



Tall Lunar Tower Project (TLT) Robotic Tower Assembly Development

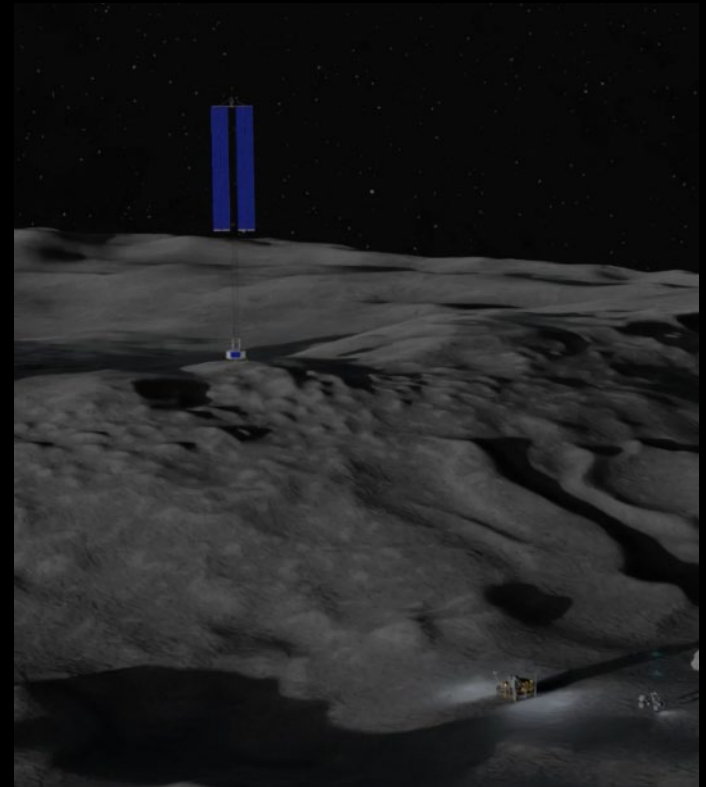
**Future In-Space Operations (FISO) Telecon Seminar
4-3-2024**

Matthew K. Mahlin – TLT Principal Investigator

*Aerospace Research Engineer
Structural Mechanics and Concept Branch
NASA Langley Research Center*



- **Project Background**
- **Reference Mission Concept**
- **Lunar Tower Analysis**
- **Engineering Development Unit**
 - Lunar Tower Design
 - Robotic Tower Assembly System Design
 - Software Overview
- **Demonstration**
- **Concluding Remarks**



Project Background

- Supported by Advanced Exploration Systems (AES)
- Managed by Space Technology & Exploration Directorate (STED)
- Two-year duration (fiscal year 22 to 23)

Purpose

The Tall Lunar Tower (TLT) In-Space Assembly (ISA) team's purpose was to design, model, fabricate, autonomously assemble, and characterize a TLT assembly engineering development unit (EDU).

Development involved cross-cutting robotic truss assembly technology to eventually enable construction of infrastructure in the lunar environment. The technology development goal was to enable the assembly of structures for energy collection, communication, blast shields, safe havens for astronauts, and in-situ resource utilization (ISRU) operations.



Focus on robotic assembly of trusses to form a tower

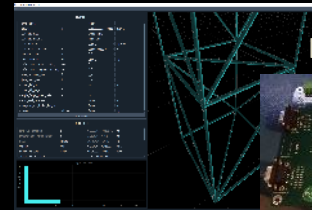
Tall Lunar Tower (TLT)

Polaris project focus: Develop robotic truss assembly technology, including a TLT engineering Development Unit (EDU)

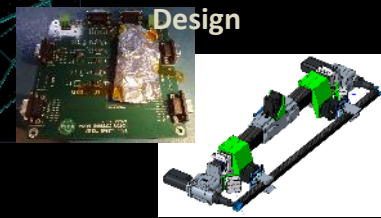
Development Objectives

Compact truss packaging for launch
Robotic assembly (supervised autonomy)
Designed for 50-meter tower height
High payload capacity (≥ 1000 kg)

Modeling & Simulation



Hardware/Software Design



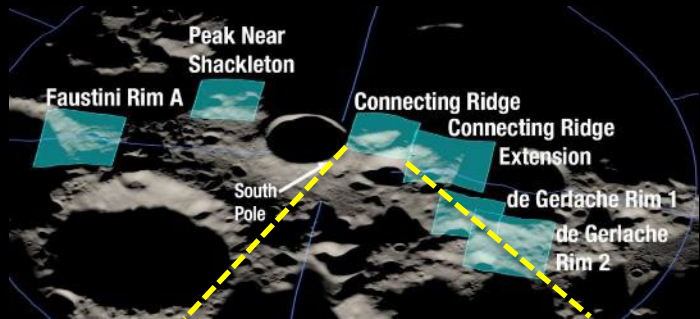
Lab Testing



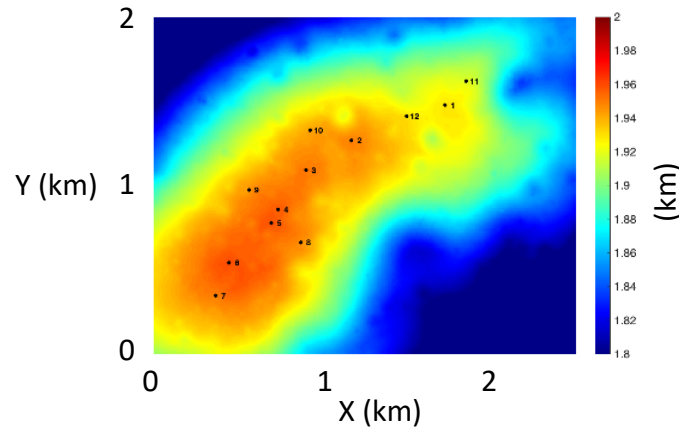
Why a tall tower? ≥ 50 -m height for solar arrays can provide near constant power supply, cutting energy storage mass in half

- **Early, scalable lunar infrastructure:** ≥ 50 -meter power, communication, & navigation tower
- Develops technologies for V&V, remote inspection/sensing, robust/repeatable autonomous operations, and robotic structural assembly needed for sustainable lunar presence
- Cross-cutting robotic truss assembly technology could also be **leveraged for habitation, blast shields, and ISRU** mining/processing/storage structure assembly

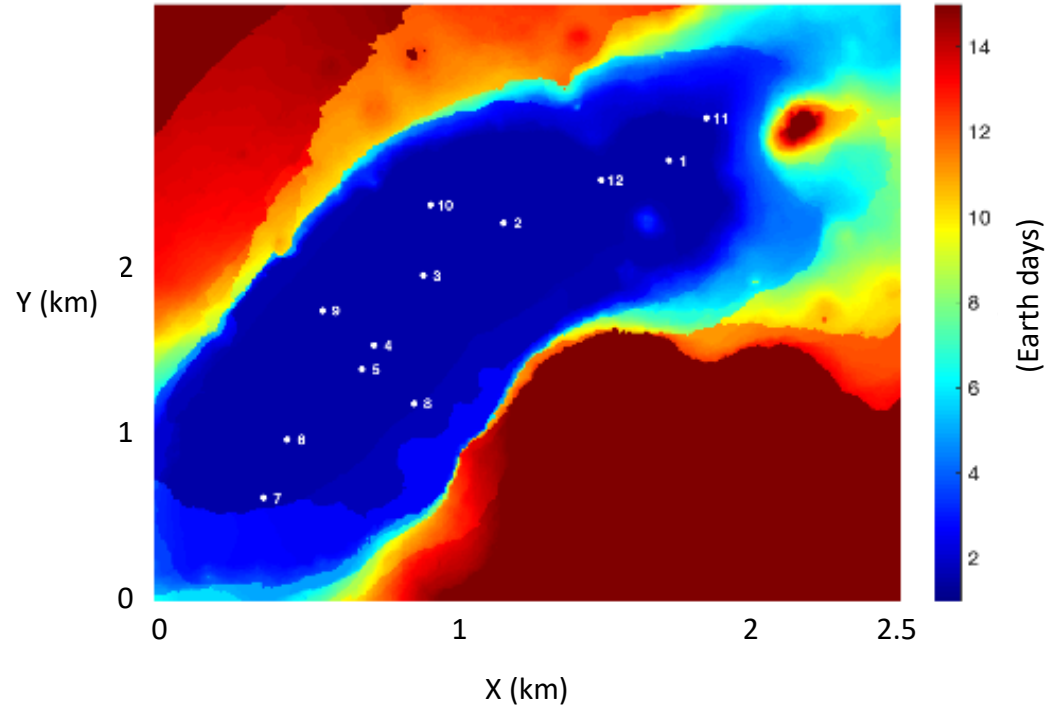
Tall Towers for Solar Power



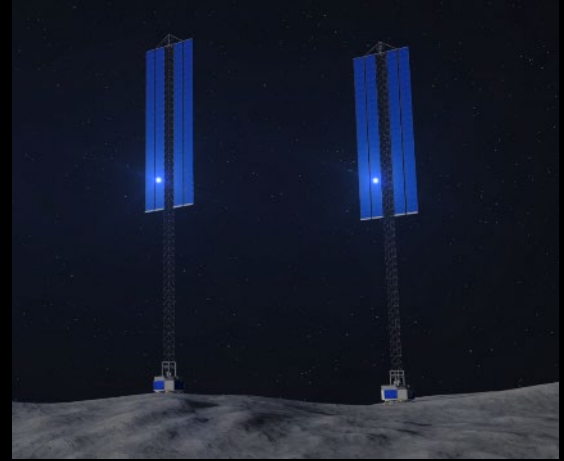
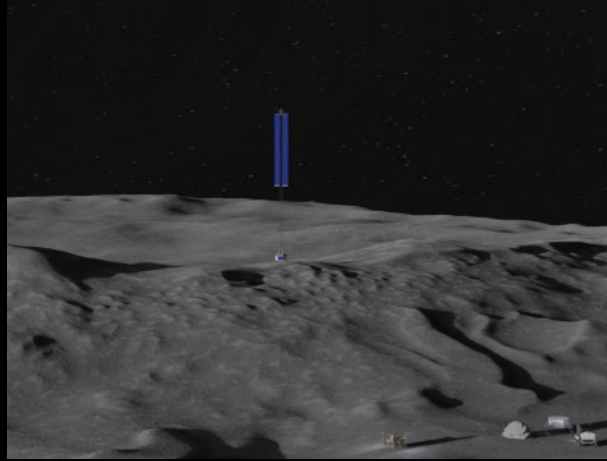
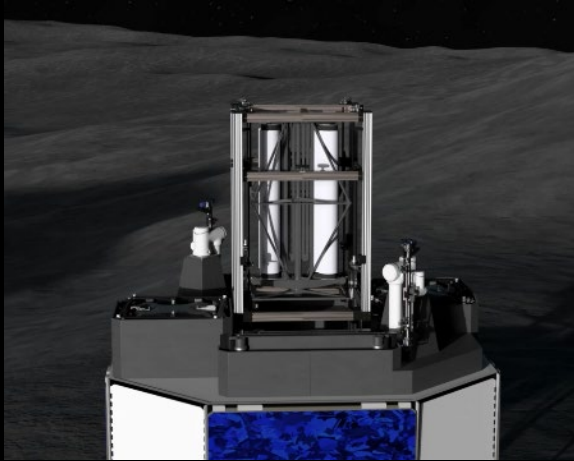
Connecting Ridge Topology



Longest darkness period
 $z = 50$ m



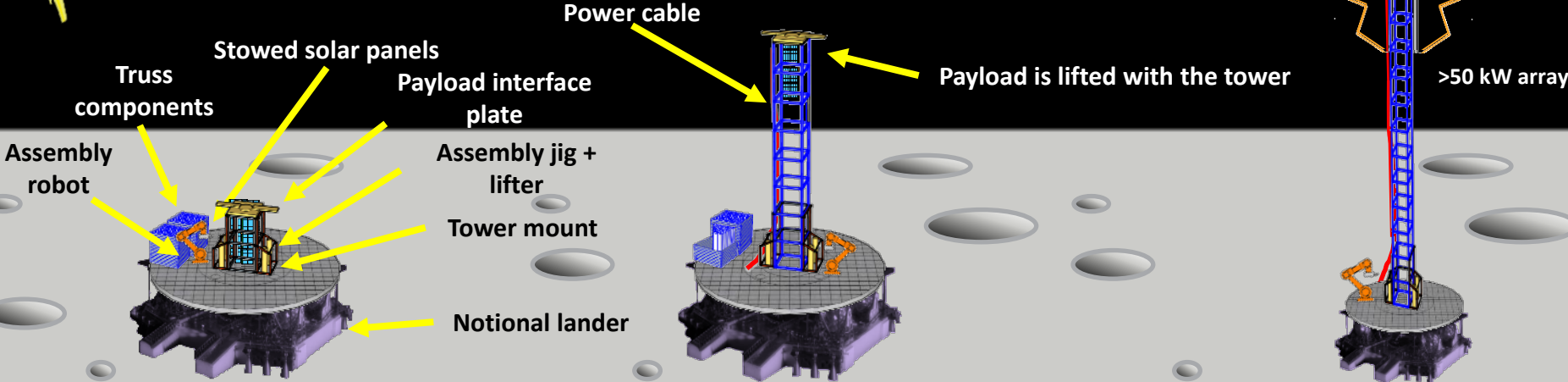
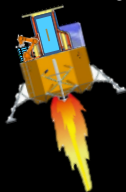
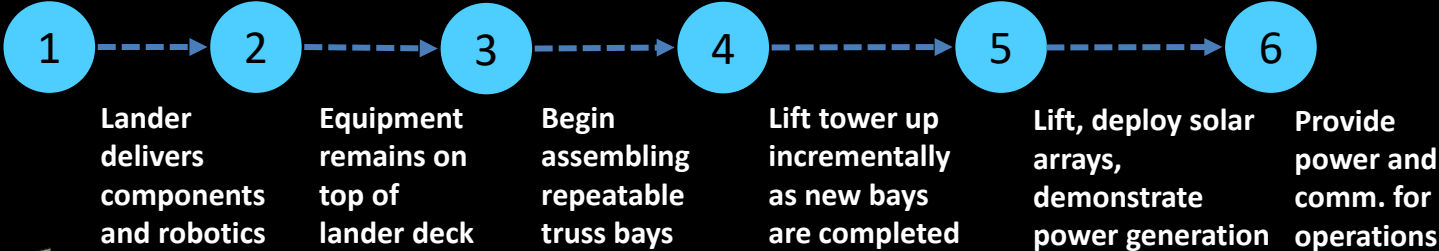
- Full Scale Lander Based Mission
- Evolution Roadmap



Renderings of a future lander-based tower assembly system



Full-Scale Lander-Based Reference Mission Concept



Next Steps: Tall Lunar Tower Evolution Roadmap

Demonstrator

1

- Composite structure
- Lander based
- 25-meter height

Power generation capability

2

- Composite structure
- Lander based
- 50-meter height

Foundation based composite structure

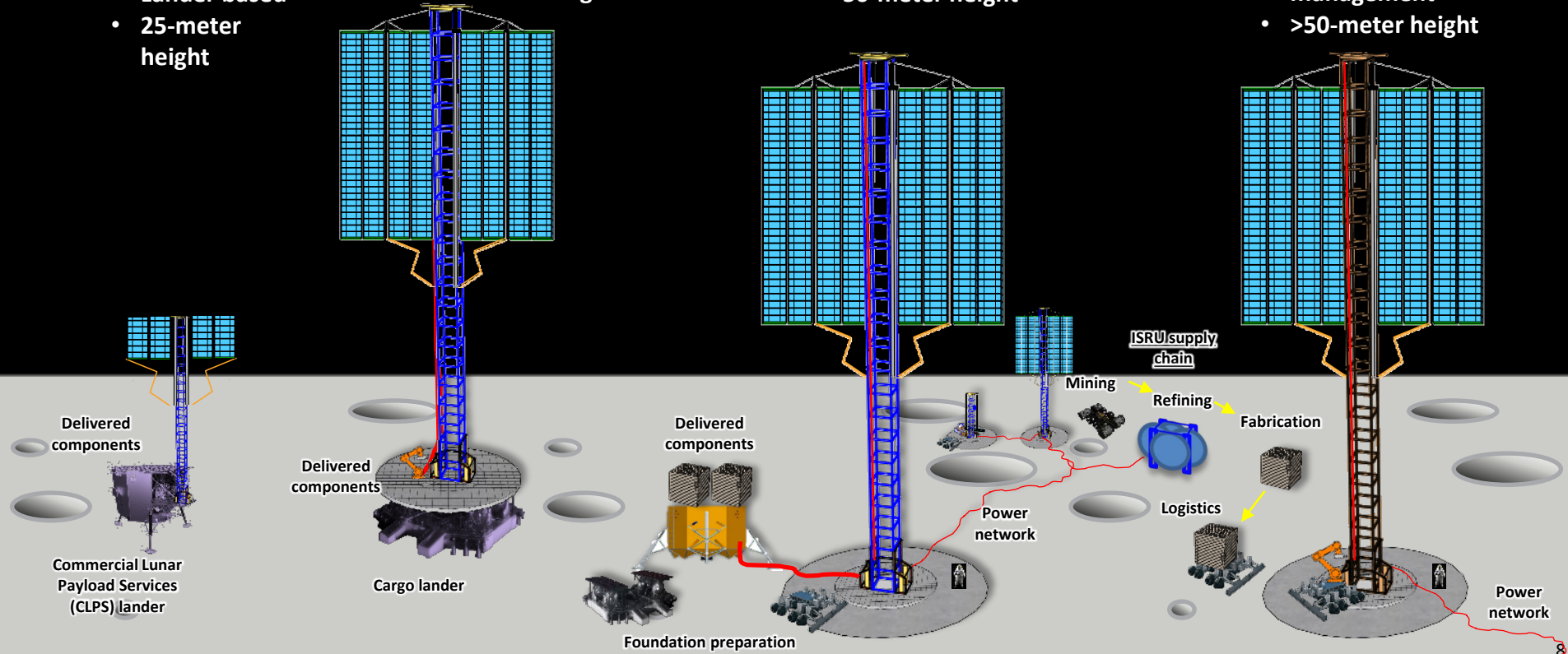
3

- Composite structure
- Prepared foundation
- 50-meter height

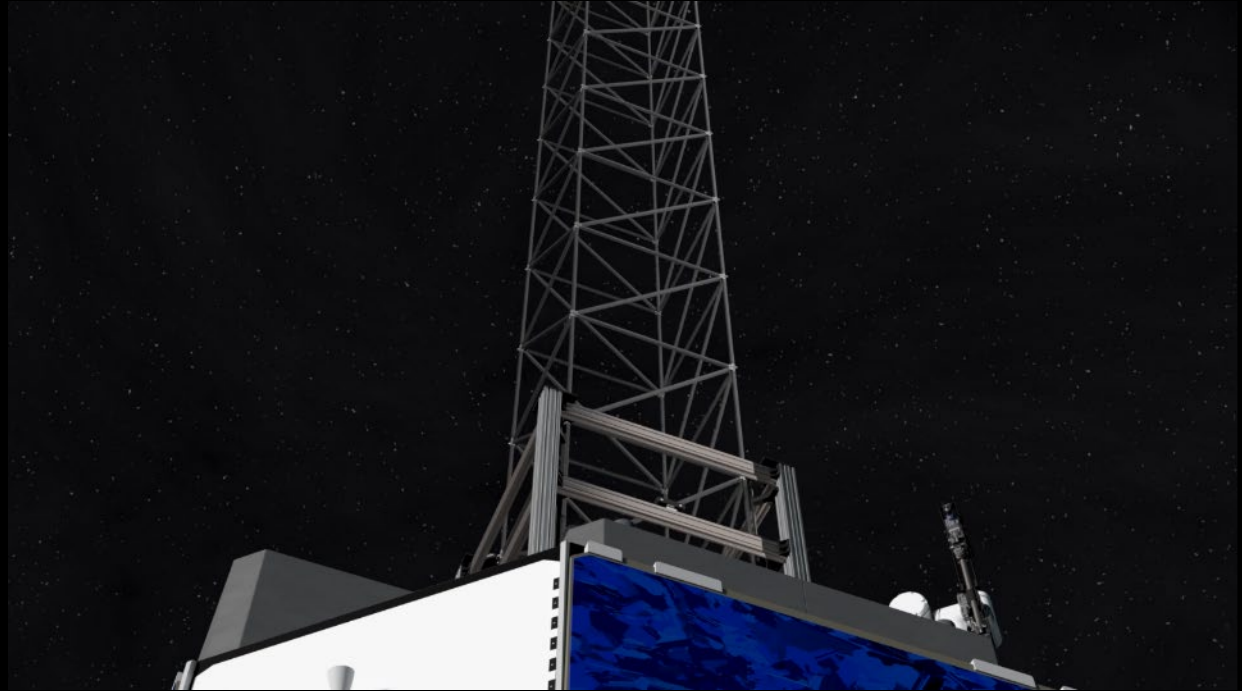
ISRU assembled structure

4

- Aluminum structure
- Thermal deformation management
- >50-meter height



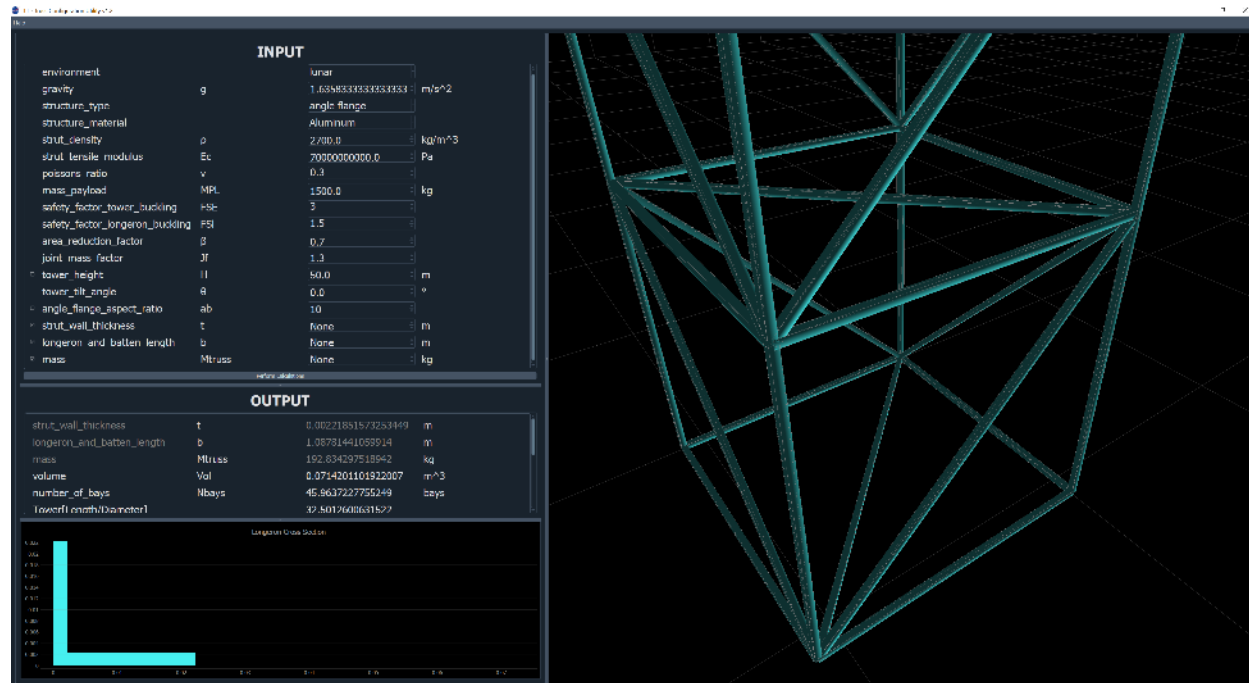
- Tower Sizing
- Tower Design
- Thermal Analysis



Tower Sizing - Truss Configuration Utility (TCU)

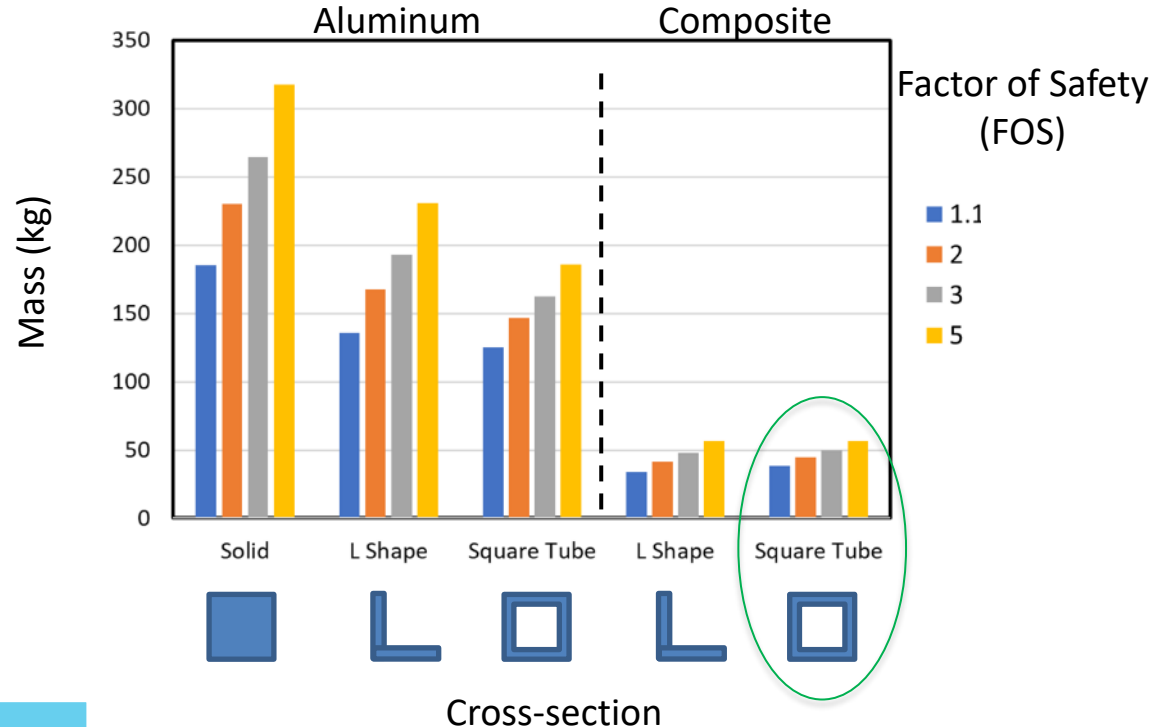


- Developed to rapidly explore the preliminary design space
- The TCU is based on three governing equations:
 - Longeron Euler buckling (PL)
 - Tower Euler buckling (PT)
 - Mass of the tower (Mtruss)
- Multiple inputs
 - Gravity
 - Payload mass
 - Material properties
 - Strut cross-section
- TCU provides
 - Mass of tower
 - Strut dimensions
 - Visualization
- Detailed thermo-structural analysis follows



Tower Design Parameters

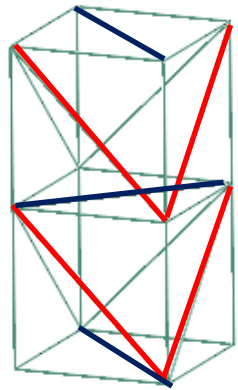
- Tower design began with material and cross section selection
- Assumptions
 - Initial payload estimate 1500 kg
 - 50-meter-tall tower
 - Lunar gravity
 - All truss members are equal cross-section
- Goals
 - Minimize mass
 - Commercially available material
 - Easy to handle with gripper
 - No additional feature needed for strut orientation



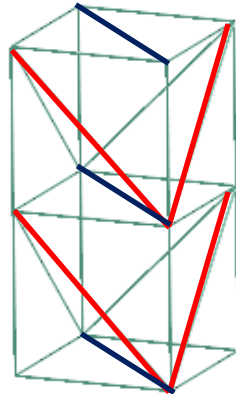
Composite square tube selected

Finite Element Model with Different Tower Design

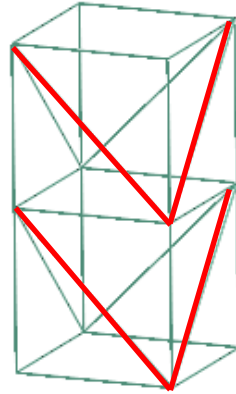
Type A
repeating diagonals



(1)
with cross
In-plane members

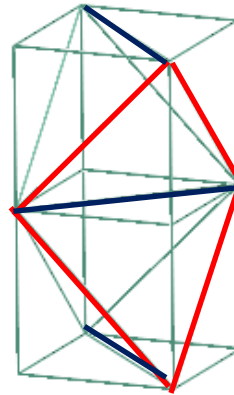


(2)
with parallel
In-plane members

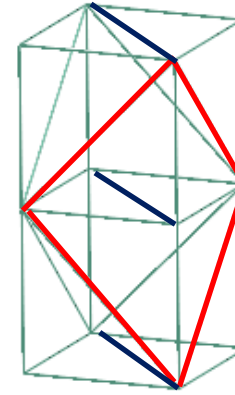


(3)
without
In-plane members

Type B
alternating diagonals

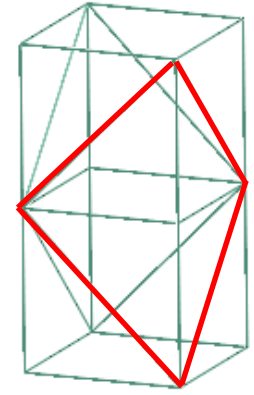


(1)
with cross
In-plane members



(2)
with parallel
In-plane members

Selected



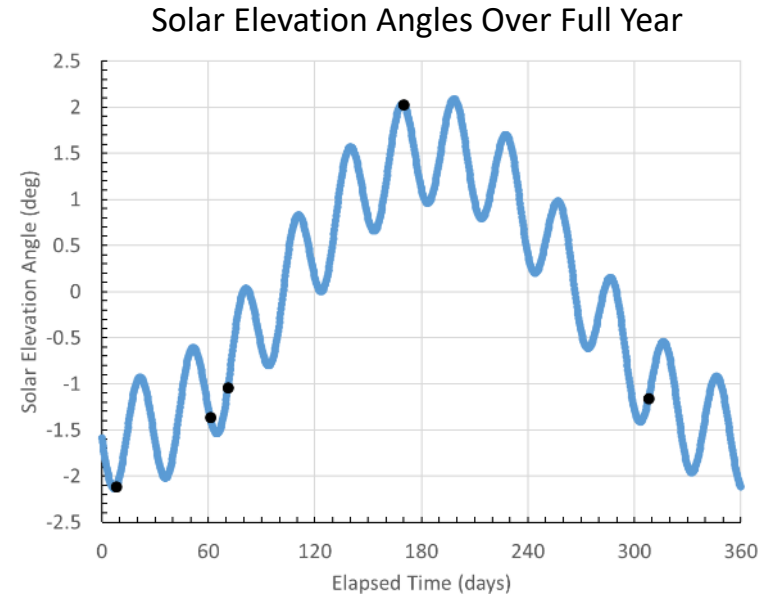
(3)
without
In-plane members

Type "B-3" selected after finite analysis
Minimizes structural mass without in-plane members
Simpler construction
Buckling failure mode still dominant

Thermal Analysis: TLT Thermal Model



- **50.25-meter tower, 0.75-meter bays**
- **Geometry maps to structural model**
- **Material properties**
 - Truss elements: graphite-epoxy M55J
 - Joints: aluminum 6061-T6
- **Temperature values are obtained from heat flux analysis**

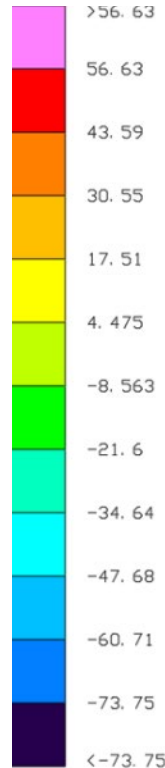


Days considered:
Day 8: cold case
Day 170: hot case
Days 61, 71, and 308: max gradients

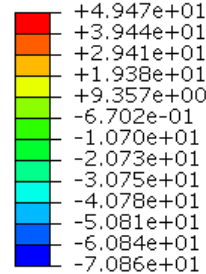
Day 170, Temperature Distribution

Thermal Model Temperature Map

Temperature °C



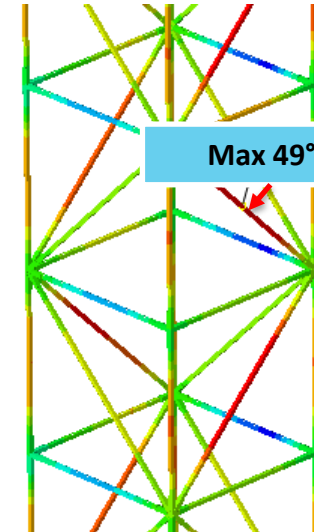
Temperature °C



Max: +4.947e+0



Structural Model Temperature Map



Max 49°C

Max Temperature is observed along the sun facing diagonal strut

Thermal-Structural Analysis (Temperature Map)

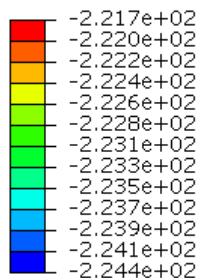


Day 8: cold case

Day 170: hot case

Days 61, 71, and 308: max gradients

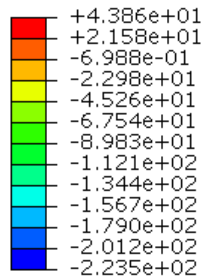
Temperature °C



-224 °C

Day 8 (Cold)

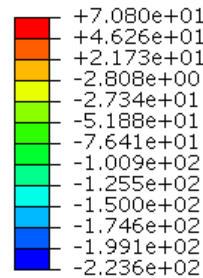
Temperature °C



+43 °C
-224 °C

Day 61

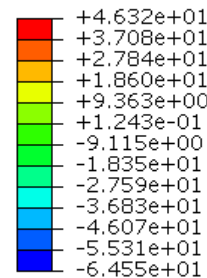
Temperature °C



+70 °C
-224 °C

Day 71

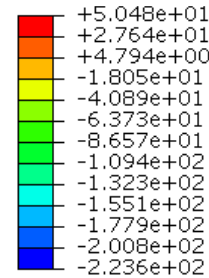
Temperature °C



+46 °C
-64 °C

Day 170 (Hot)

Temperature °C



+50 °C
-224 °C

Day 308

Von Mises Stress Results

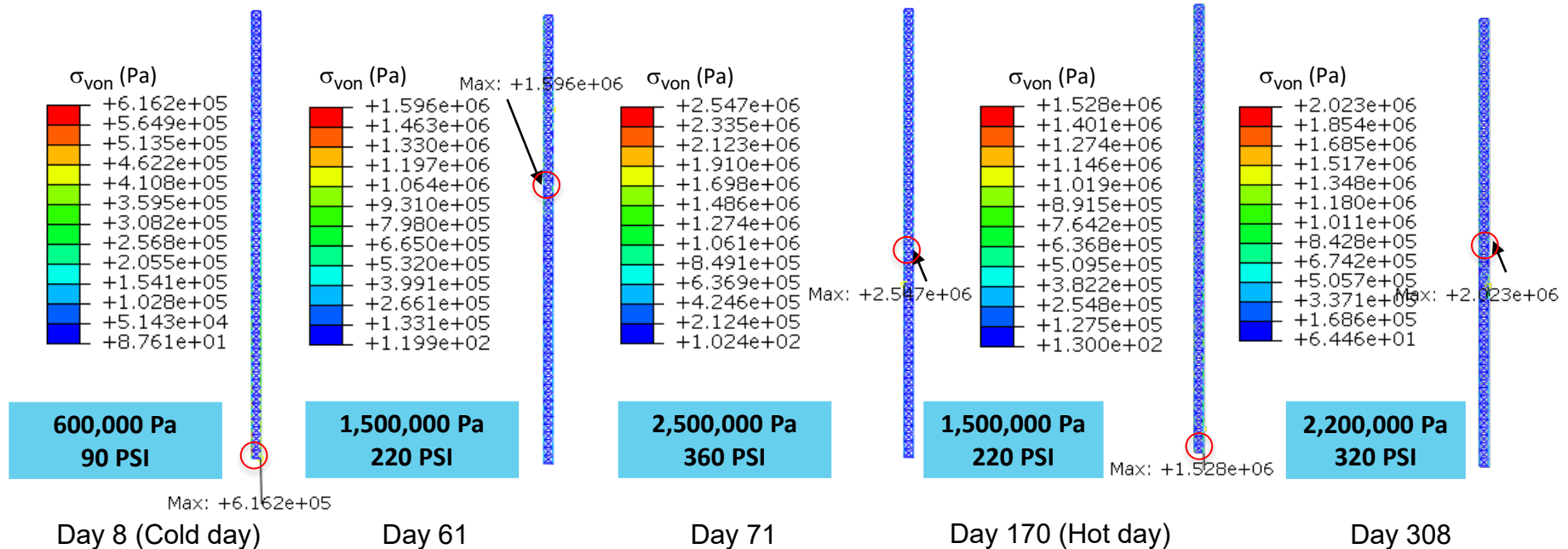


Day 8: cold case

Day 170: hot case

Days 61, 71, and 308: max gradients

Max stress induced by temperature gradient
Generally lower stresses when tower fully illuminated or dark



Engineering Development Unit (EDU) Section



Goal: Demonstrate an EDU analogous to a lander-based system

Demonstration Highlights

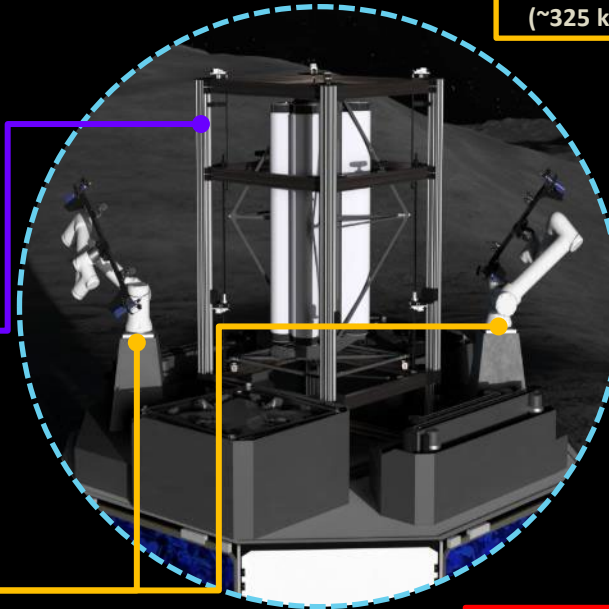
Laboratory environment
Multi-bay assembly
~5-meter height
No payload

Construction Robot System (CRS)

- Primary control
- Jigging
- Lifting

Assistant Robot System (ARS)

- Part placement
- Fastening



>50 kW Solar Array
(~325 kg + Structure)

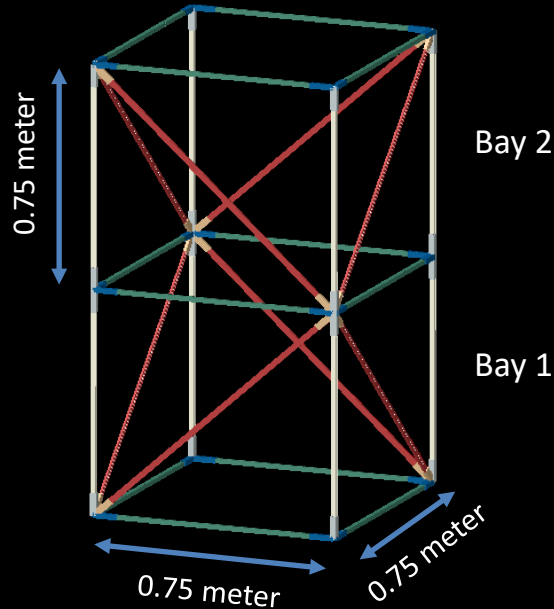
Communication

50 meters



50.25-Meter Tower
0.75 m x 0.75 m x 0.75 m Bays
(~110 kg Structure)

- Joints
- Struts
- Assembly Sequence
- Analysis



NOTE: 0.75 meter $\cong$ 2.46 feet

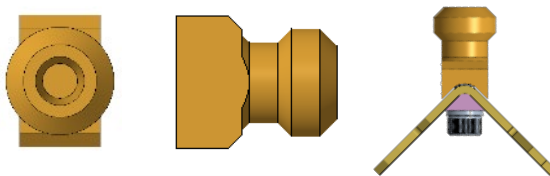
Dimensions of a repeatable TLT truss bay

Goal: Simple to machine joint design compatible with robotics and ISRU material

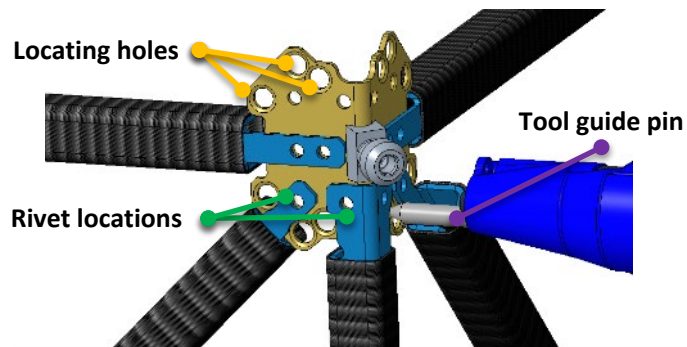
- **Simplistic 90° gusset plate interface**
 - Easy to manufacture from 2 mm thick sheet material
 - Intended for future compatibility with ISRU material
- **Locating holes to guide rivet tool to attachment points**
 - Countersunk holes
 - Guide pins mounted to rivet tool
- **Lifting Node**
 - Tapered hole to accept pin
 - Rounded exterior for alternate gripping (unused)
- **Rivets used to attach struts to joint – 5 mm diameter**
 - Single sided blind fasteners
 - Off-the-shelf riveting tools implemented



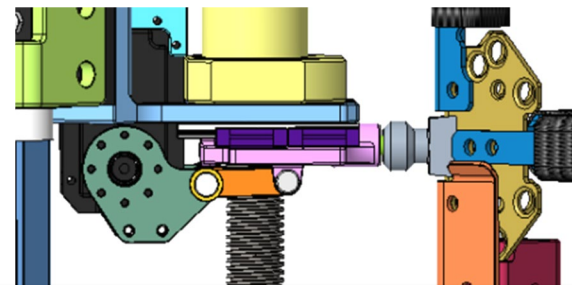
Rivet



Lifting node



Truss joint with rivet and locating holes



CRS lifting gripper interfacing with truss node

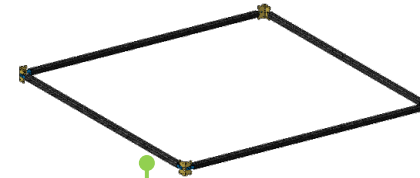
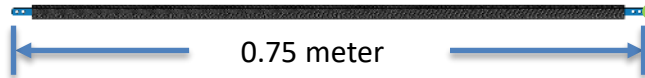
Strut Components

Goal: Light-weight, stiff, and low CTE truss components compatible with robotics and metallic joining techniques

- Ultra high modulus carbon fiber square tubes
- End fittings are bent aluminum sheet metal parts
- Strut assemblies are bonded with glass bead to set bond line thickness

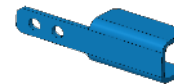
1) Cross frame assembly:

Cross frames are built from four horizontal struts and four joints.

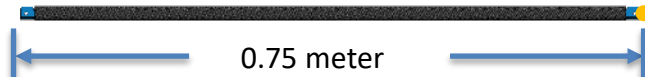


Cross frame assembly

Horizontal end-fitting



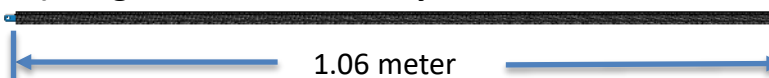
2) Longer strut assembly:



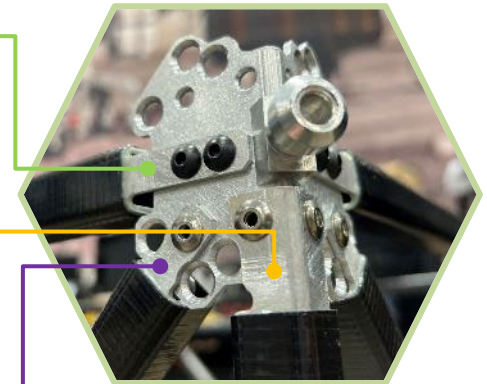
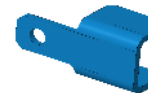
Longeron end-fitting



3) Diagonal strut assembly:



Diagonal end-fitting



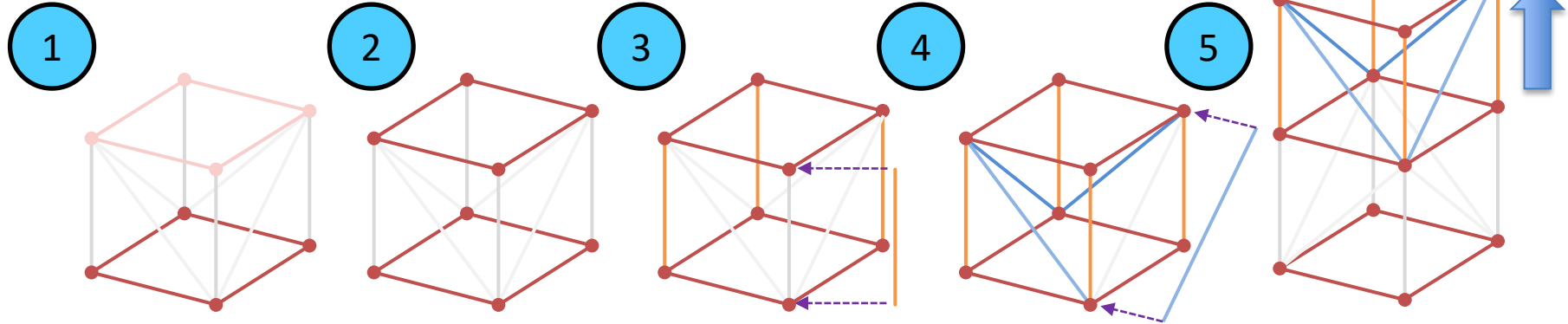
Partially riveted joint

Cross Frame Assembly Sequence

- Semi-modular assembly sequence
- Reduced assembly steps from strut-by-strut assembly approaches
- Cross frames handled like single struts

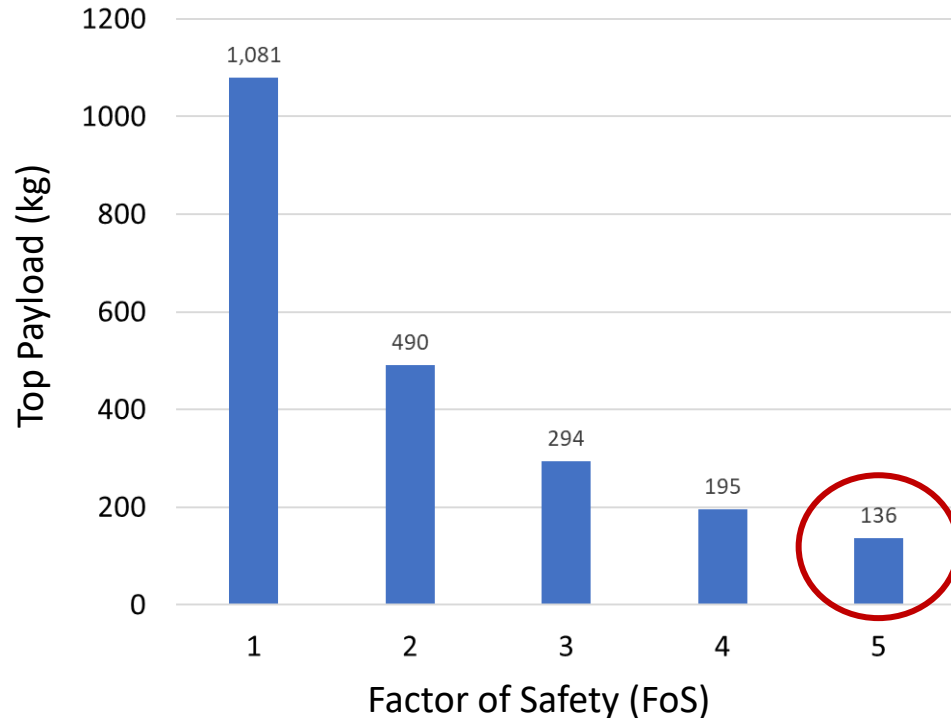
Steps

1. Top cross frame inserted into assembly jig
2. Top cross frame is lifted, and a bottom cross frame is inserted into the assembly jig
3. Vertical Longerons attach top cross frame to bottom cross frame
4. Diagonal struts attached to rigidize and complete new bay
5. Completed bay is lifted with all bays above it, and a new bay is started



Analysis of EDU and Joint Test

Calculated Top Payload Capability (50-meter tower)



Joint under loading



120 kg

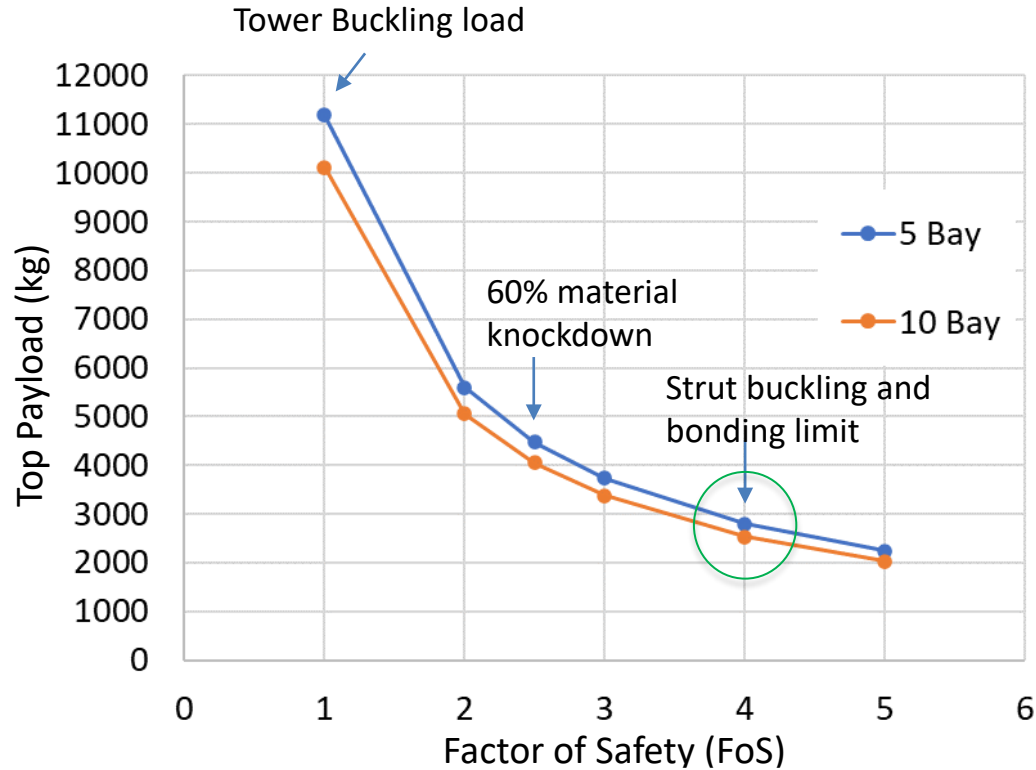


Joint under loading

Static load joint test

Subscale assembly loaded to 120 kg to test assembled joint loading

Capability of EDU (5 Bay and 10 Bay)

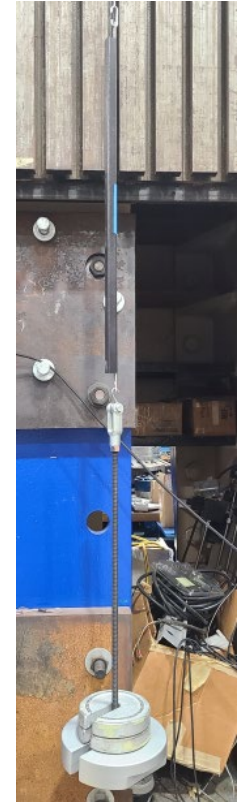


Expected Load capability of tower EDU ≥ 2000 kg



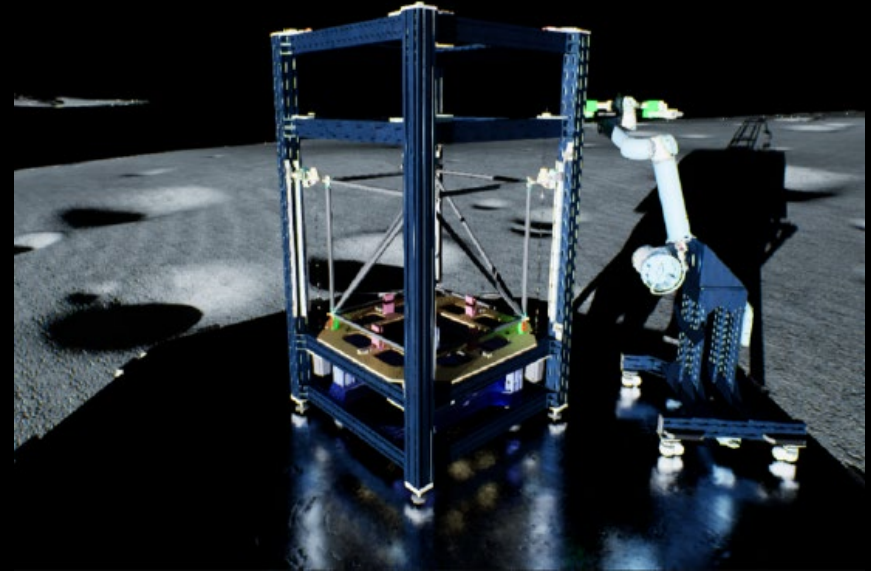
Multi-Strut Compression Test

Note: Off-center end fittings were not well suited for load frame testing



Tension Test

- Robotics Overview
- Construction Robot System (CRS)
- Assistant Robot System (ARS)
- Riveting End Effector



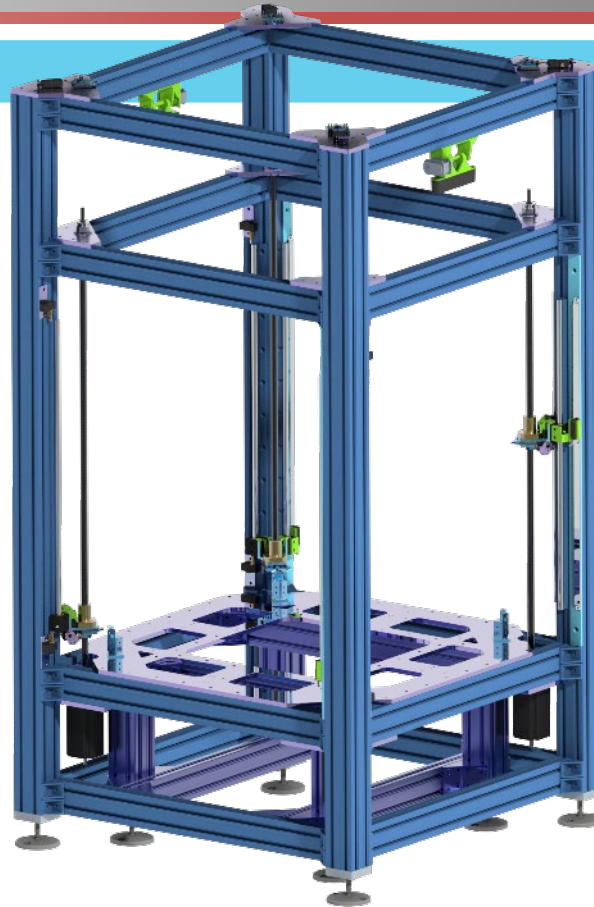
Jigging and lifting system for vertical assemblies

- **Construction Robot System (CRS)**

- One CRS system serves as the core of the TLT assembly system
- Metrology cameras aid the assembly and situational awareness
- A Jetson Orin serves as the control computer

- **Purpose:**

- Coordinate assembly robotics
- Jigging - accurately position truss components
- Lifting - incrementally raise the entire tower structure



Construction Robot System (CRS) Overview

Key CRS Hardware

A. Top grippers (x4)

Captures the top cross frame

B. Camera system (x2)

Depth and object recognition capability for part and build inspection

C. Truss footing (x4)

Assembly guides and supports completed structure

D. Lifting lead screw and bearings (x4)

Bears load from structure and payload during lift actions

E. Lifting grippers (x4)

Captures truss nodes to perform lift synchronized with absolute position sensors

F. Lifting stepper motor (x4)

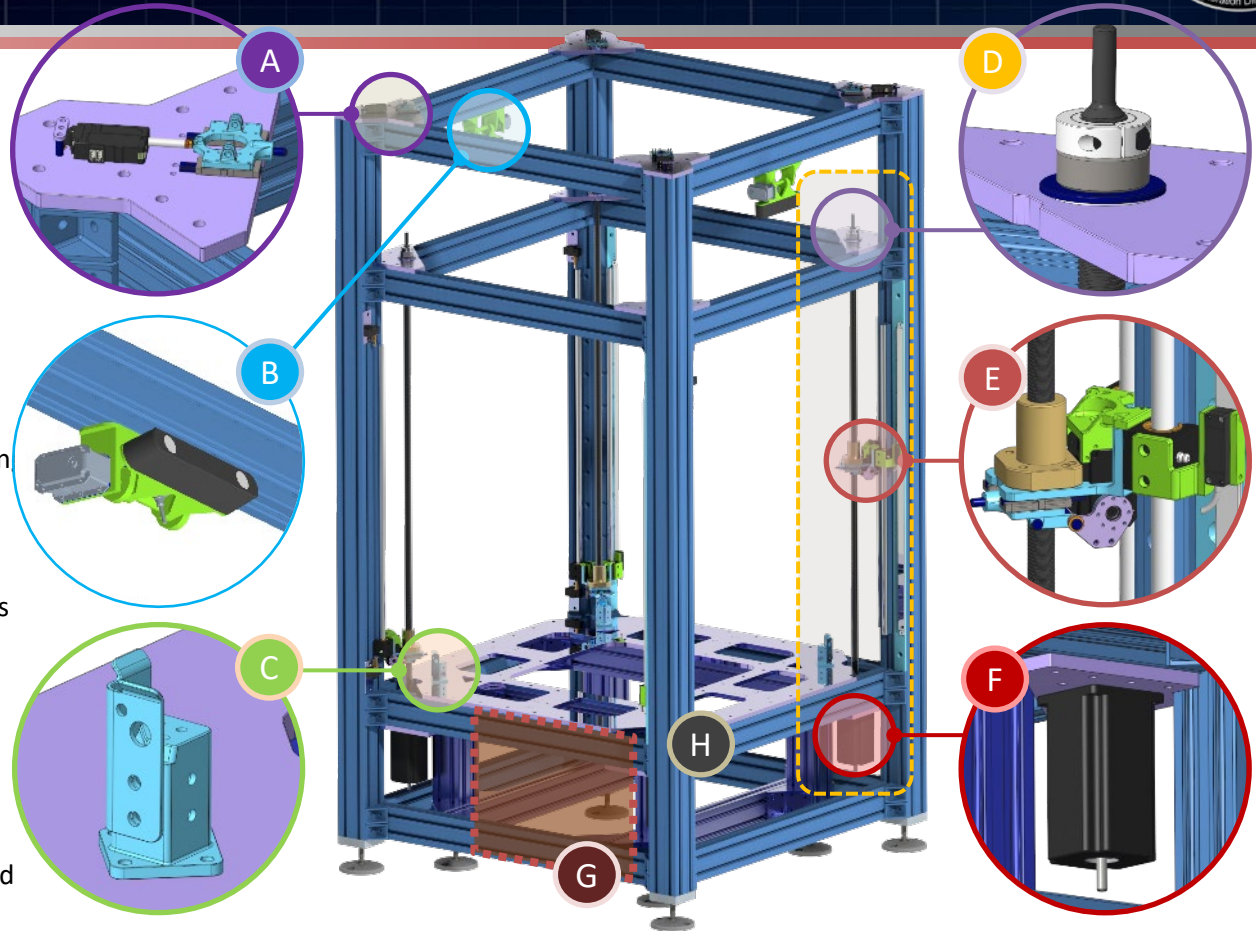
Drives the linear actuator

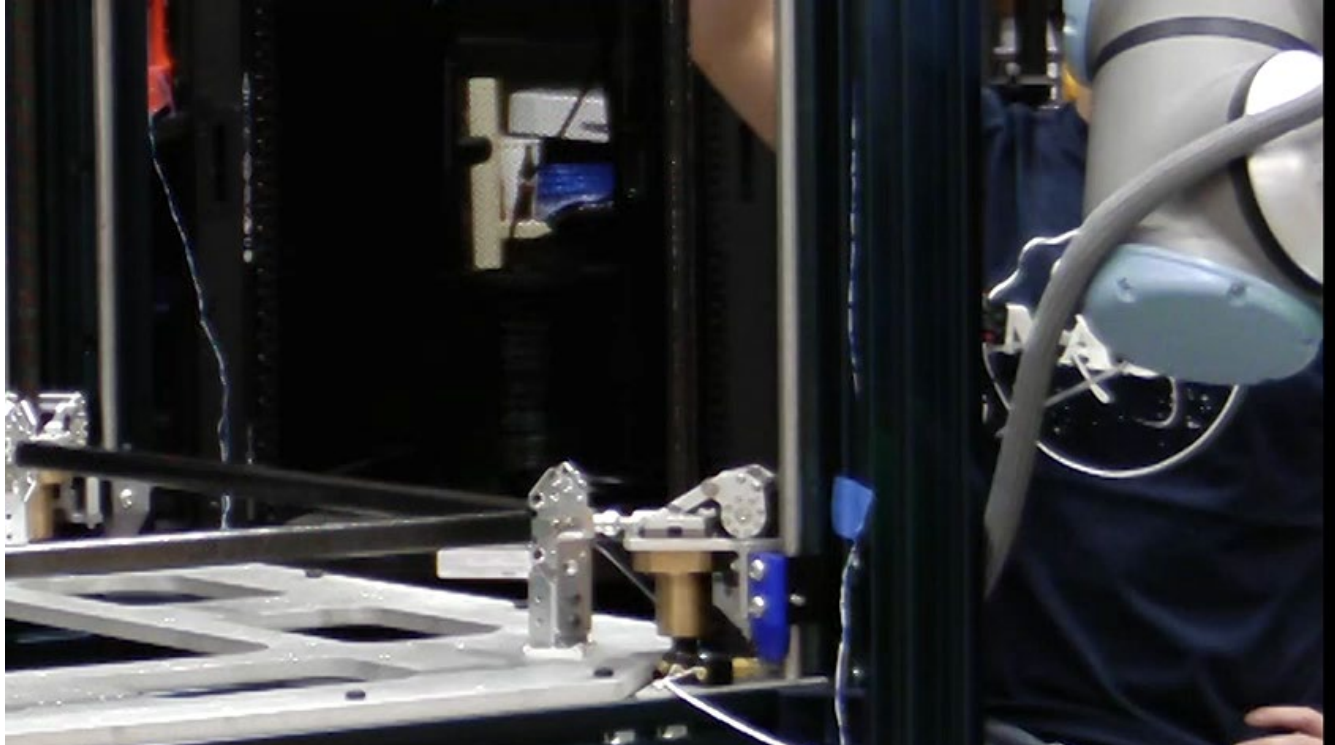
G. CRS electronic system

Controlling the on-board systems and coordinates with ARS

H. Structural jiggig frame

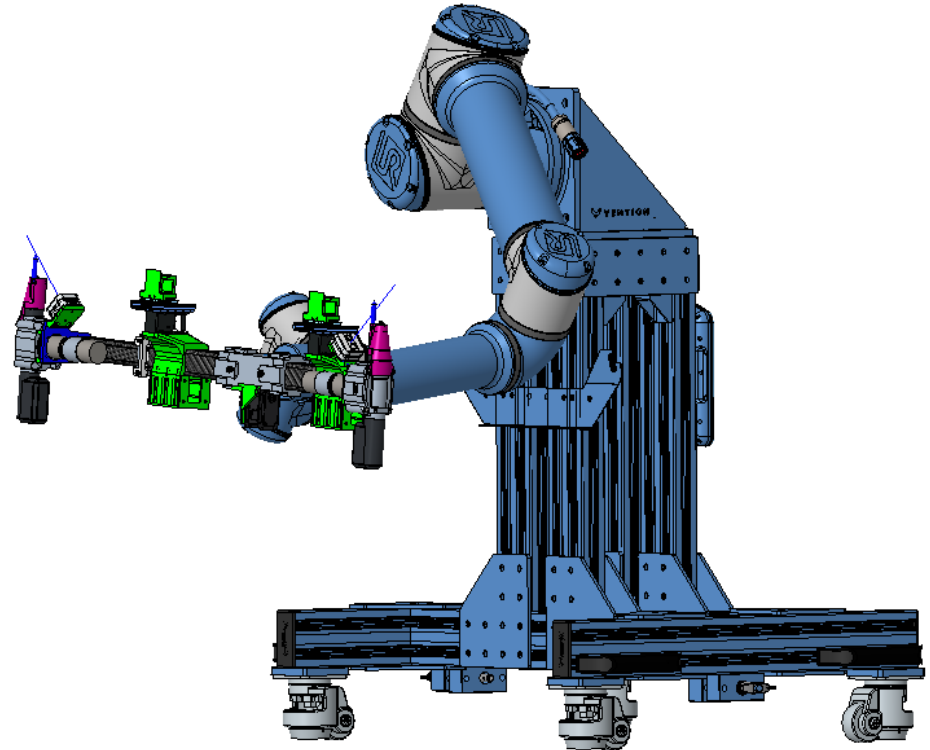
Load bearing structure provides stability and leveling for assembly





CRS – Test of Synchronized Lifting

- **Assistant Robot System (ARS) – UR10e manipulators**
 - Two ARS are positioned on opposite sides of the CRS
 - Each ARS can reach two of the four vertical faces of the TLT bays
- **Purpose:**
 - Positioning end effectors
- **Riveting end effector**
 - Identical end effectors
 - Fixed grippers position
 - Extendible width joining tools
 - Tool alignment cameras
- **Purpose:**
 - Hold
 - Align
 - Inspect
 - Joining with rivets

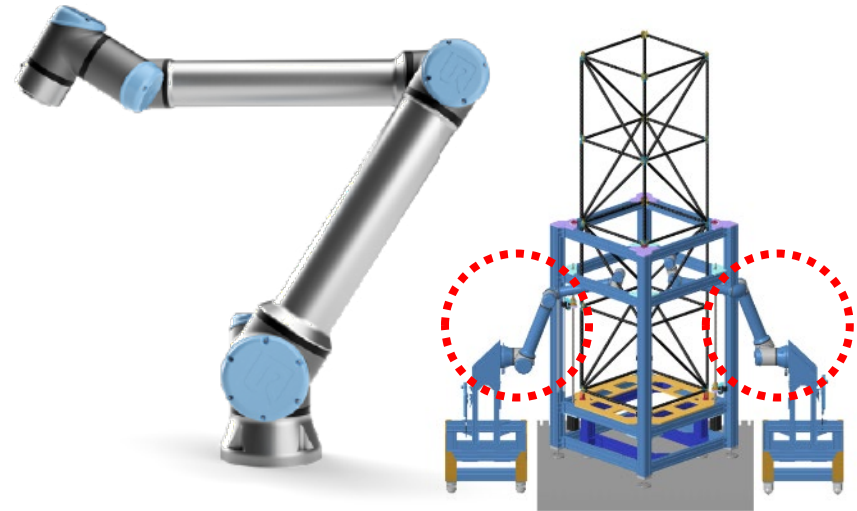


Assistant robot system (ARS) with end effector

Manipulator analogous to industry developed flight arms selected
Sufficient reach, payload, and degrees of freedom
Fixed locations relative to CRS

UR10e - Specification

Payload	12.5 kg (27.5 lbs)
Reach	1300 mm (51.2 in)
Degrees of Freedom	6 rotating joints
Power Consumption MAX avg	615 W
Power, Consumption Typical	350 W
Weight (cable included)	33.5 kg (73.9 lbs)



UR10e and locations on the TLT assembly EDU

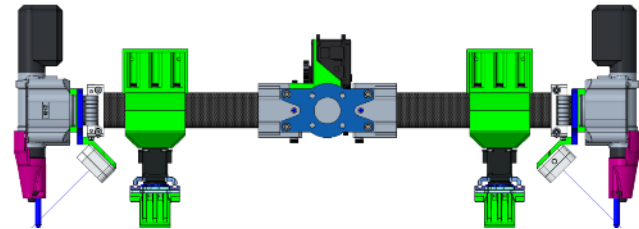
Light weight end effector that can handle and join struts of various lengths

- **Riveting End Effector**

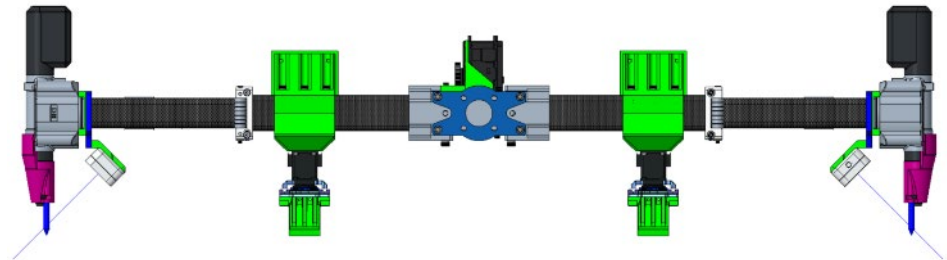
- Retrieves struts from storage
- Manipulates struts
- Fasten all three strut configurations

- **End Effector Specifications**

- Mass: 7 kg
- Actuators:
 - 3 Servos
 - 2 Riveting tools
- Sensors:
 - 2 Positioning and metrology cameras
 - 1 Positioning limit switch



End effector retracted to minimum width



End effector extended to maximum width

Key End Effector Hardware

A. Telescoping tool mount

Allows adjustability to fasten different strut lengths (0.7 m to 1.1 m) driven by a twin lead ACME screw supported by rolling bearings

B. Central hub

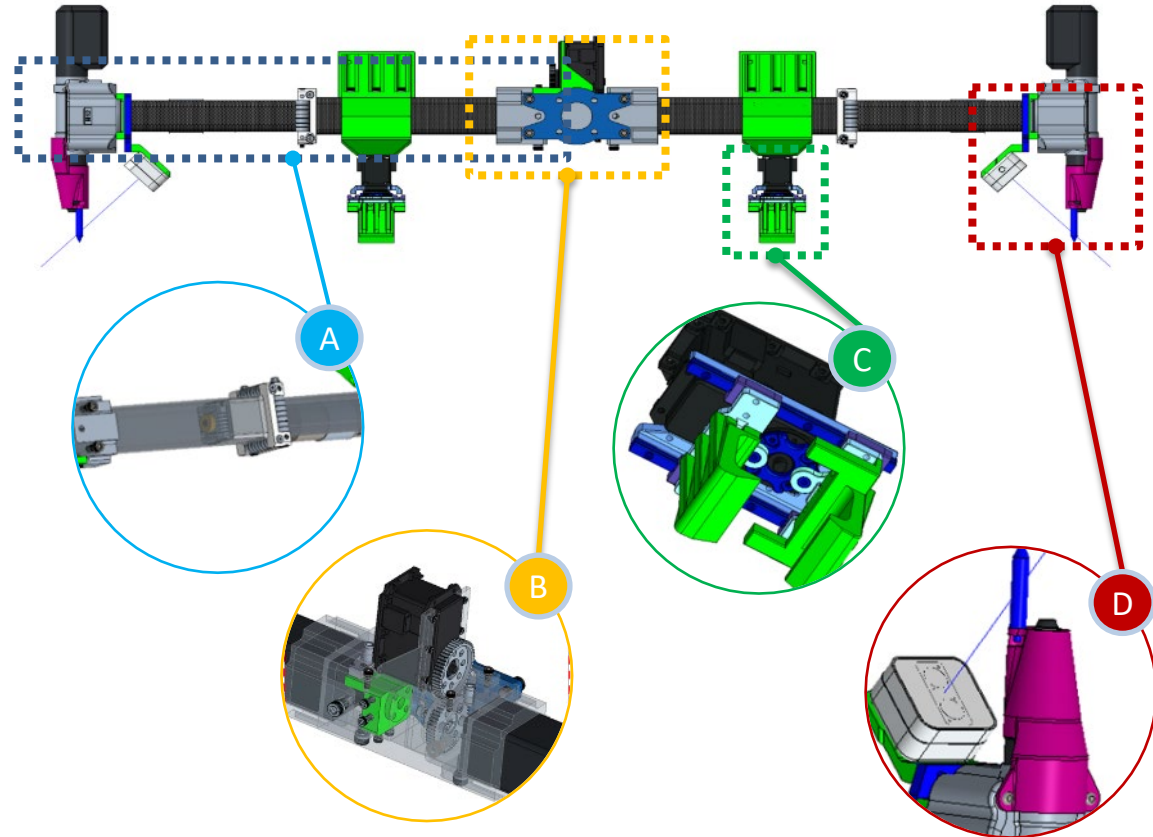
Provides manipulator mounting bracket, telescoping tool mount drive actuator housing, and electrical subsystem routing

C. Truss gripper (x2)

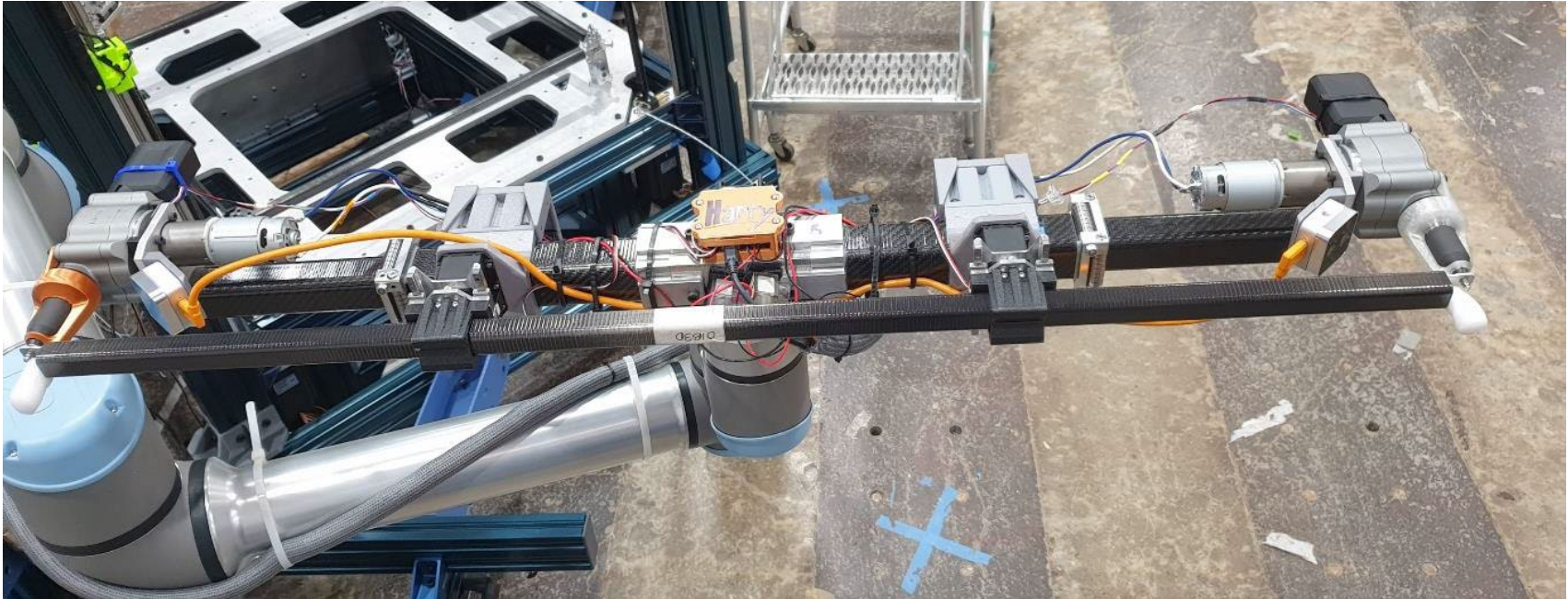
Separates and grips the individual square struts, actuated by a Dynamixel MX-106

D. Rivet tool, guide pin, and camera (x2)

Integrated motorized pop rivet tool with guide pin providing alignment and a co-located depth camera for visual servoing and inspection

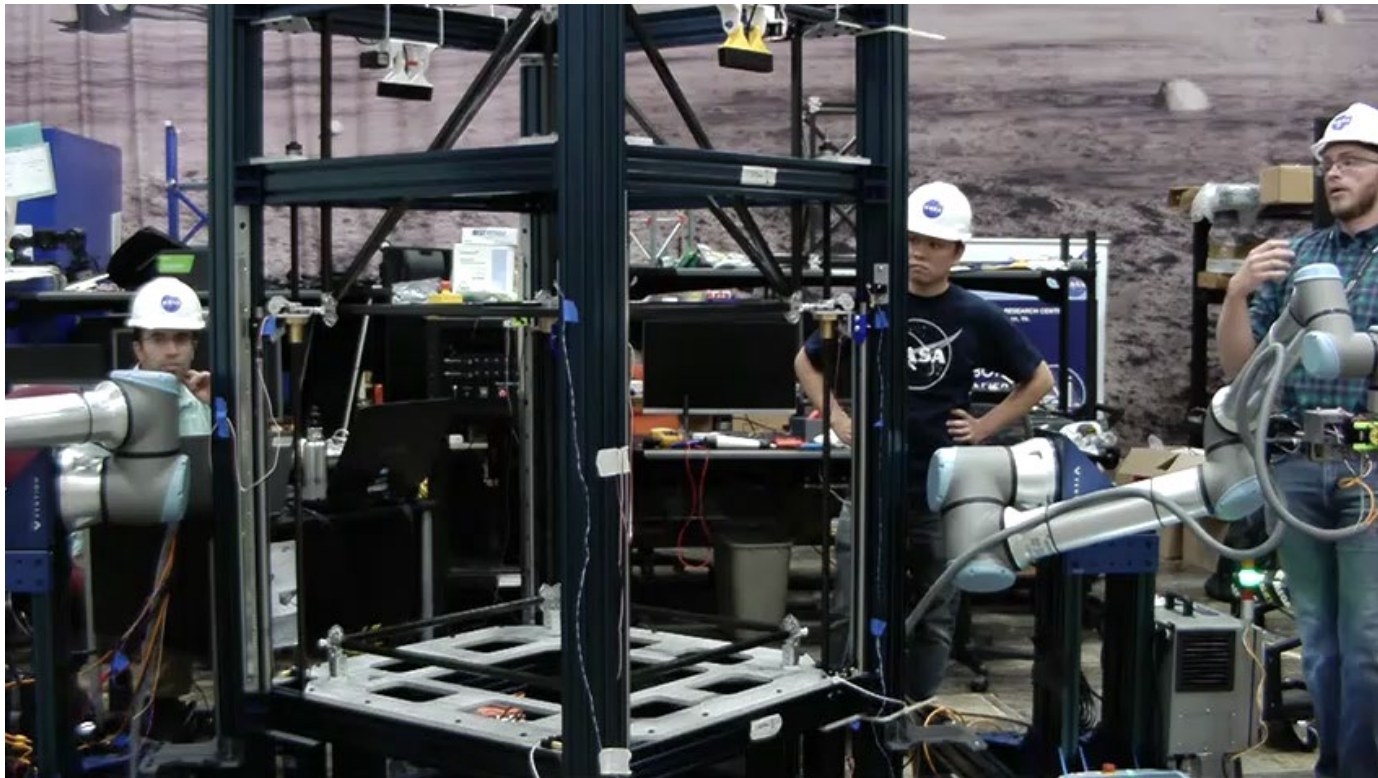


ARS – End Effector Mounting

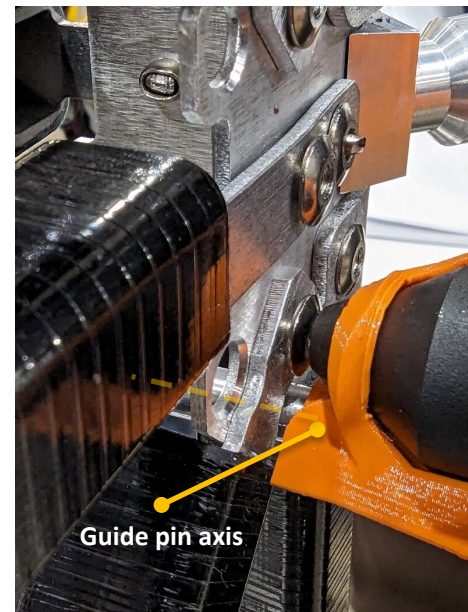


End effector mounted on UR10e

ARS – Strut Placement Test

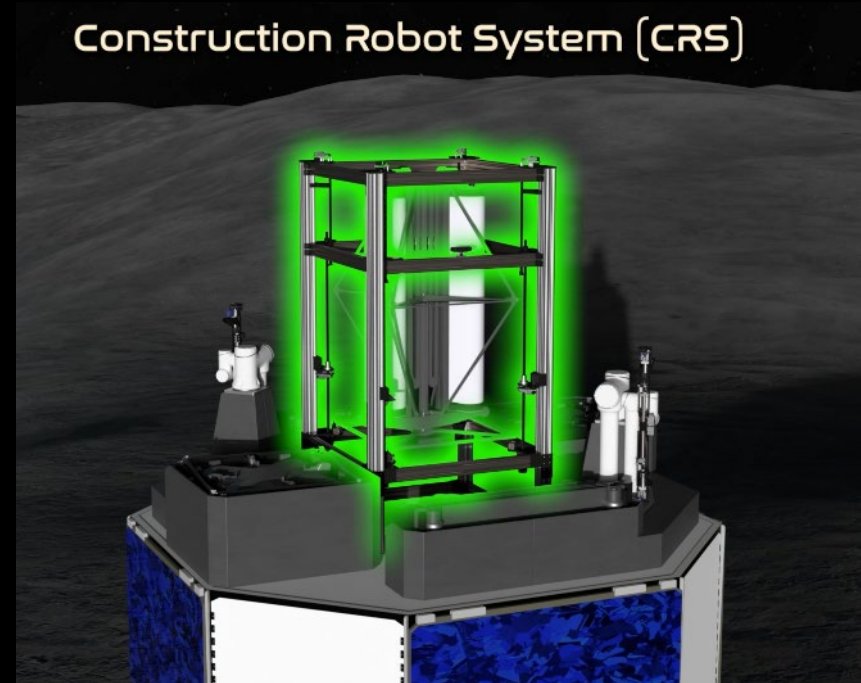


Diagonal strut placement test



Closeup of diagonal strut joining

- System Configuration
- Construction Robot System Configuration (**CRS**)
- Assistant Robot System Configuration (**ARS**)



System Configuration



CRS (v0.1.0)

- Focus on validating Build Tower subtree
- Full implementation of behavior tree (except foundation rivets)
- Control of all actuators managed by behaviors and ros2_control

ARS (Simulated)

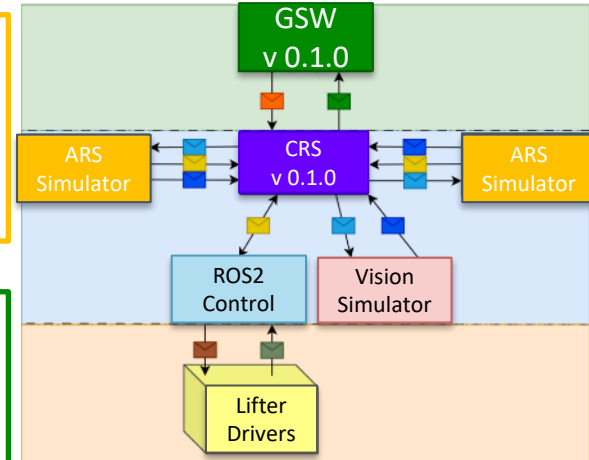
- Simulated localization and UR10e motion planning using teach pendant
- Software control of end effector through command line behaviors and ros2 messages
- Command response interaction with CRS simulated by operator

GSW (v0.1.0)

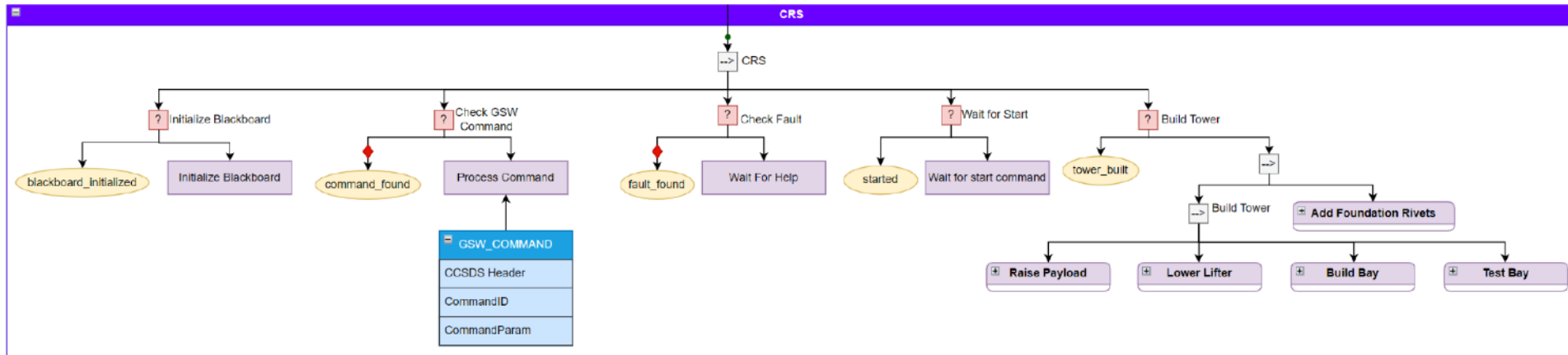
- Focus on display of CRS behavior tree and actuator states
- Start, stop, pause, play commands integrated
- Telemetry data logging

Vision (Simulated)

- Inspection command response interaction with CRS simulated by operator



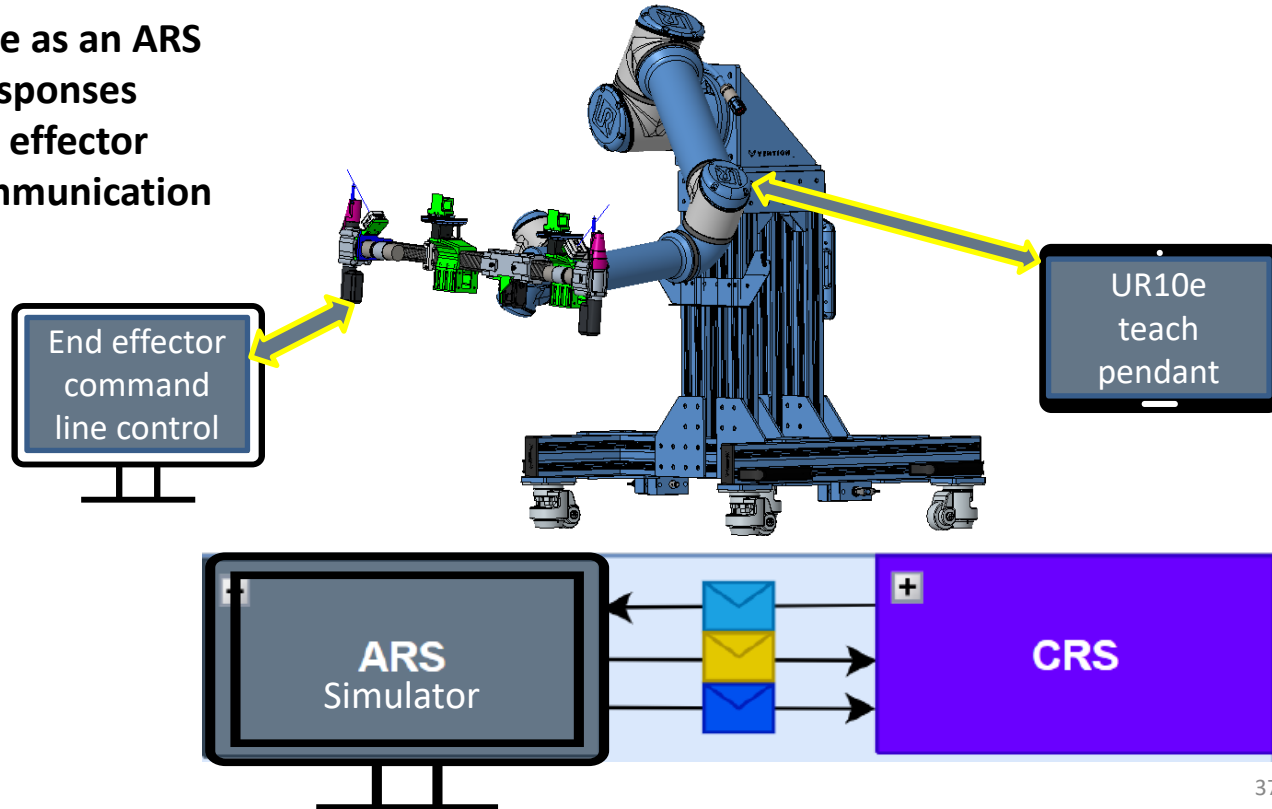
CRS behavior tree for truss assembly implemented for supervised autonomous operation



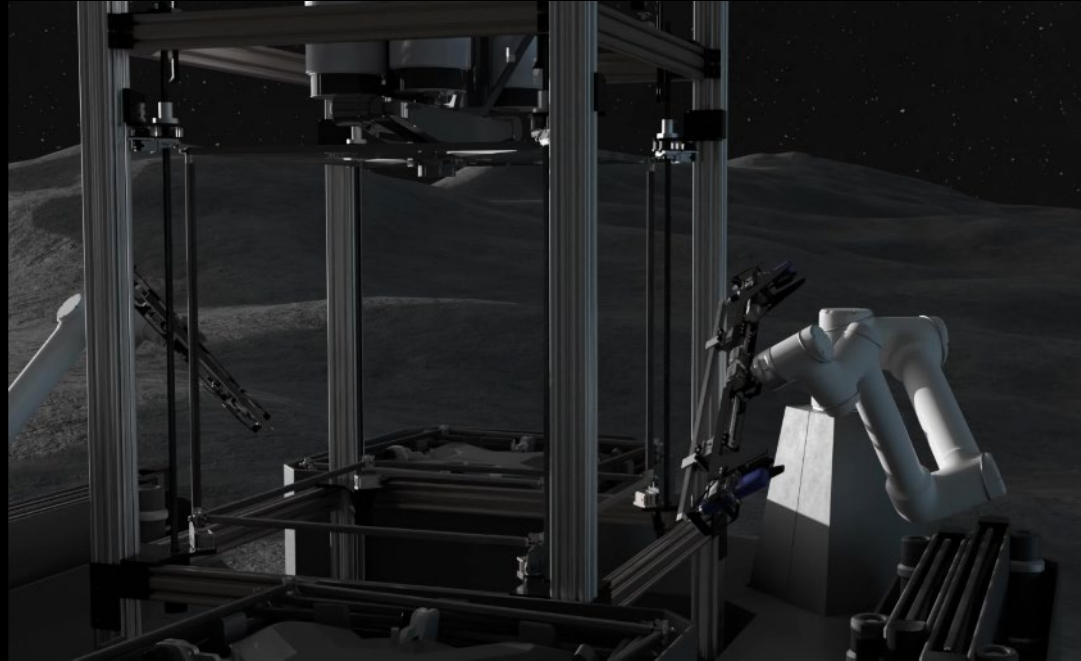
- Tree pauses after every action completes and waits for operator to send a resume command
- Actuator control is managed by behavior tree nodes and `ros2_control`
- Tree state is saved on each tick and can be reloaded upon unexpected shutdown

ARS behavior tree was simulated for testing and requires further development

- Utilizes behavior tree test code as an ARS simulator providing proper responses
- Control of the UR10e and end effector managed separately from communication with CRS



- **Demonstration Overview**
- **Videos**
- **Demonstration Activities**
- **Results**



Demonstration Overview



The test was a proof-of-concept demonstration to increase system TRL to 4 with the following test objectives:

1. Demonstrate functional robotic tower assembly prototype
2. Demonstrate tower assembly process

- **Demonstration details**

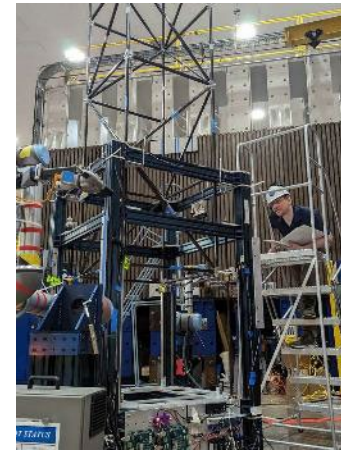
- Tested integrated software and hardware systems with supervised semi-autonomous operation for the CRS
- Built 5 bays of TLT (3.75 m)
- Located in the B1148 High Bay at NASA Langley Research Center
- Overhead crane with all cables attached to the tower slacked for safety
- September 2023



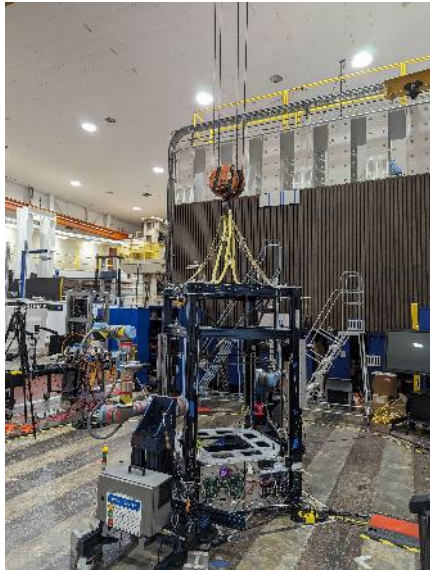


Demonstration Activities

- **Open items on September 27th were quickly resolved**
 - Rivet tools required troubleshooting
 - End effector extension behavior incomplete
 - Robot behaviors needed operator to trigger
 - Commands to ARS not responding
 - UR10e pre-programs needed fine tuning
- **Demonstration September 28th to 30th**
 - First bay completed in 4 hours
 - Final bay completed in 1 hour and 10 minutes
 - Lifted tower to height of 6 bays (4.5 meters)



Tower Assembly Snapshots



Start – Day 1



1.5 bays – Day 2



3 bays – Day 2

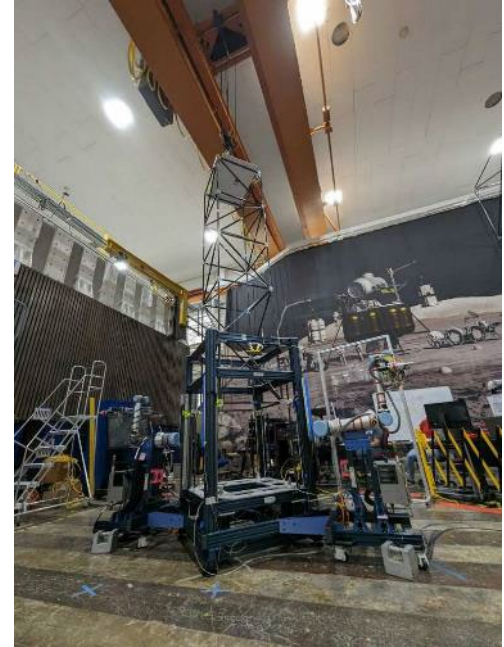


5 bays – Day 3

Demonstration Results

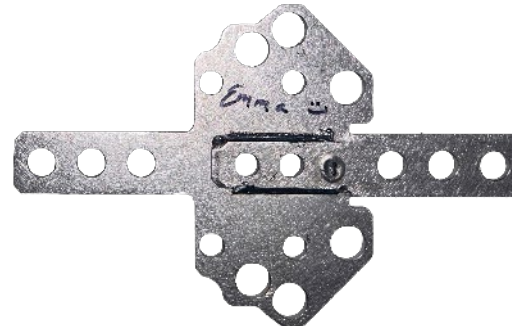
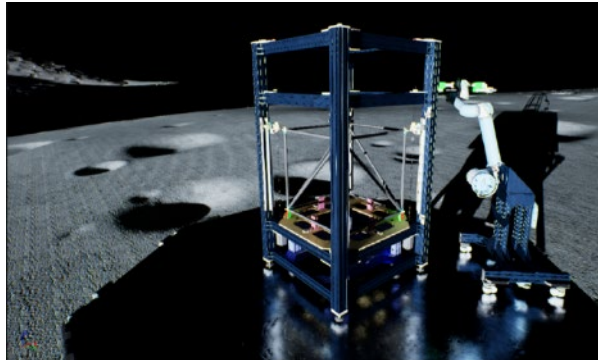


- **Assembled a 5-bay tower**
 - Placed components with 6 DOF manipulators
 - Rivets used for fastening
 - Used guide features to align and rivet parts
- **Successfully demonstrated robotic tower assembly approach**
 - Synchronized lifting of tower
 - Five lifting operations
 - Used behavior trees for operations
- **Manual operations**
 - Cross frame and strut loading
 - Secondary riveting for near verticals and corner “0” due to jig error
 - Fine alignment for some rivets
 - Activation of behavior trees



Concluding Remarks

- The TLT robotic tower assembly approach has been successfully demonstrated
- Further testing of the EDU would increase autonomous functions, the build height, and incorporate a payload with utility routing
- The tower design, assembly system designs, and software can be significantly improved with further development
- Five papers presented at AIAA ASCEND 2023
- Exploring further proposal options and partnering opportunities



- 

PDF



PDF



PDF



PDF

Questions?

- **Co-investigators**

- Kyongchan Song (Structural Analysis), Jacob Cassady (Software Development), Iok Wong (Hardware Development)

- **Team members**

- Jacob Martin, Matthew Vaughan, Emma Brand, Amanda Stark, Stephen Bowen, David Long, Derrick Seubert, Salma Hassanain, Caden Knutsvig, Paola Amadeo, John Merila, Brian Notosubagyo, Carl Nicklas, Myles Badami, Matthew Rodgers, Tyler Hudson

- **Acknowledgements**

- Advanced Exploration Systems – Project Polaris for funding the work
 - NASA Langley Engineering Directorate and Research Directorate leadership for technical review and demonstration support