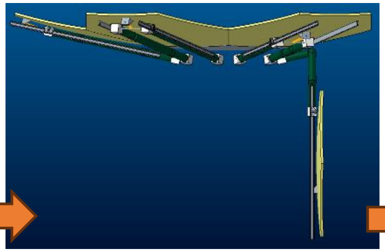


Side view

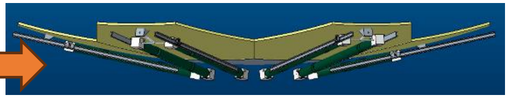


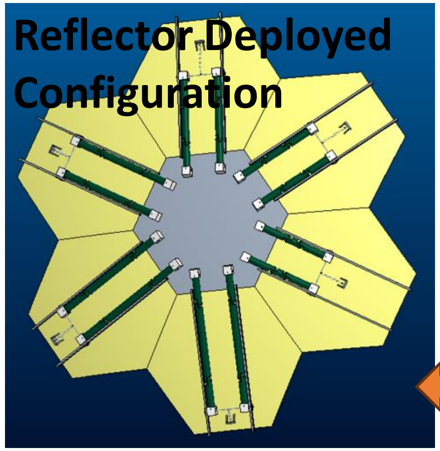




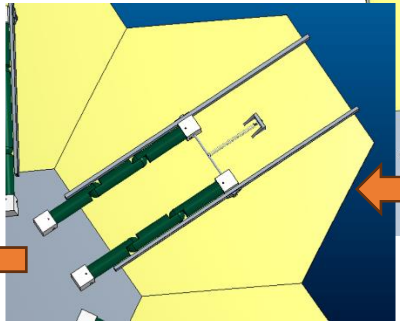


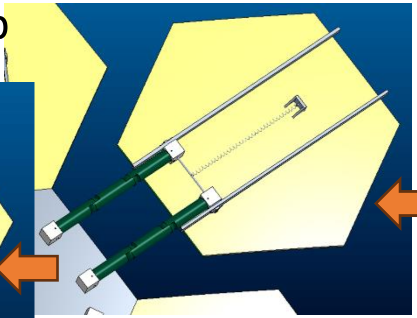
Deploying one panel at a time



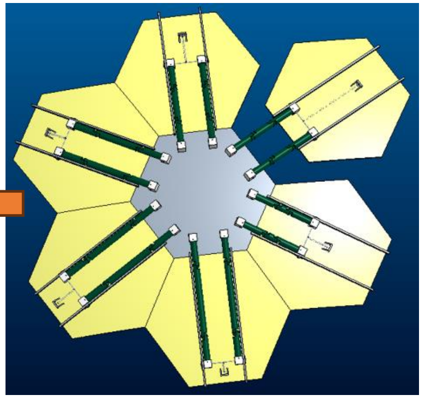


Secondary locking mechanism to close the initial panel-to-panel gap

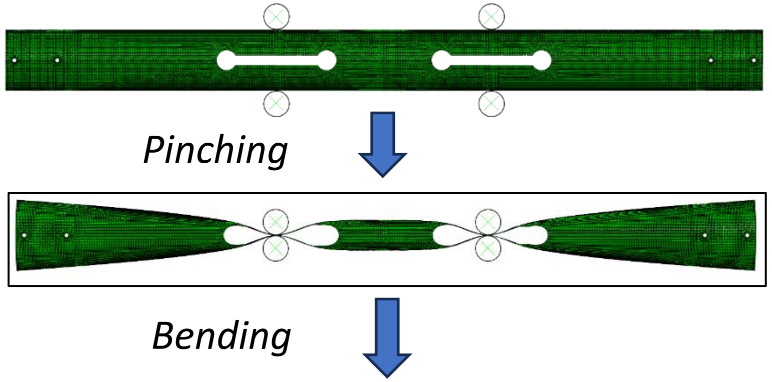


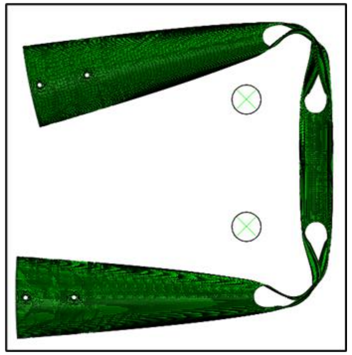


Trading different mechanism concepts

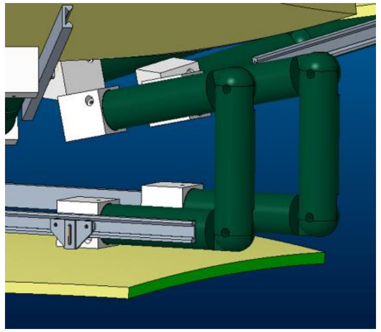


- **Final Shape memory composite (SMC) tubular hinge folding analysis**





Finite element analysis (FEA) of folded hinge



Simple kinematic representation of hinge for computer-aided design (CAD) model