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Aerospace Materials and Structures Laboratory

Bend-Forming: A CNC Deformation Process for Fabricating 3D Wireframe Structures

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MIT LINCOLN LABORATORY

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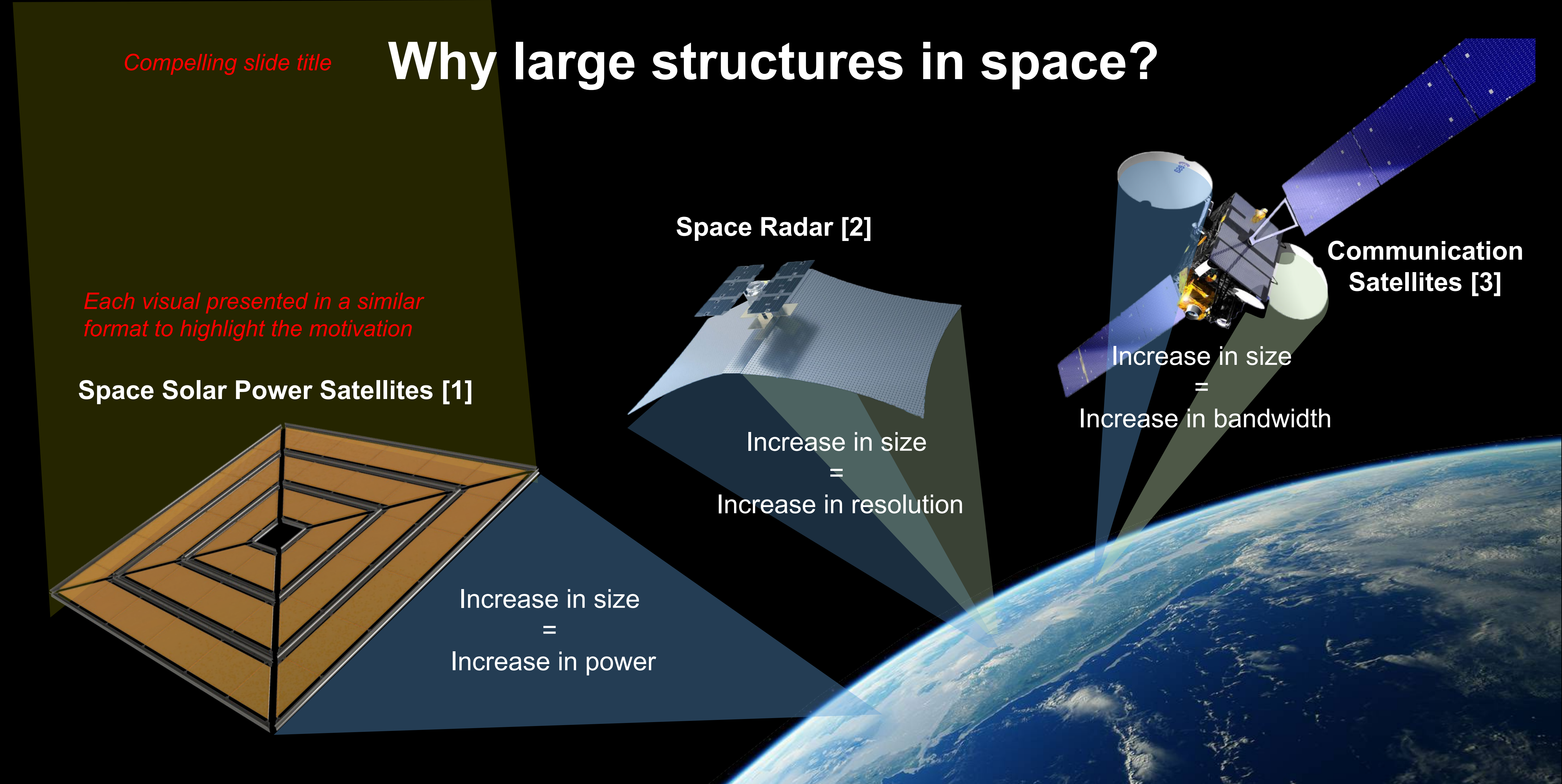
Albuquerque, NM • 07/26/23

NORTHROP GRUMMAN

Why large structures in space?

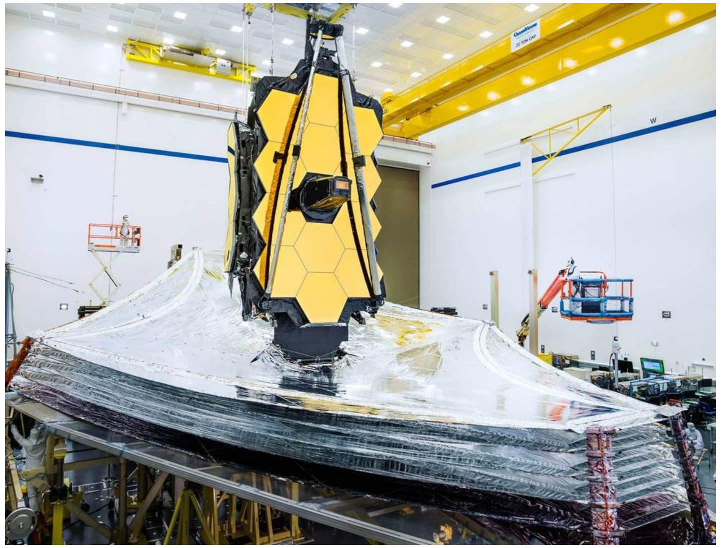


[1] Image from the Caltech Space Solar Power Project
[2] Image from Capella Space
[3] Image from ESA

Current and future approaches to large space structures

State-of-the-art: deployable structures

JWST stowed



JWST partially deployed

Limitations of deployables:

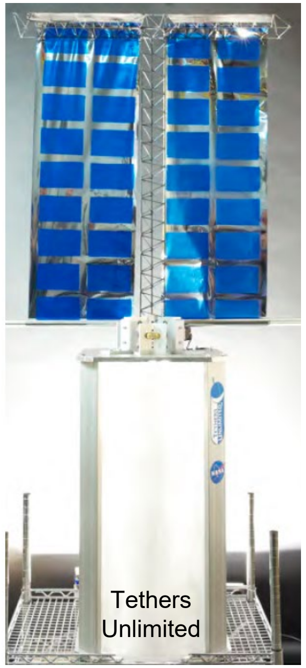
- Designed for launch loads
- Costly testing and integration
- Size constrained by packaging and precision [1]

Succinct bullet points to minimize text and emphasize visuals

Left and right sides of slide are organized similarly to emphasize the comparison

New paradigm: in-space manufacturing (ISM)

Acronym defined



Extrusion of CF/PEEK trusses

Advantages of in-space manufacturing:

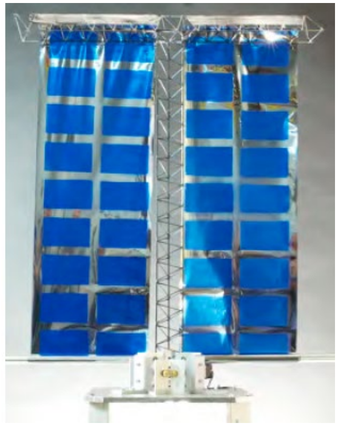
- Structures optimized for loads on orbit
- On-demand fabrication
- Potentially larger structures

[1] Banik, "Realizing large structures in space" (2015)

Minimal energy consumption motivates deformation processing in space

Colored labels serve as a legend for figure on the right

thermoplastic extrusion



Extrusion of CF/PEEK

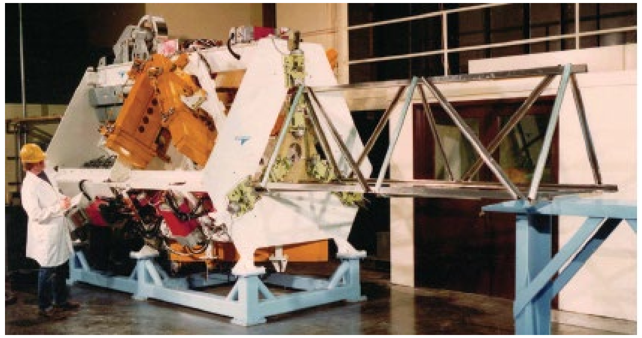
melt-based processing

Electron beam metal additive manufacturing (EBAM)

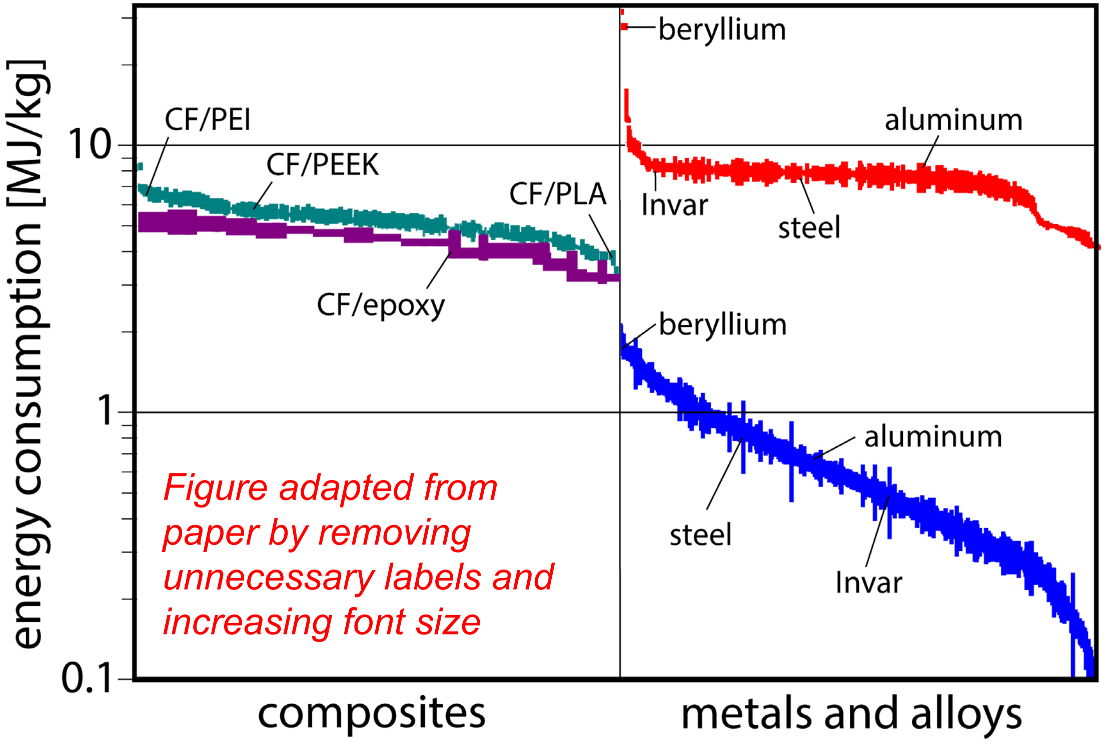
thermoset extrusion

Extrusion of CF/epoxy

deformation processing



NASA Grumman beam builder
Roll forming and spot welding

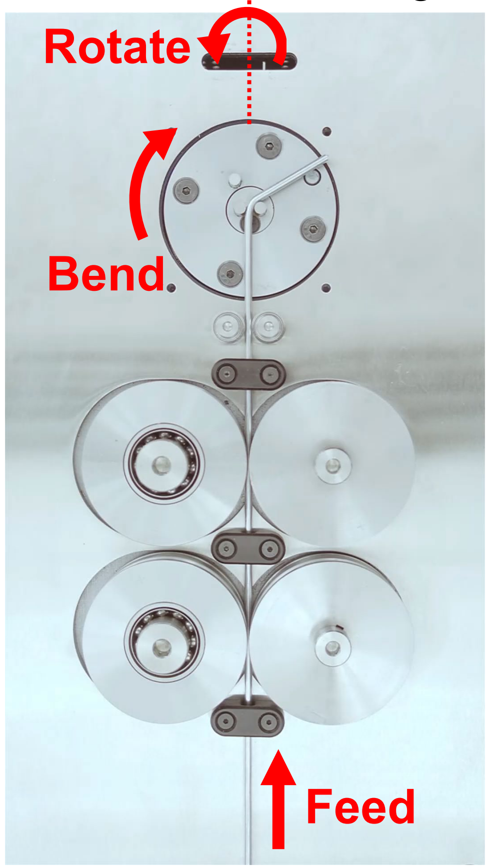


Deformation processes have minimal energy consumption [2]

[2] Bhundiya, Royer, Cordero, "Engineering Framework for Assessing Materials and Processes for In-Space Manufacturing," *JMEP*, 2022

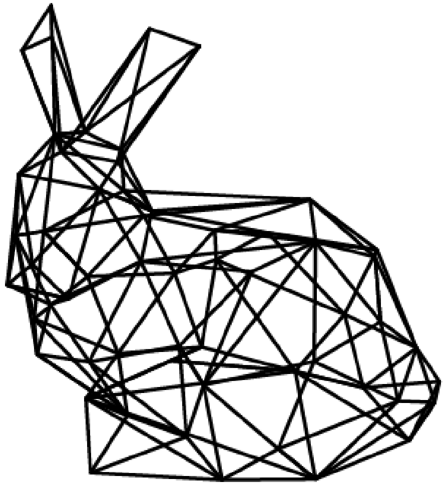
Bend-Forming: a CNC deformation process for fabricating 3D wireframe structures

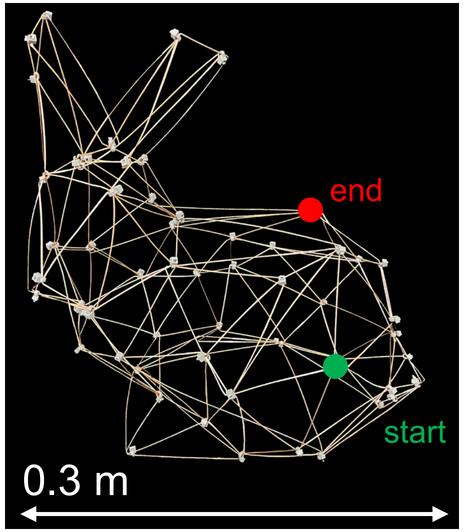
CNC wire bending



+ mechanical joints [3]

Minimal text to emphasize the visuals

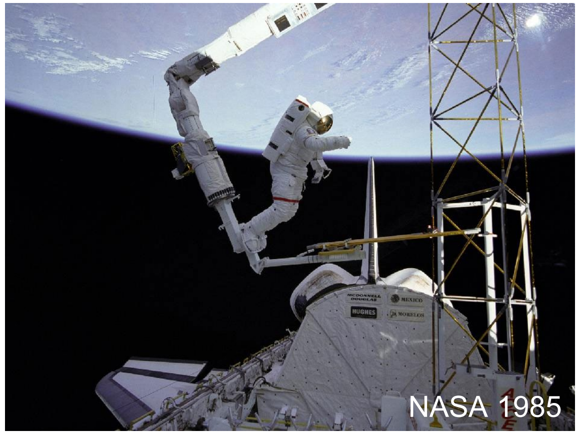




Arrows highlight sequential steps of the process

FEED 59.7 [mm]
BEND 60.7 [°]
ROTATE 134 [°]
FEED 45.1
BEND 124.7
FEED 85.3
BEND 148.1
.
.
.
FEED 66.8

Compelling image to show application



Key application:

Robotic fabrication of truss support structure

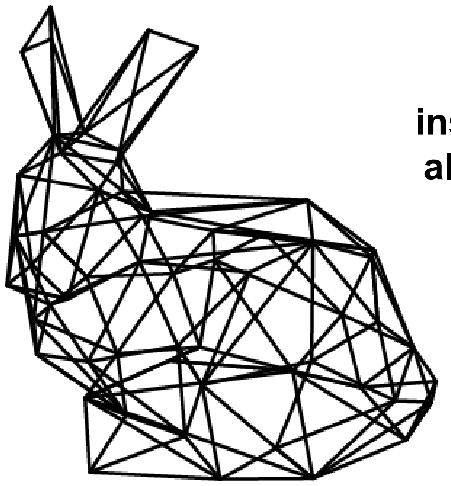
Key advantages:

- Low energy consumption
- High compaction ratio
- No size limit

[3] Bhundiya, Cordero, "Bend-Forming: A CNC Deformation Process for Fabricating 3D Wireframe Structures," *Additive Manufacturing Letters*, 2023

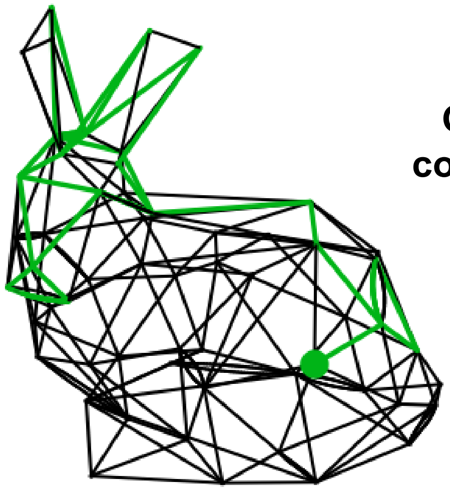
Path planning framework for Bend-Forming

Good use of arrows to highlight steps of the process



Desired truss

Route inspection algorithm →



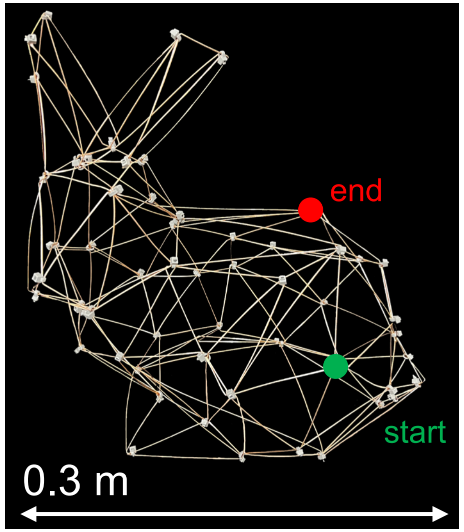
Bend path

Geometric computations →

FEED 59.7 [mm]
BEND 60.7 [º]
ROTATE 134 [º]
FEED 45.1
BEND 124.7
FEED 85.3
BEND 148.1
.
.
.
FEED 66.8

Machine instructions

Attach joints →



Bend-Formed truss

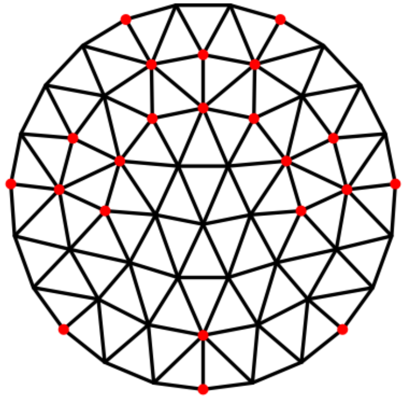
Finding bend paths via route inspection algorithm

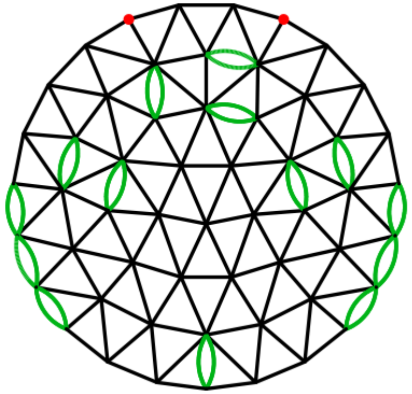
Graph $G(V,E)$

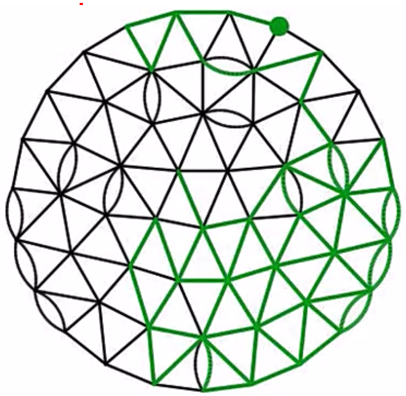
Multigraph $G(V,E,r)$

Bend path = $\{v_1, v_2 \ldots v_n\}$

2D

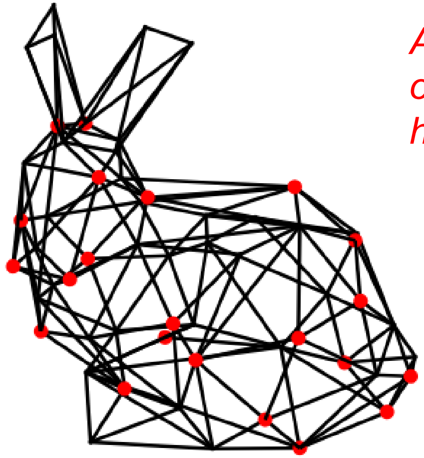




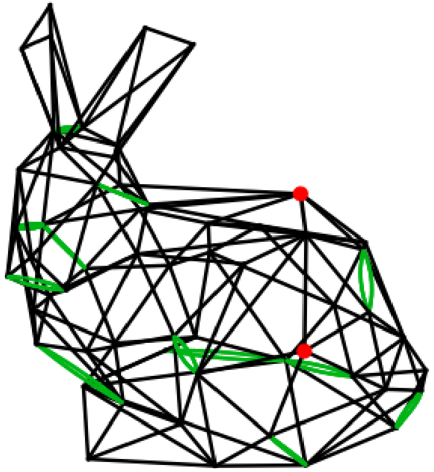


Find nodes of odd degree → **Add doubled edges with minimum length** → **Compute bend path (many possible)**

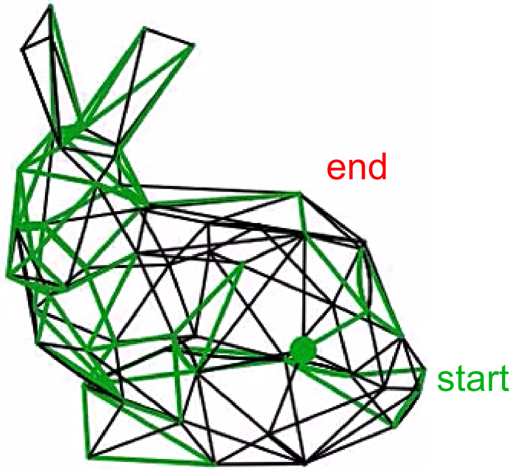
3D



Again good use of arrows to highlight steps

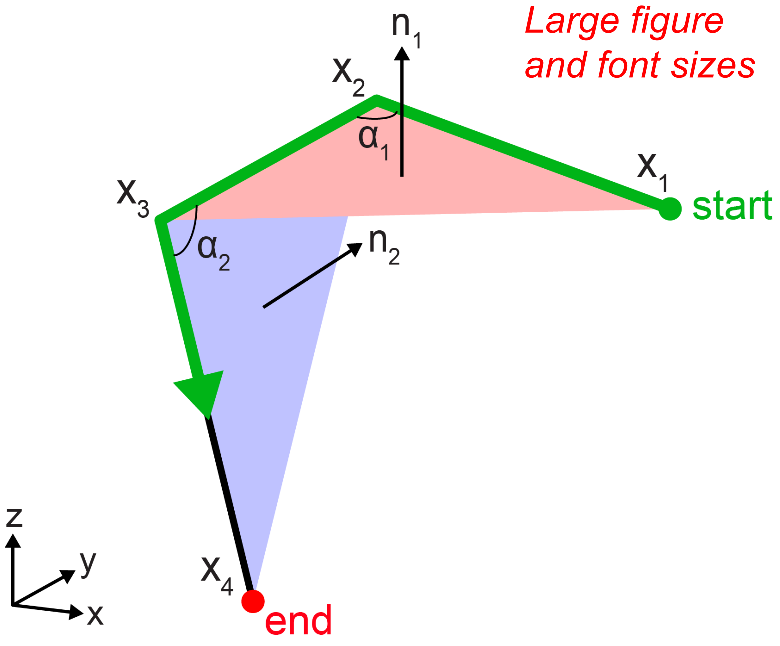


Repeated visuals from left to right to highlight effect of each step



Converting to machine instructions via geometric computations

Large figure and font sizes



Bend Path

Geometric Computations:

$\mathbf{L}_i = ||x_{i+1} - x_i||$

$\theta_{bi} = 180^o - \alpha_i$

$\theta_{ri} = 180^o - \angle(n_{i+1}, n_i)$

FEED $\mathbf{L}_1$

BEND θ_{b1}

FEED $\mathbf{L}_2$

ROTATE θ_{r1}

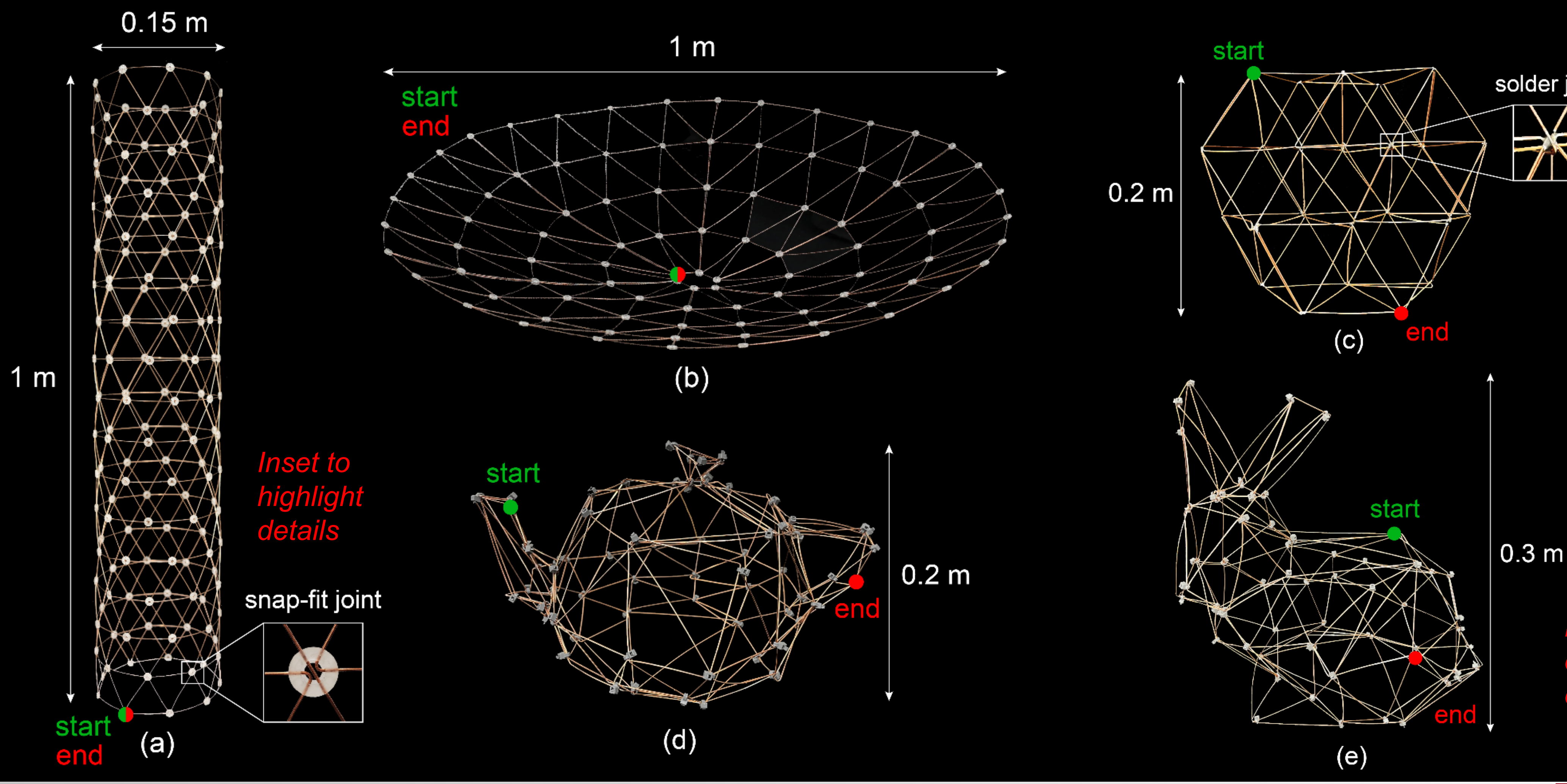
BEND θ_{b2}

FEED $\mathbf{L}_3$

Machine Instructions

Bend-Formed prototypes

Fabricated with D.I. Wire Pro machine, 1-mm diameter steel wire, and soldered, snap-fit, or zip-tie joints:



Inset to highlight details

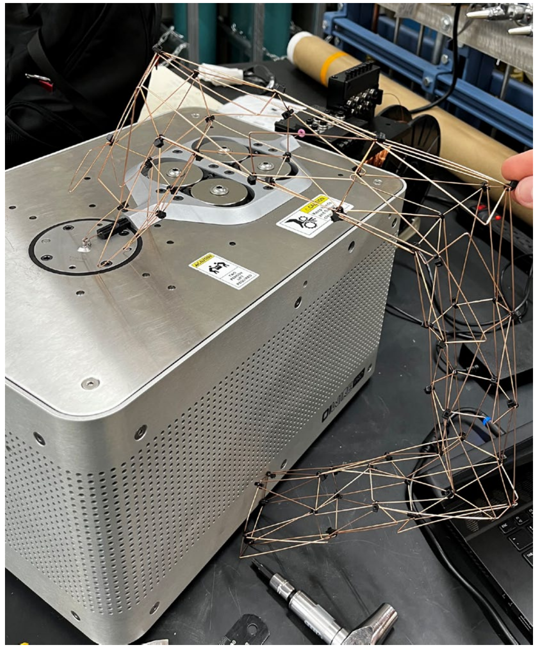
Dimensions on each picture to emphasize scale

Bend-Formed prototypes

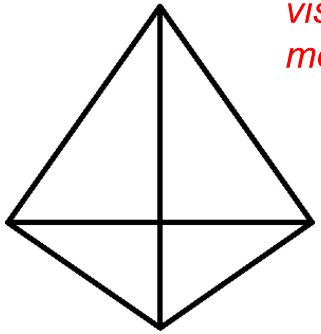
Prototype	Feedstock Length (m)	Bends	Mass (g)	Embodied Energy (kJ)	Theoretical Build Time (min)
Tetrahedral Truss	5.6	79	29	9.5	6
Utah Teapot	10.6	216	54	18	12
Stanford Bunny	11.9	176	60	20	13
Curved Gridshell	28.5	241	183	60	40
Isogrid Column	27.4	271	218	72	48

Generally tables are not good to put in presentations, but here it highlights important details regarding the images in the previous slide

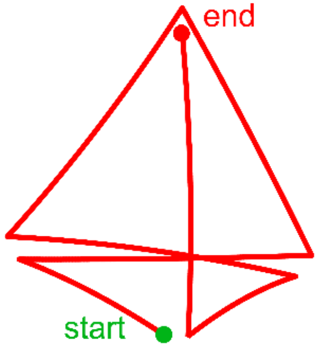
Accuracy model of Bend-Forming



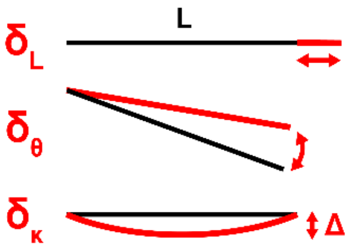
Arrows and redundant visuals to show how model works



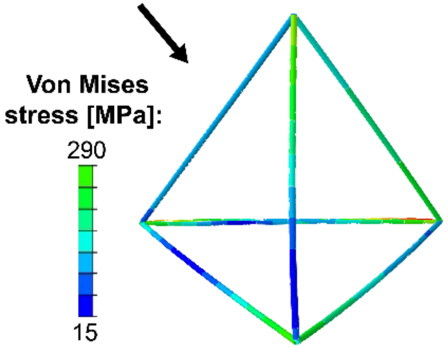
Perfect structure



Imperfect structure with fabrication defects



Fabrication defects



Imperfect structure after closing fabrication defects

Many sources of defects:

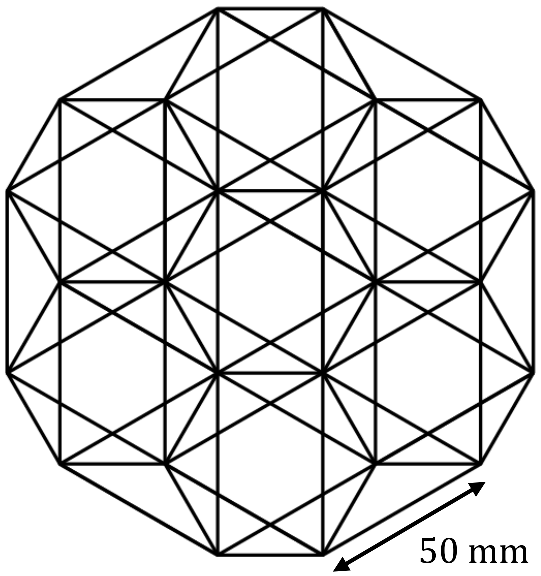
- Incomplete compensation for springback
- Incomplete straightening of feedstock
- Angular errors of stepper motors

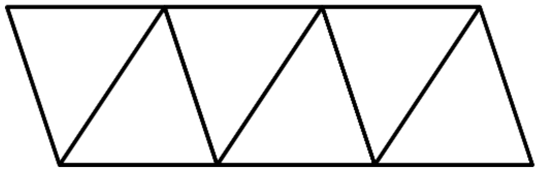
Model assumptions:

- No residual stresses from bending operations
- Worse-case fabrication: bend and rotate errors are identical
- Random direction for δ_κ
- Perfect joint attachment

Fabrication defects in Bend-Formed tetrahedral truss

Perfect tetrahedral truss:

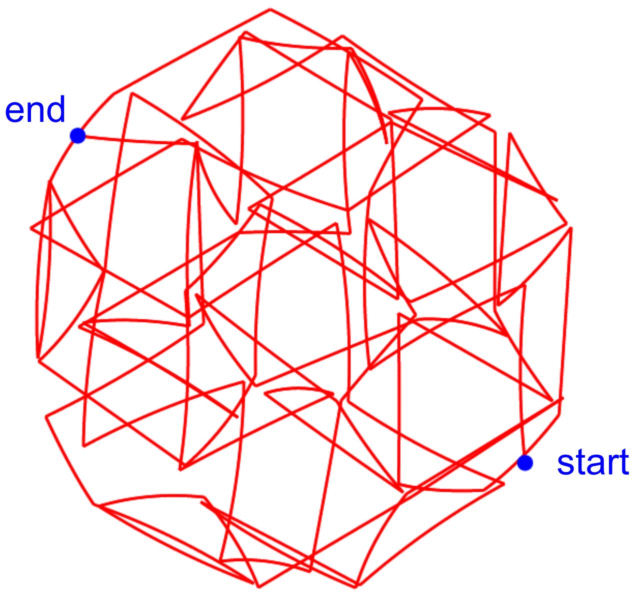


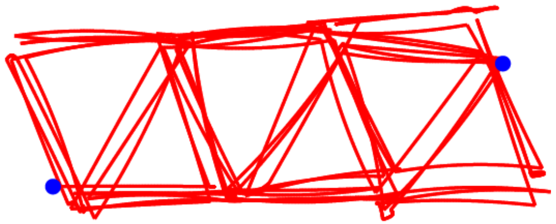


N_{ring} = 1

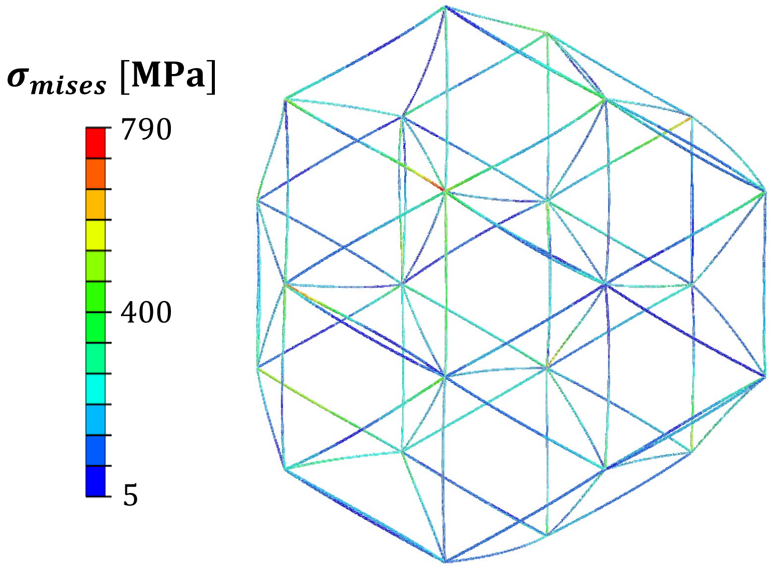
Imperfect tetrahedral truss with defects:

$\delta_L = -1$ mm
$\delta_\theta = -1^o$
$\delta_\kappa = 3\%$





Imperfect tetrahedral truss after closing defects:

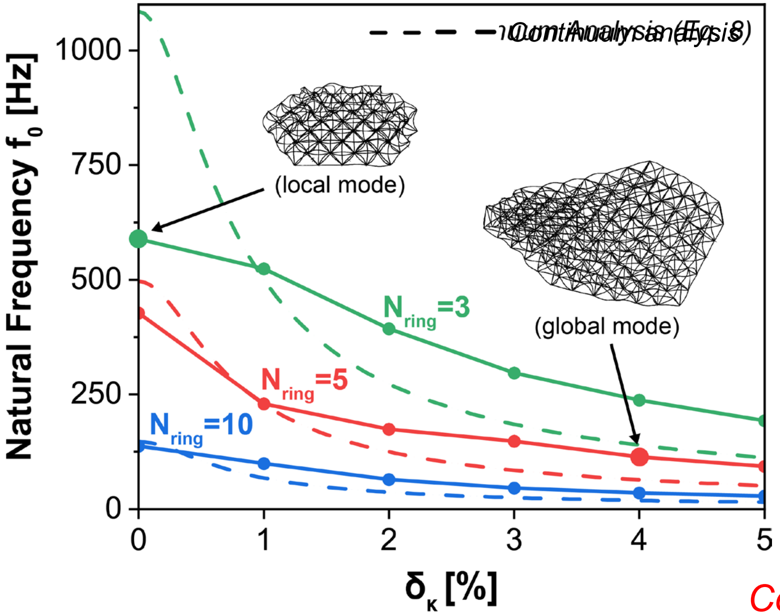


- Modeled as 1-mm steel wire with beam elements in Abaqus ($E = 200$ GPa, $\nu = 0.3$)
- Two simulation steps: 1) fixed displacements, 2) relaxation with kinematic coupling at nodes

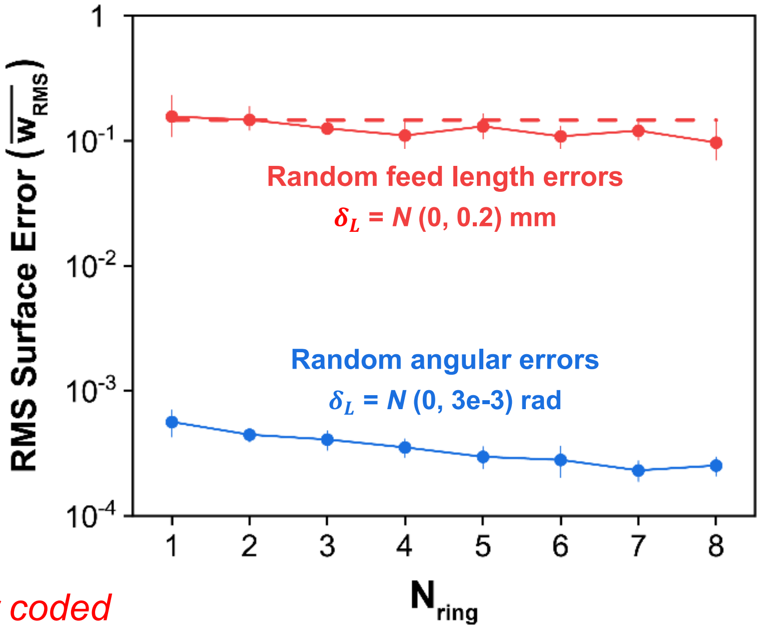
Natural progression of slide from left to right

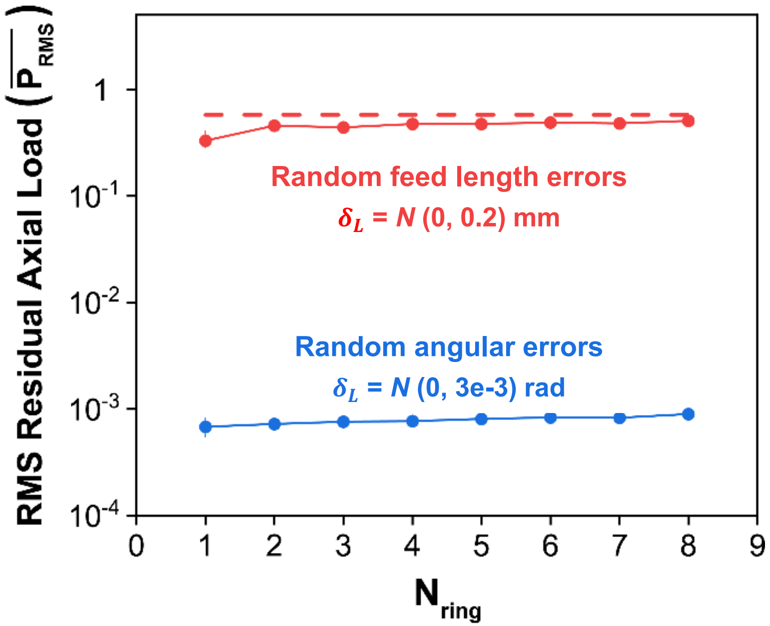
Effect of fabrication defects on structural performance of tetrahedral truss

Effect of strut curvature on **natural frequency**:



Effect of random feed and angular errors on **surface error** and **residual load** in tetrahedral trusses:





Color coded plot labels

Bend-Forming a 50-m diameter truss with 1-mm surface error, 5 N of residual load and <50% drop in natural frequency requires:

$$\sigma_L \leq 4\ \mu\text{m} \text{ and } \delta_\kappa \leq 1\%$$

Key point highlighted at bottom of slide

Contributions and current work

Contributions and current work succinctly summarized with large font size

Contributions:

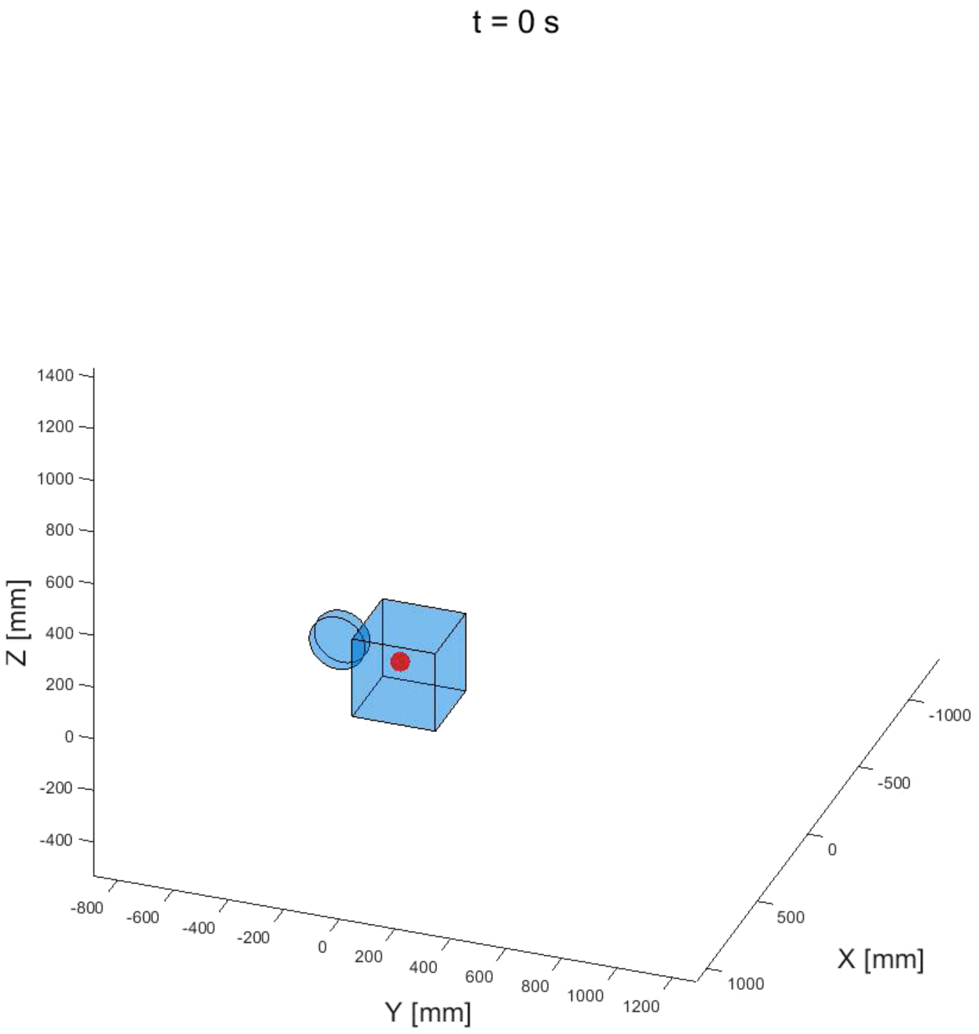
1. Path planning framework for fabricating 3D wireframe structures with Bend-Forming
   - Uses route inspection algorithm and geometric computations
2. Accuracy model to understand effect of fabrication defects on structural performance of Bend-Formed trusses

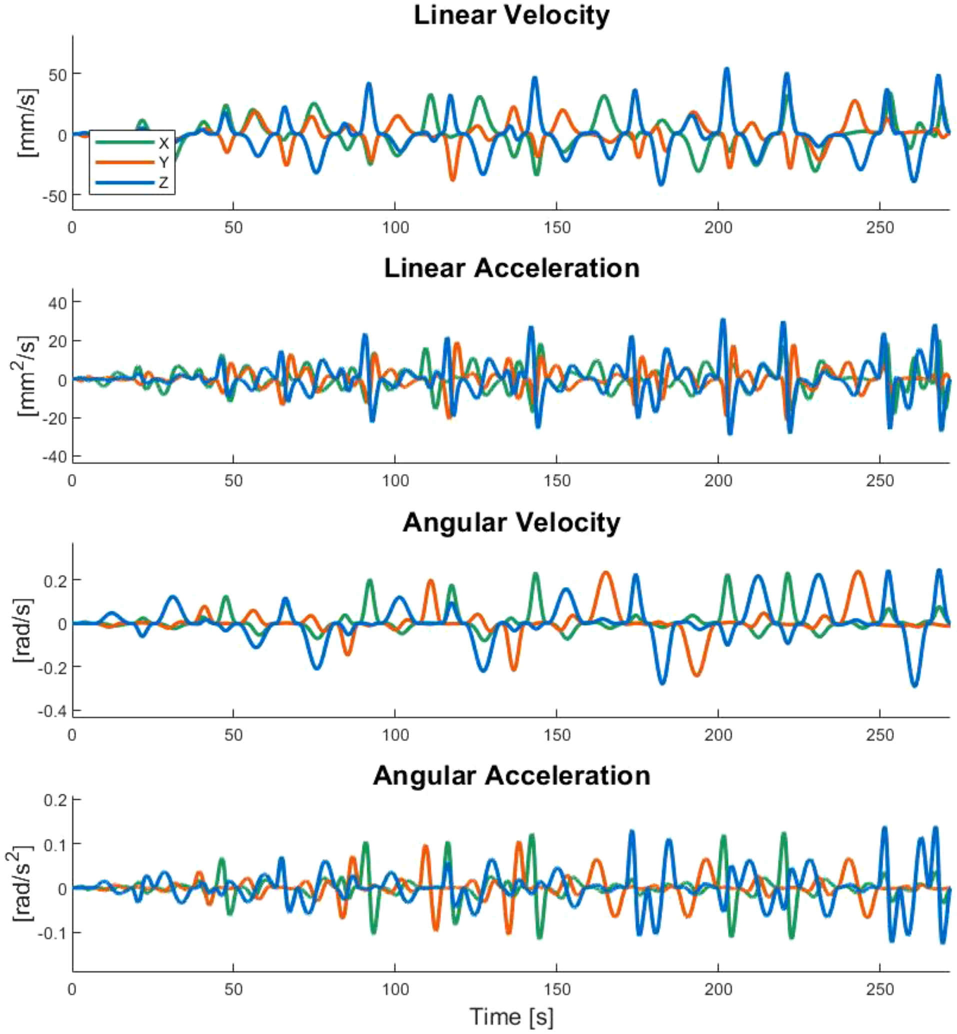
Current work:

- Automated Bend-Forming with pulsed-electrical discharge welding at the nodes + testing in TVac
- Modeling the spacecraft dynamics of Bend-Forming on orbit

Photo to highlight application again

Spacecraft dynamics of Bend-Forming on orbit





Final slide highlights preliminary results from current research, to leave the audience wanting more

Simulation parameters:

- Modeled as one rigid body with varying geometry and mass distribution
- S/C mass: 100 kg
- Final truss mass: 15 kg
- Feed rate = v_L = 150 mm/s
- Angular rate = v_θ = 10 deg/s
- Fixed timestep: $dt = 0.02$ s (8 min solve time)