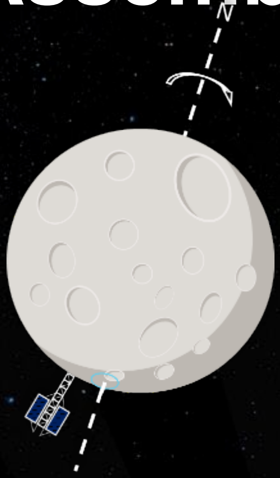
Tall Lunar Tower Project (TLT)
Robotic Tower Assembly Development



Lunar Surface Innovation Consortium
2-28-2024

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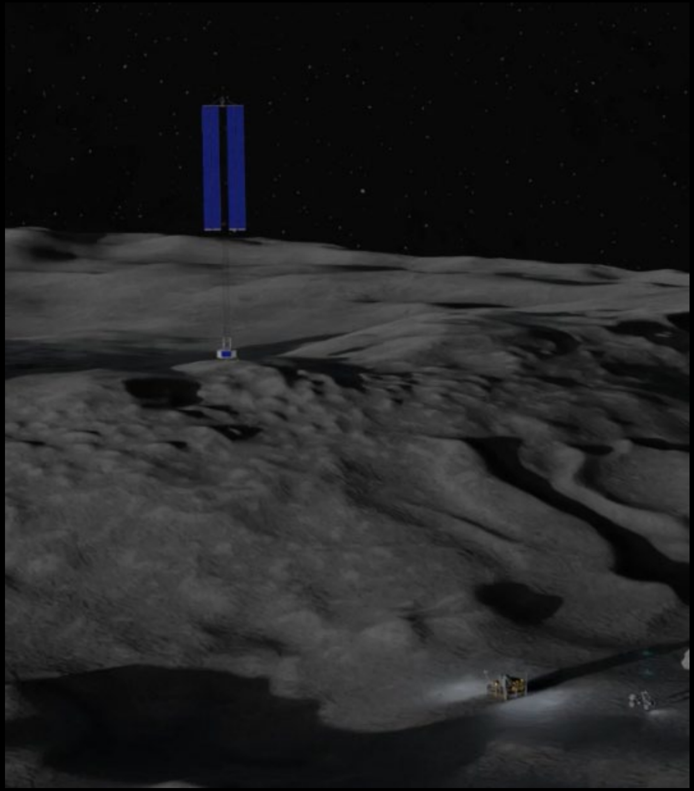
Outline

- **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

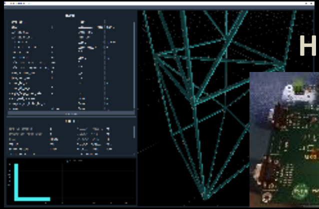
Tall Lunar Tower (TLT)

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

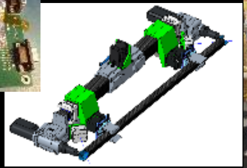
Development Objectives

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

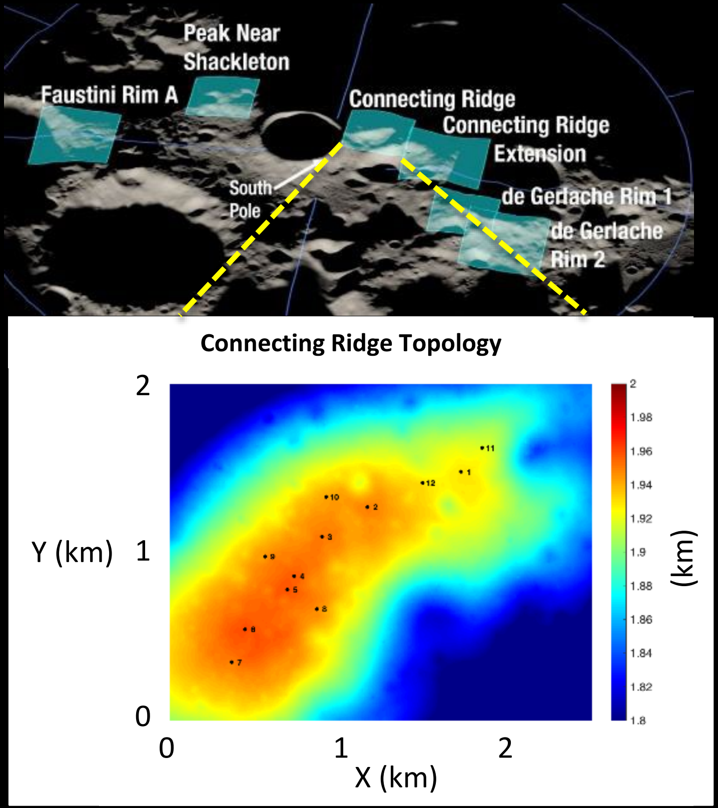


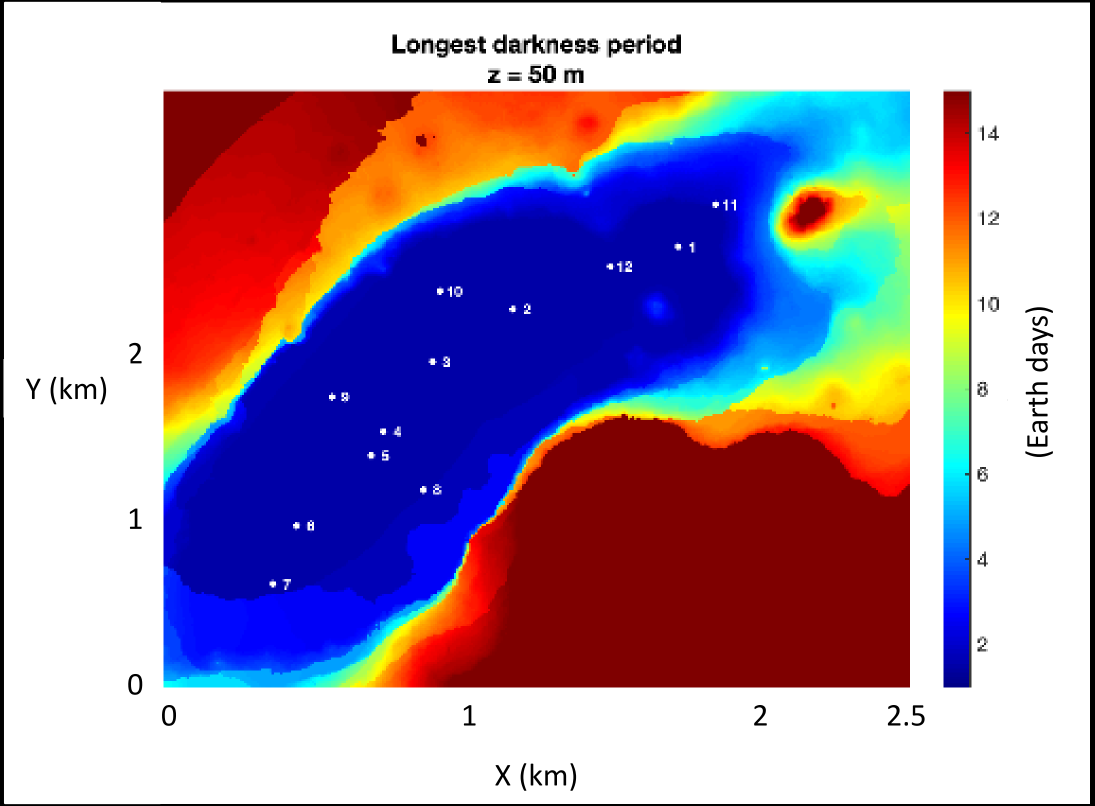
Lab Testing

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

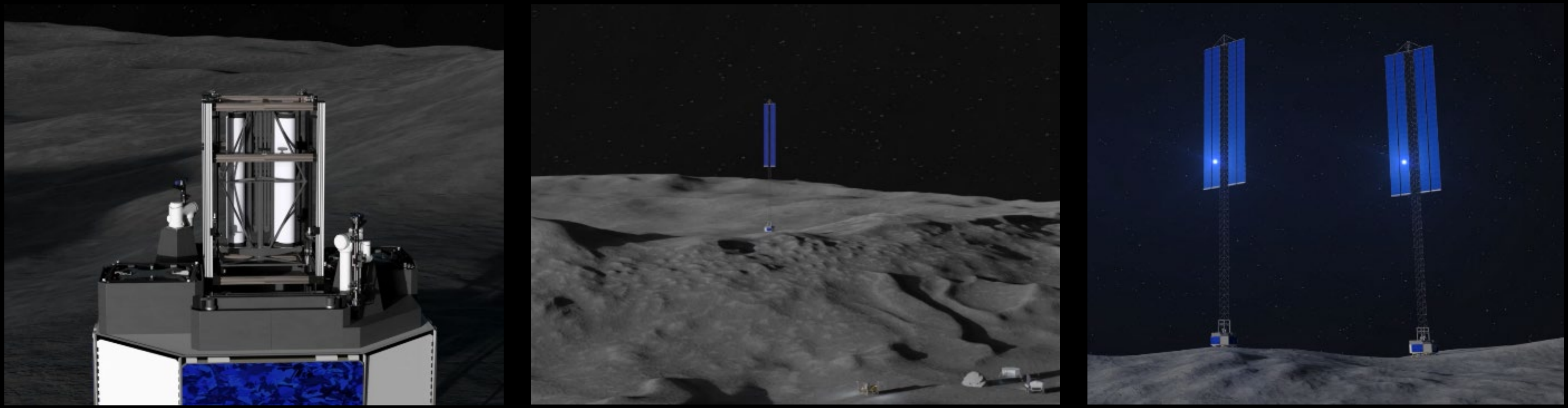
- **Early, scalable lunar infrastructure:** ≥50-meter power, communication, & navigation tower
- Develops technologies for V&V, remote inspection/sensing, robust/repeatable autonomous operations, and robotic structural assembly needed for sustainable lunar presence
- Cross-cutting robotic truss assembly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

Tall Towers for Solar Power





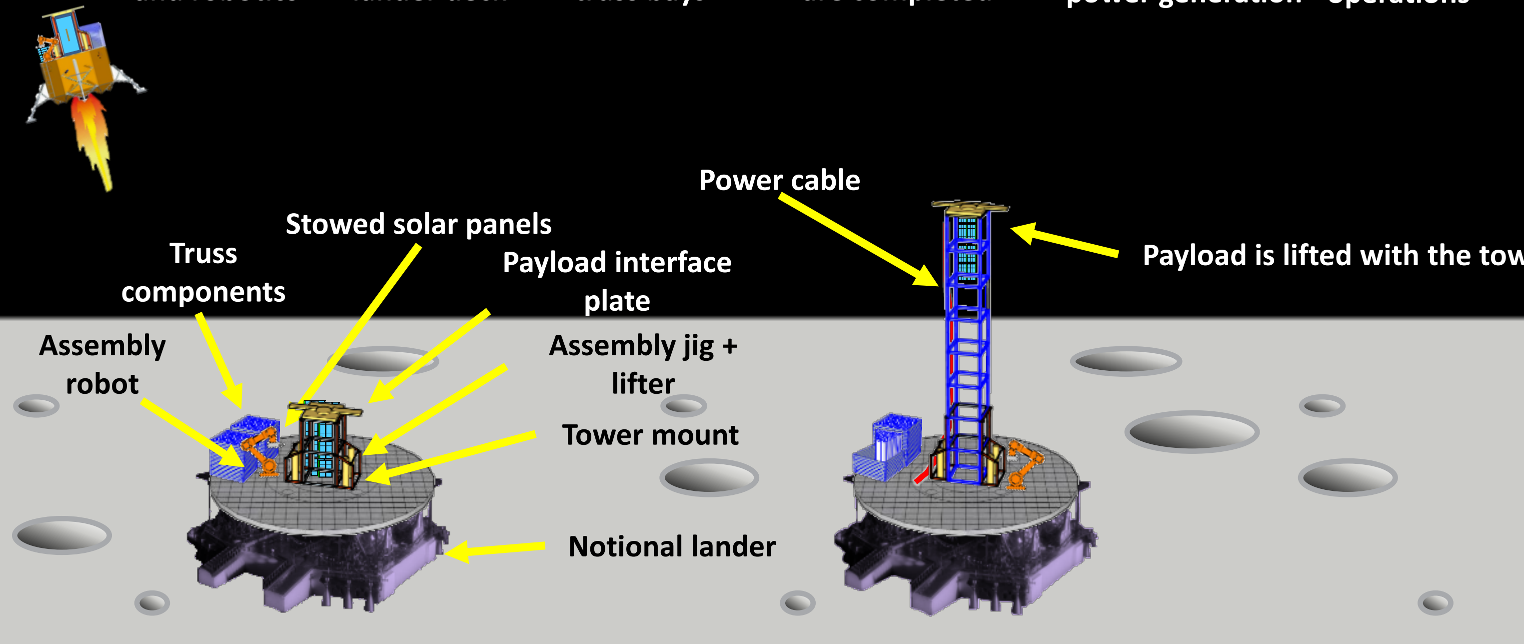
- **Full Scale Lander Based Mission**
- **Evolution Roadmap**

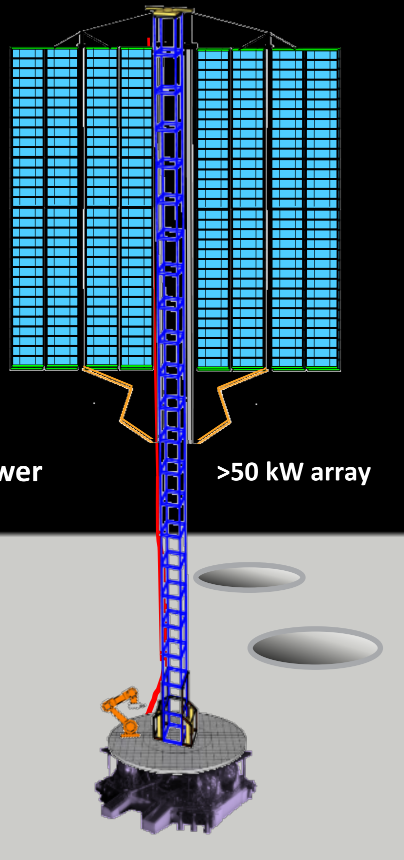


Renderings of a future lander-based tower assembly system

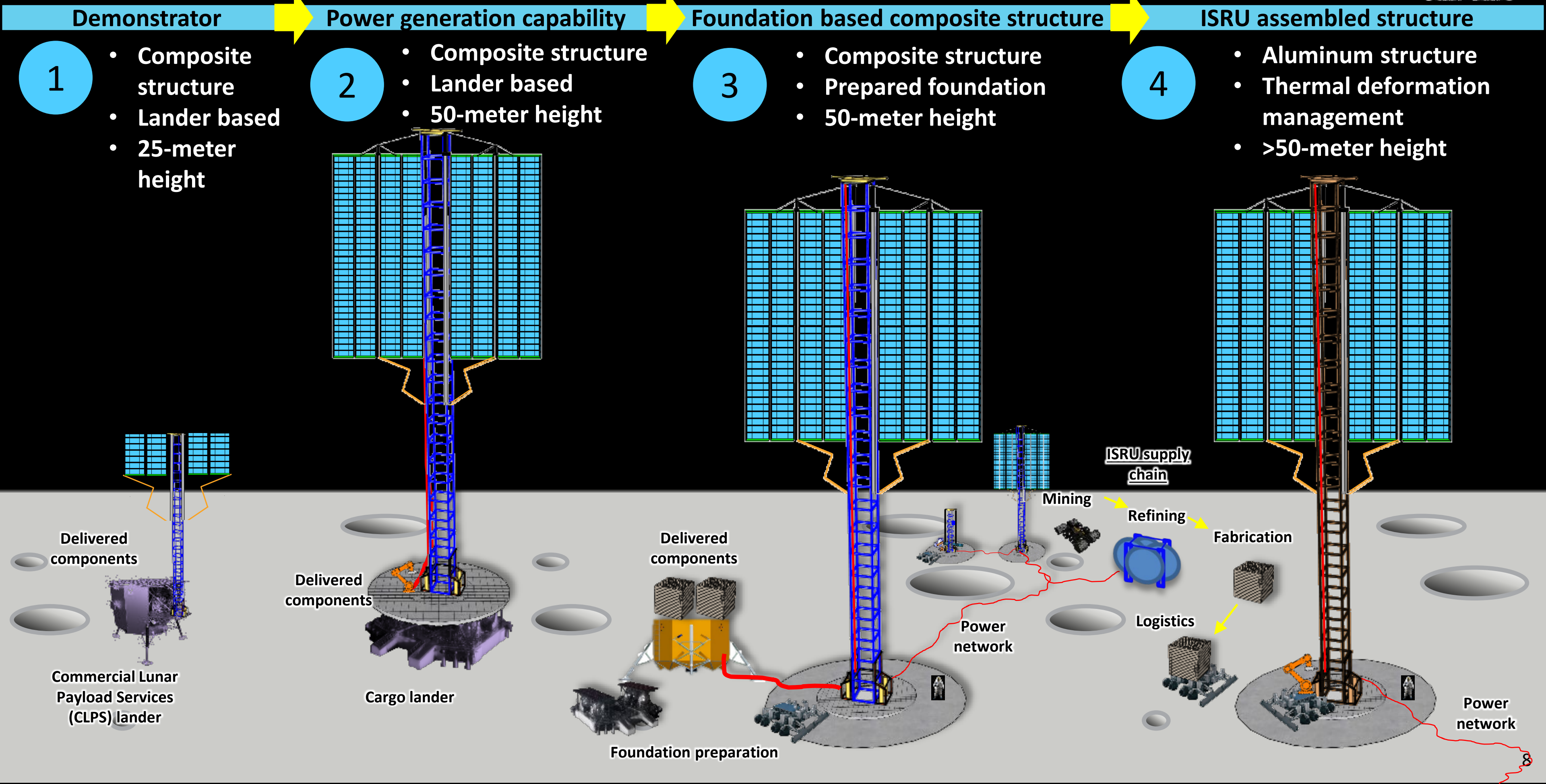
Full-Scale Lander-Based Reference Mission Concept

1. Lander delivers components and robotics
2. Equipment remains on top of lander deck
3. Begin assembling repeatable truss bays
4. Lift tower up incrementally as new bays are completed
5. Lift, deploy solar arrays, demonstrate power generation
6. Provide power and comm. for operations



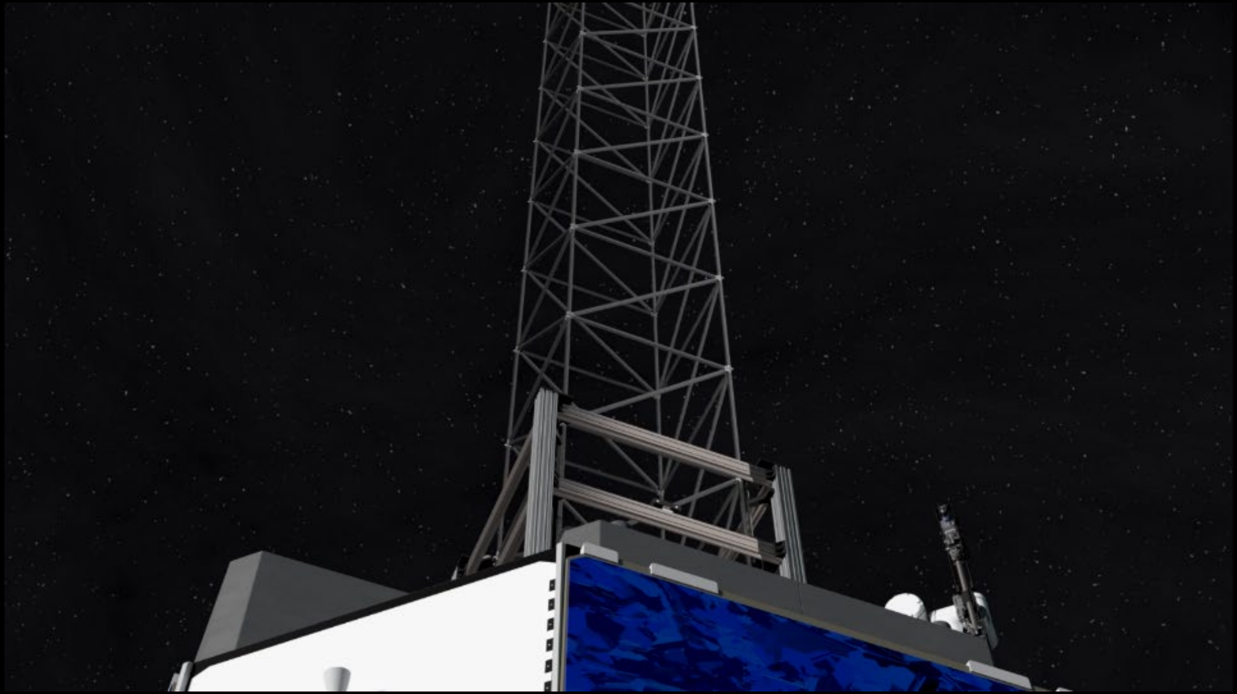


Next Steps: Tall Lunar Tower Evolution Roadmap



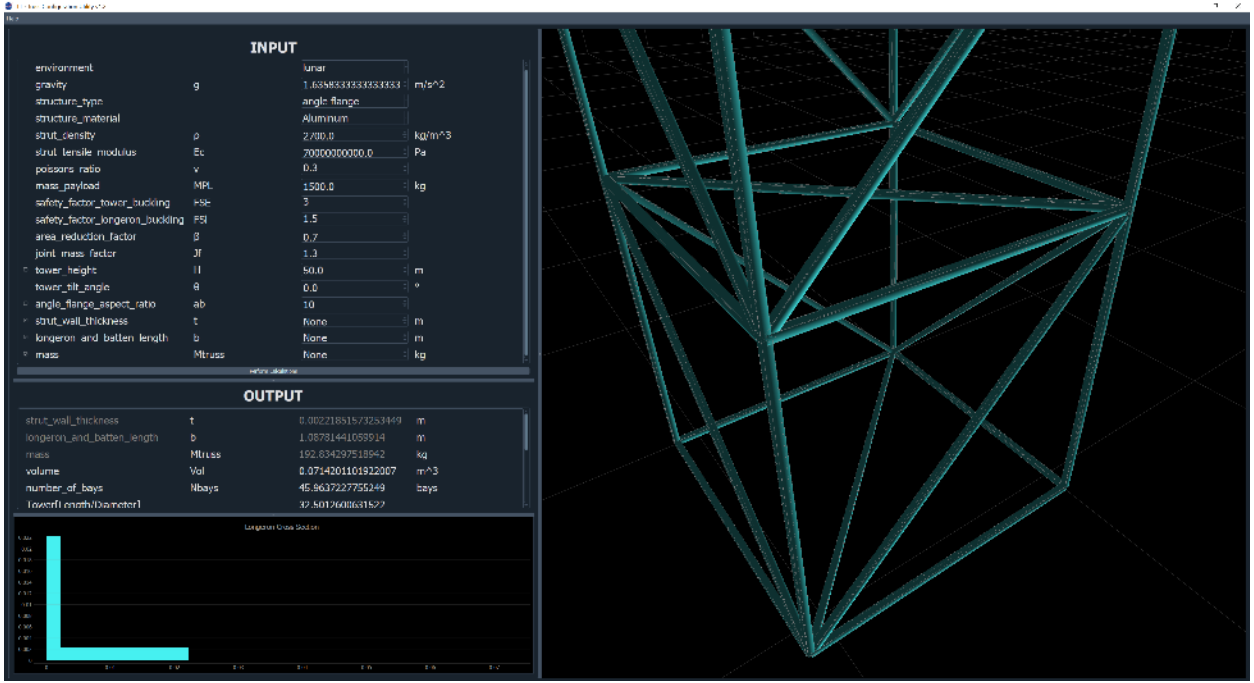
Lunar Tower Analysis Section

- Tower Sizing
- Tower Design
- Thermal Analysis



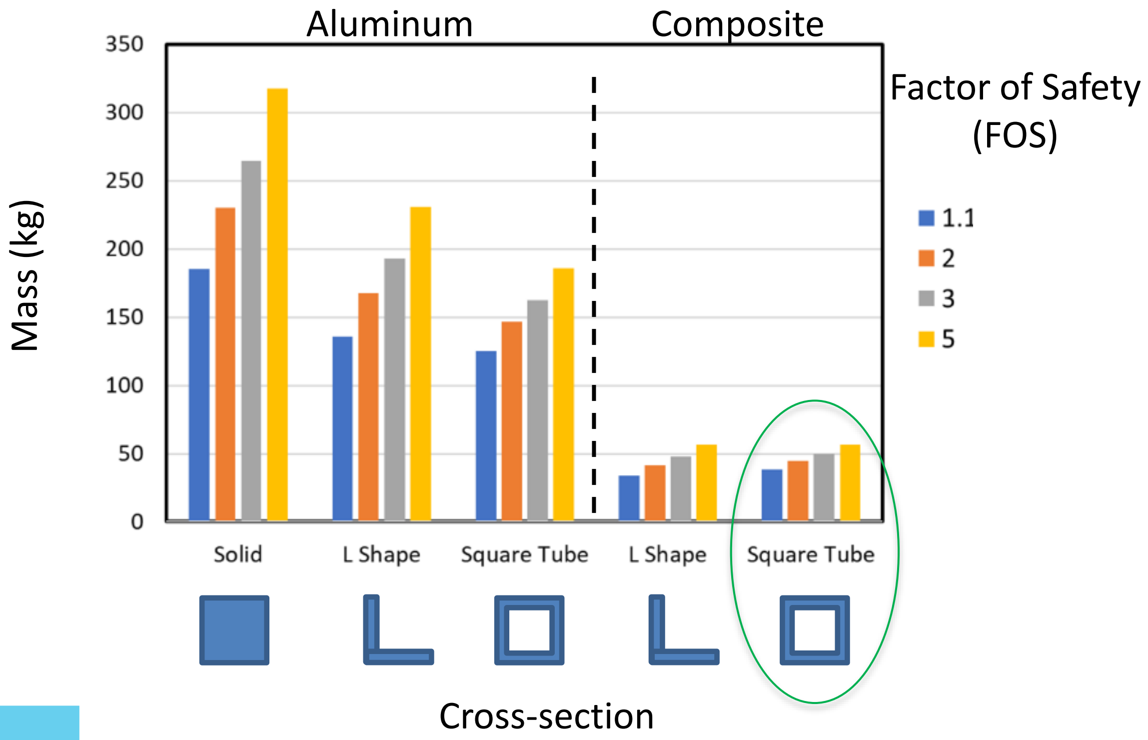
Tower Sizing - Truss Configuration Utility (TCU)

- **Developed to rapidly explore the preliminary design space**
- **The TCU is based on three governing equations:**
  - Longeron Euler bucking (PL)
  - Tower Euler bucking (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



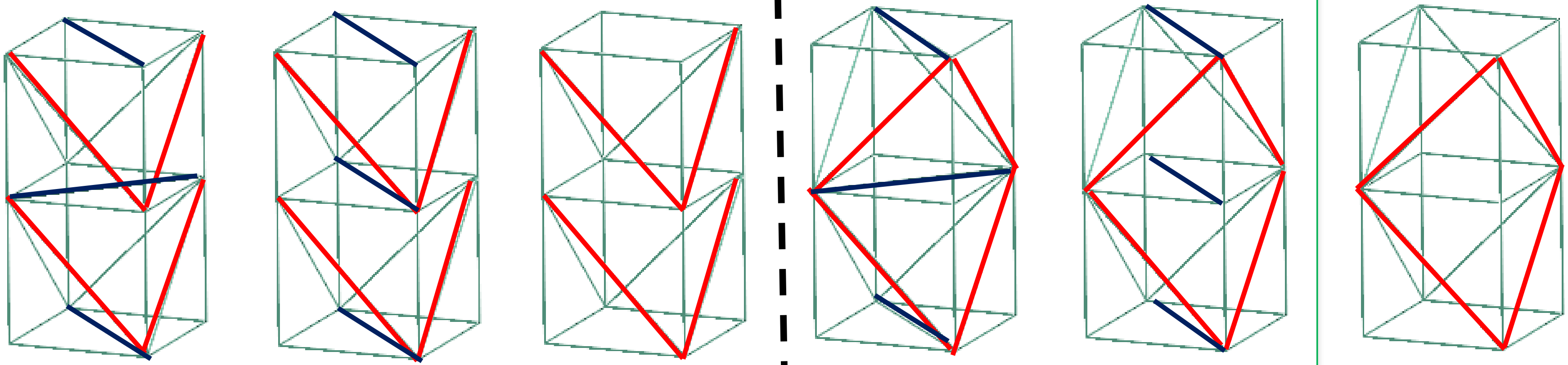
Composite square tube selected

Finite Element Model with Different Tower Design

Type A
repeating diagonals

Type B
alternating diagonals

Selected

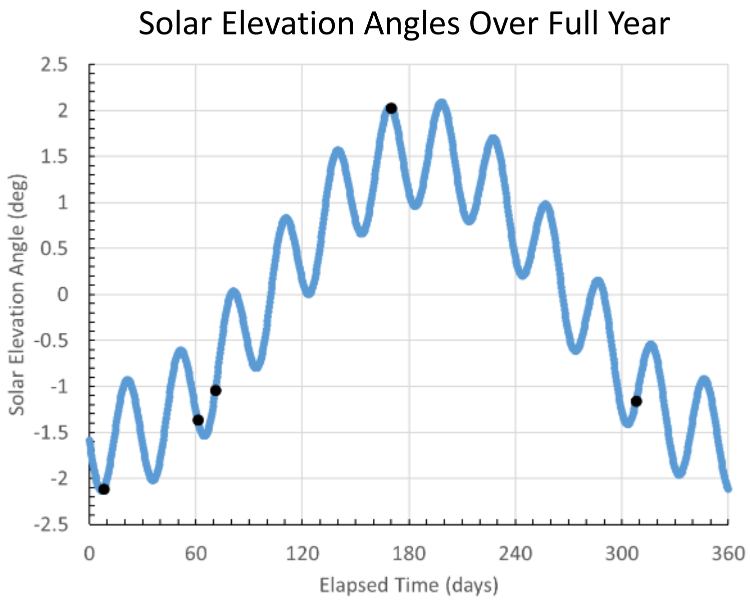


(1) with cross In-plane members	(2) with parallel In-plane members	(3) without In-plane members	(1) with cross In-plane members	(2) with parallel In-plane members	(3) without In-plane members

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

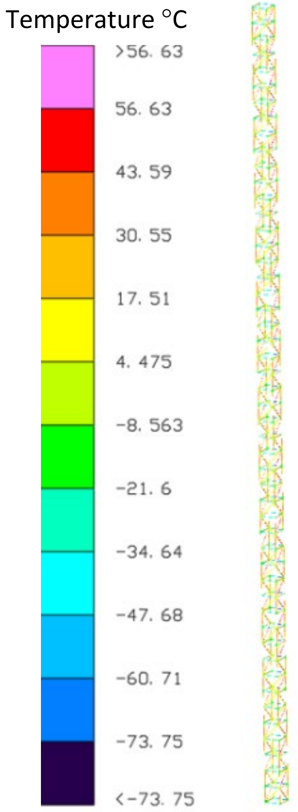
- **50.25-meter tower, 0.75-meter bays**
- **Geometry maps to structural model**
- **Material properties**
  - –Truss elements: graphite-epoxy M55J
  - –Joints: aluminum 6061-T6
- **Temperature values are obtained from heat flux analysis**



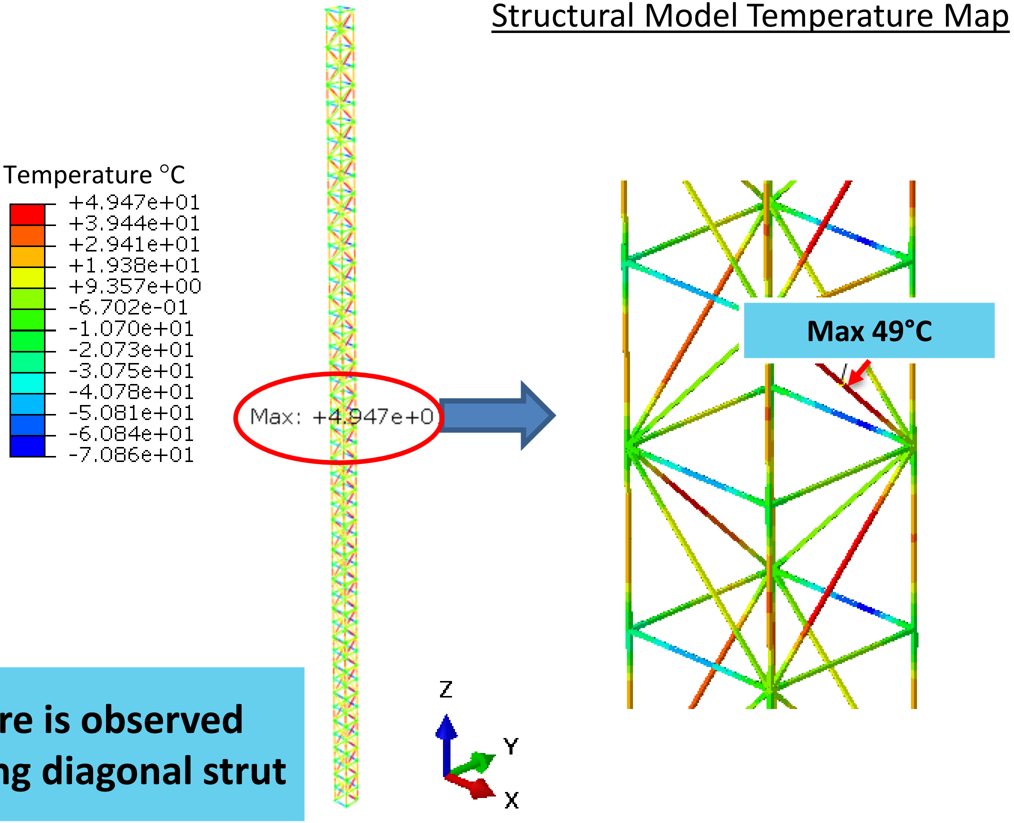
Days considered:
Day 8: cold case
Day 170: hot case
Days 61, 71, and 308: max gradients

Day 170, Temperature Distribution

Thermal Model Temperature Map



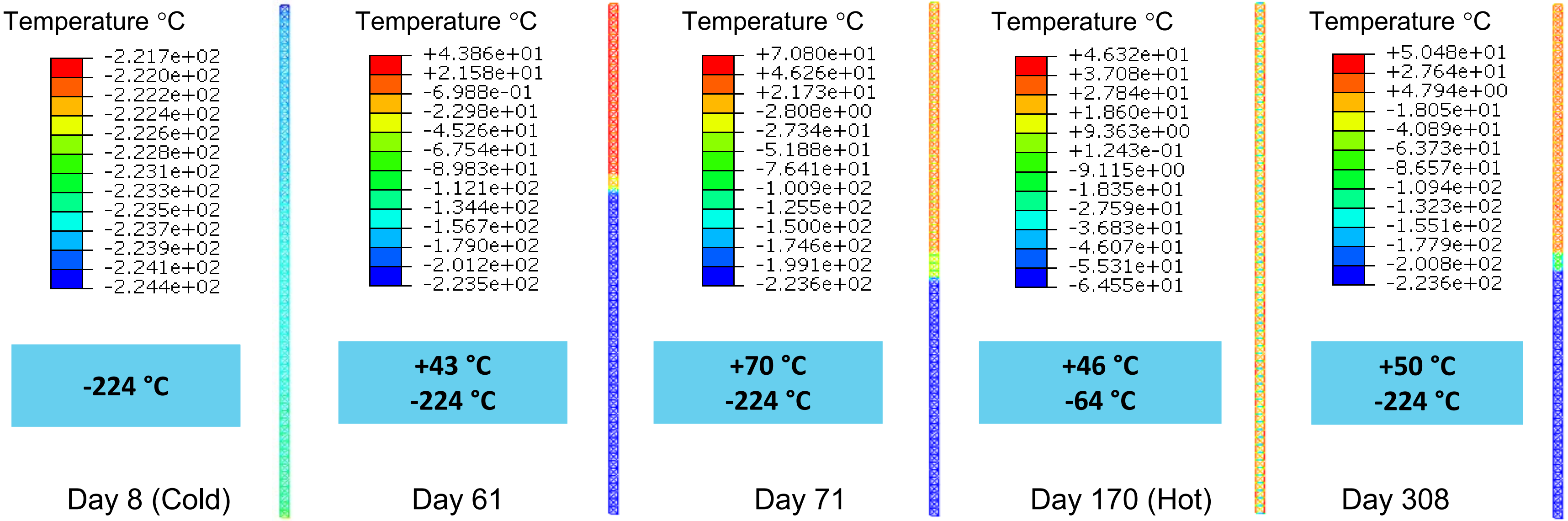
Structural Model Temperature Map



Max Temperature is observed along the sun facing diagonal strut

Thermal-Structural Analysis (Temperature Map)

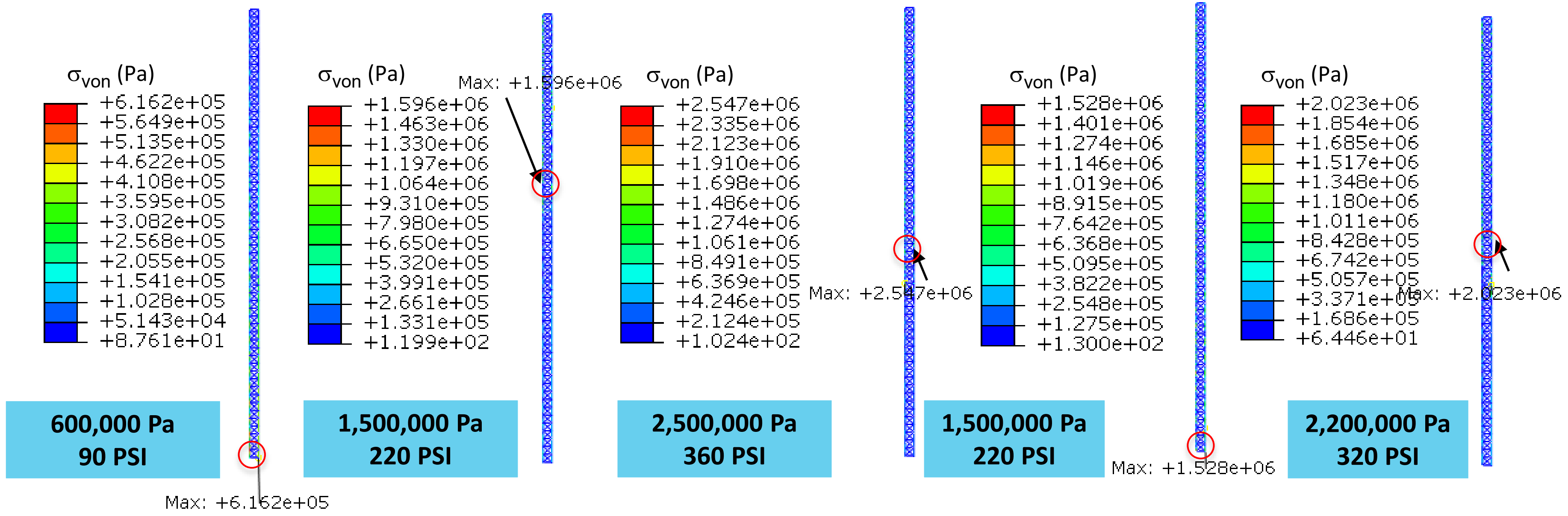
Day 8: cold case
Day 170: hot case
Days 61, 71, and 308: max gradients



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



Day 8 (Cold day) | Day 61 | Day 71 | Day 170 (Hot day) | Day 308

Engineering Development Unit (EDU) Section

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

Demonstration Highlights

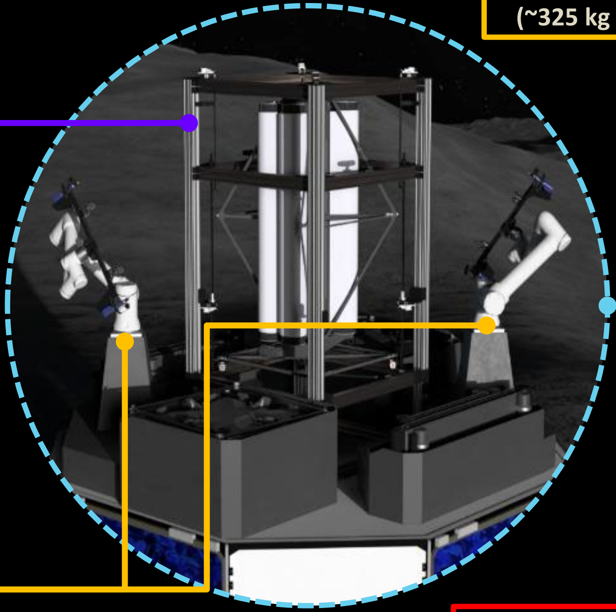
Laboratory environment
Multi-bay assembly
~5-meter height
No payload

Construction Robot System (CRS)

- Primary control
- Jigging
- Lifting

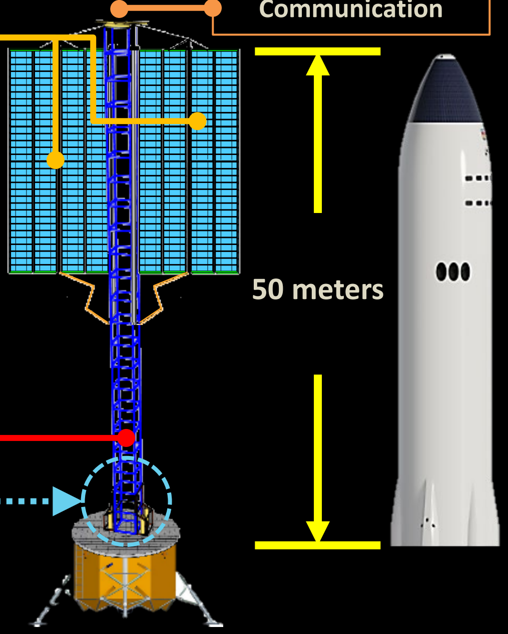
Assistant Robot System (ARS)

- Part placement
- Fastening



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

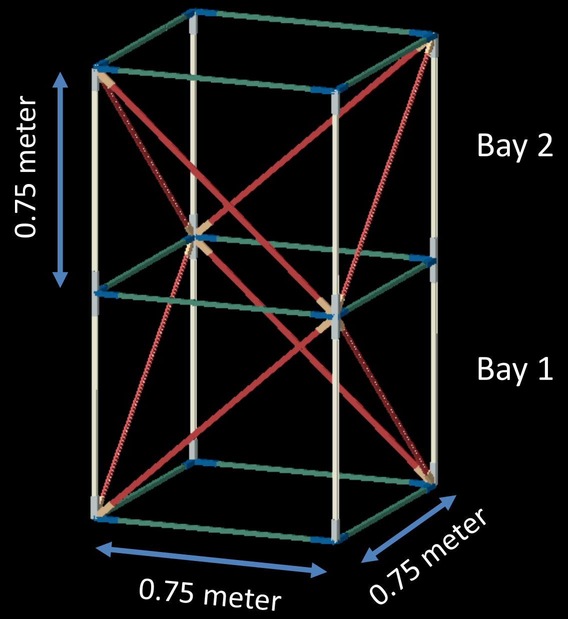
Communication



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

Tower Design Overview

- Joints
- Struts
- Assembly Sequence
- Analysis



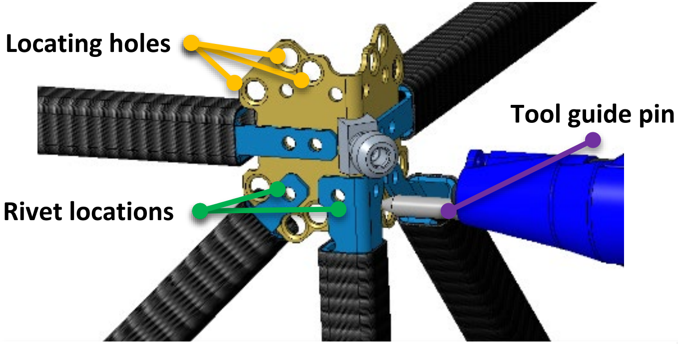
NOTE: 0.75 meter ≅ 2.46 feet

Dimensions of a repeatable TLT truss bay

Joint Design

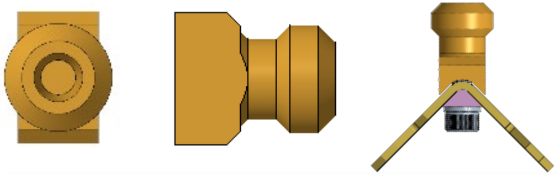
Goal: Simple to machine joint design compatible with robotics and ISRU material

- **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

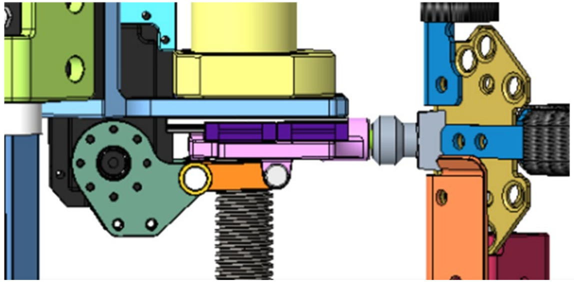


Truss joint with rivet and locating holes

Rivet



Lifting node

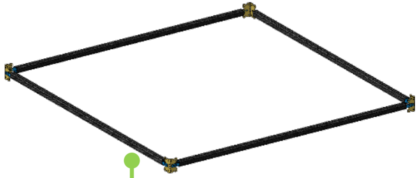


CRS lifting gripper interfacing with truss node

Strut Components

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

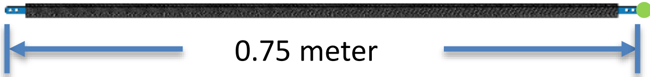
- Ultra high modulus carbon fiber square tubes
- End fittings are bent aluminum sheet metal parts
- Strut assemblies are bonded with glass bead to set bond line thickness



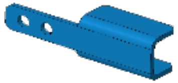
Cross frame assembly

1) Cross frame assembly:

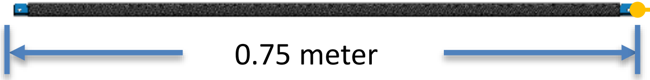
Cross frames are built from four horizontal struts and four joints.



Horizontal end-fitting

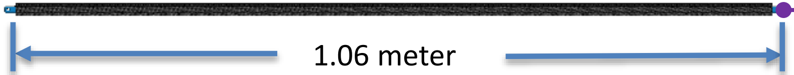


2) Longeron strut assembly:

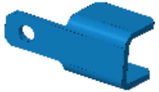


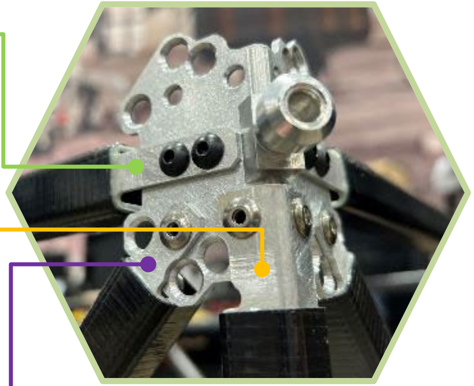
Longeron end-fitting

3) Diagonal strut assembly:



Diagonal end-fitting





Partially riveted joint

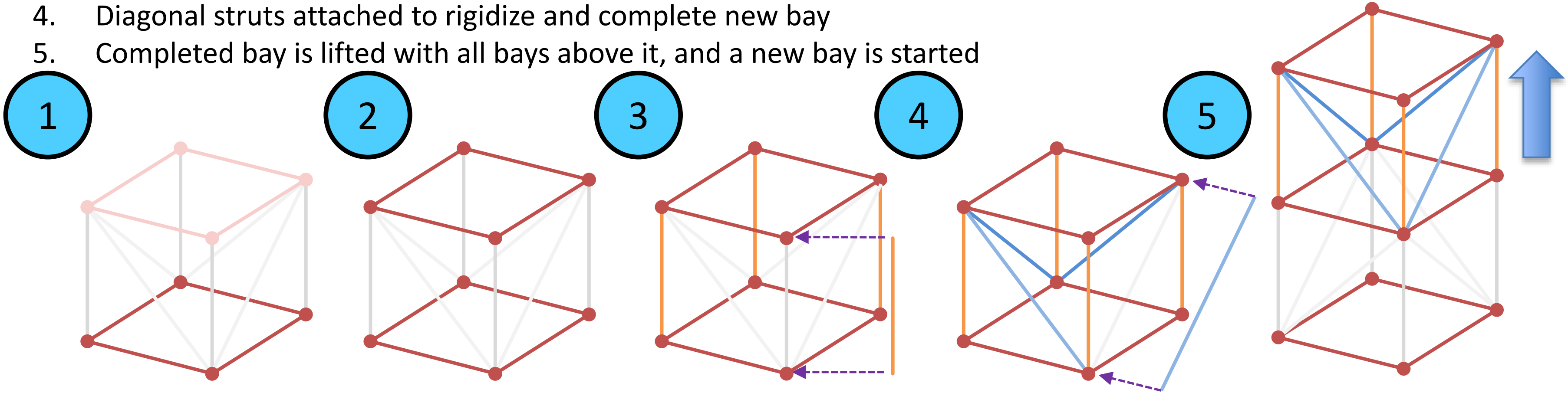
Truss Assembly Sequence – Cross Frame

Cross Frame Assembly Sequence

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

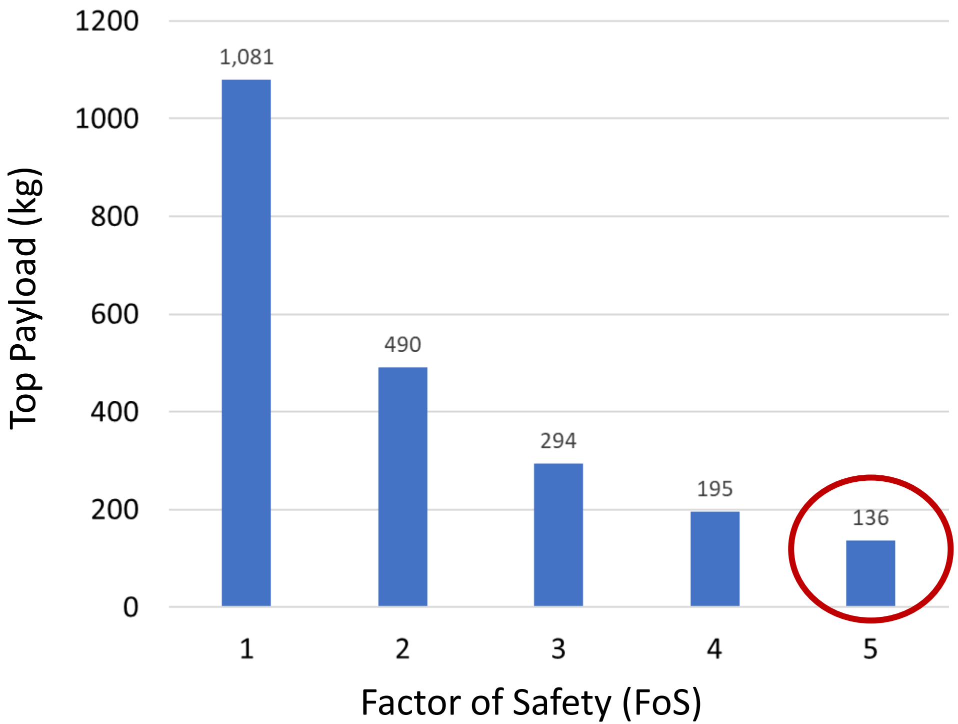
Steps

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)



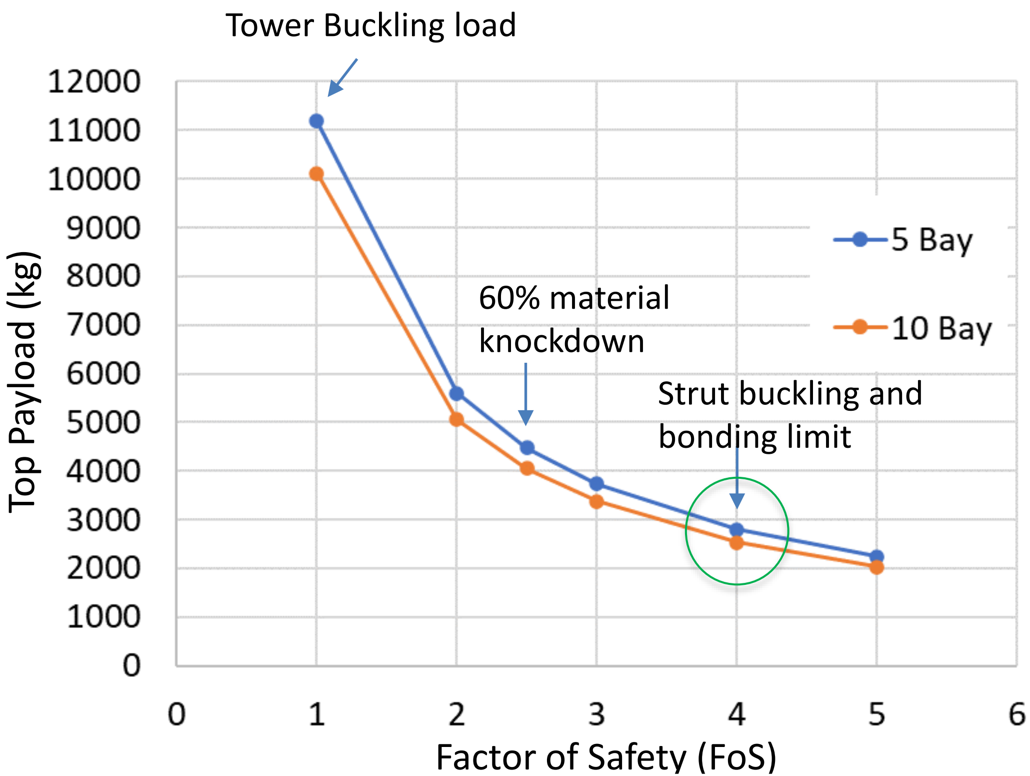
Joint under loading

Joint under loading

Static load joint test

Subscale assembly loaded to 120 kg to test assembled joint loading

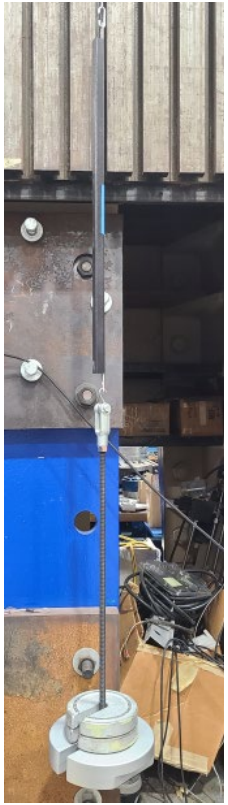
Capability of EDU (5 Bay and 10 Bay)



Expected Load capability of tower EDU ≥2000 kg

Multi-Strut Compression Test

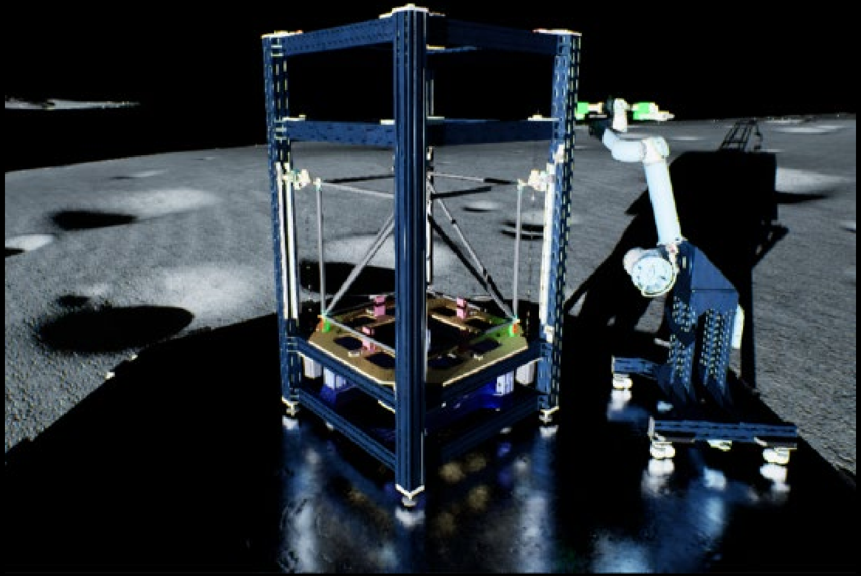
Note: Off-center end fittings were not well suited for load frame testing



Tension Test

Robotic Tower Assembly System Design

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



Robotics Overview

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

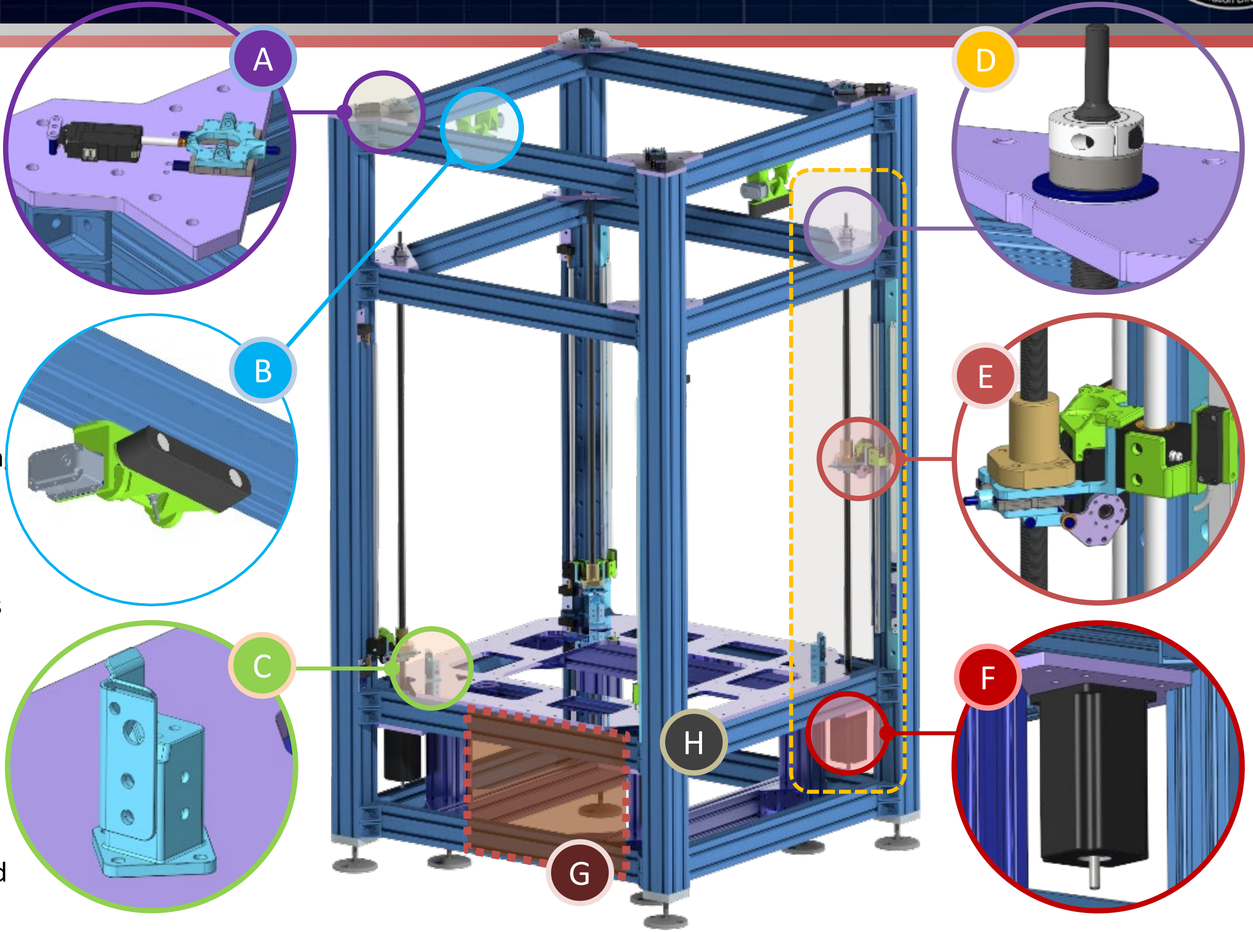
D. Lifting lead screw and bearings (x4)
Bears load from structure and payload durin lift actions

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 jigging frame
Load bearing structure provides stability and leveling for assembly

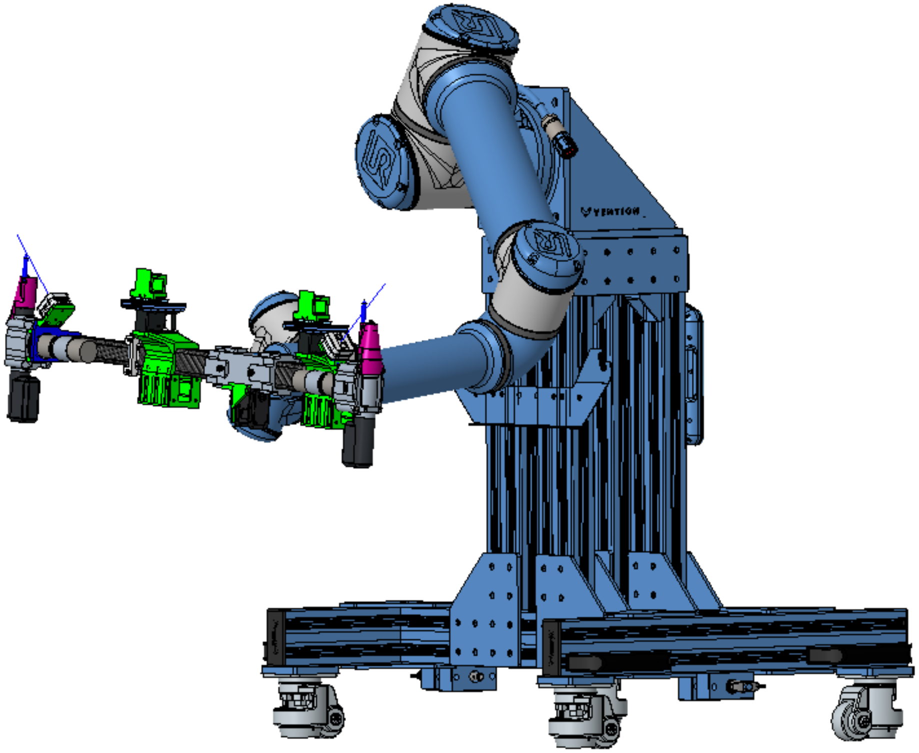


CRS Functional Tests

CRS – Test of Synchronized Lifting

ARS Overview

- **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

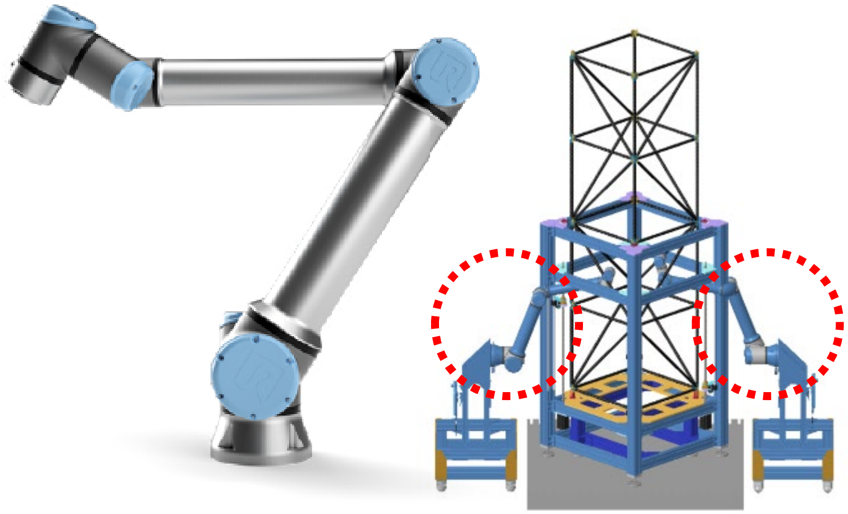


Assistant robot system (ARS) with end effector

ARS – UR10e Manipulators

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)

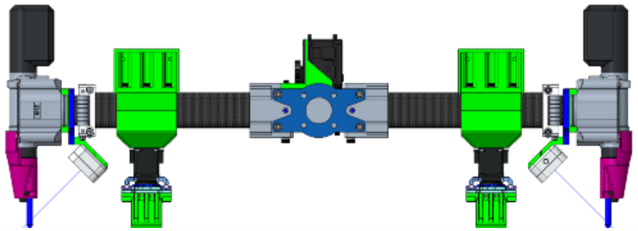


UR10e and locations on the TLT assembly EDU

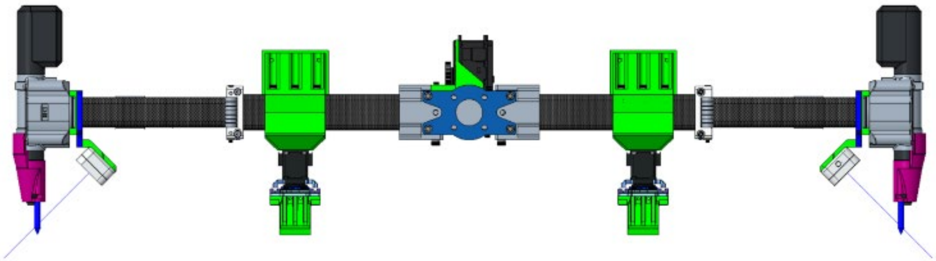
ARS – End Effector System Design

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

ARS – End Effector Overview

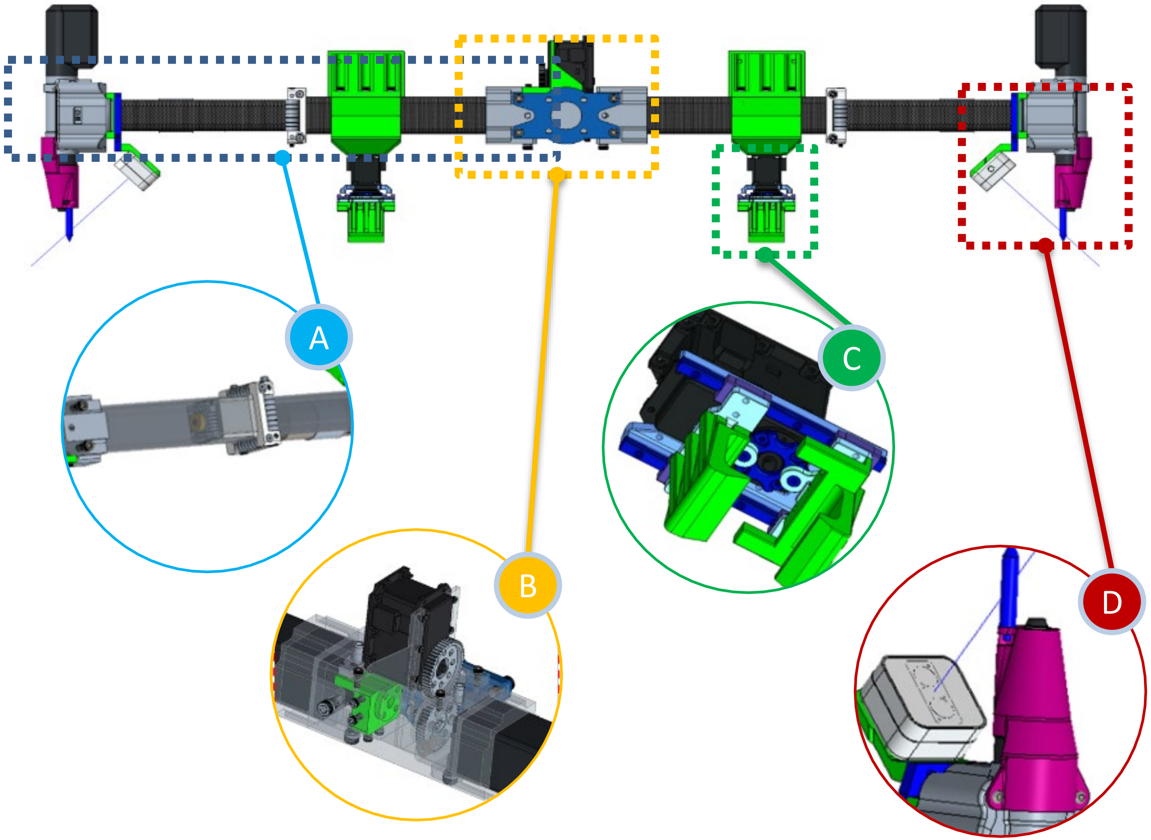
Key End Effector Hardware

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

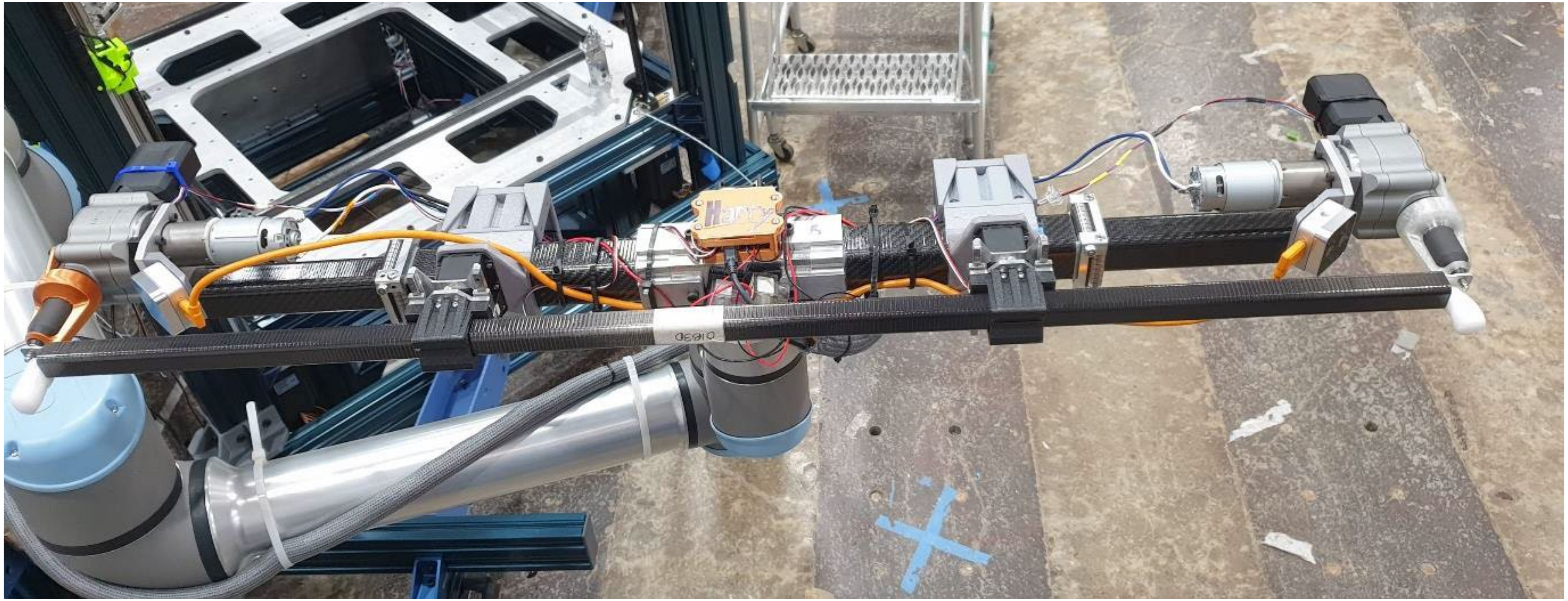
B. Central hub
Provides manipulator mounting bracket, telescoping tool mount drive actuator housing, and electrical subsystem routing

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

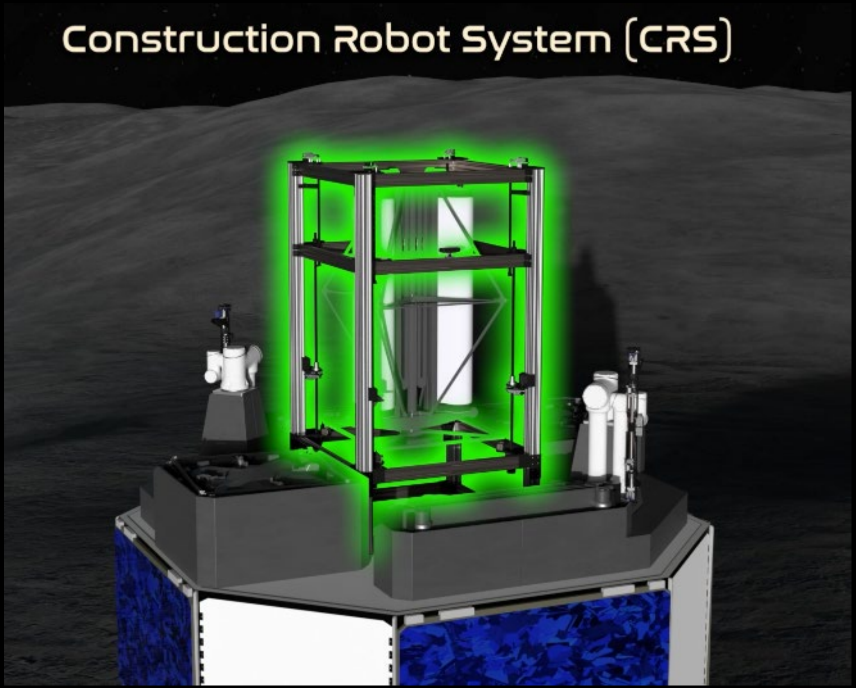
ARS – Strut Placement Test

Diagonal strut placement test

Closeup of diagonal strut joining

Software Overview

- 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)

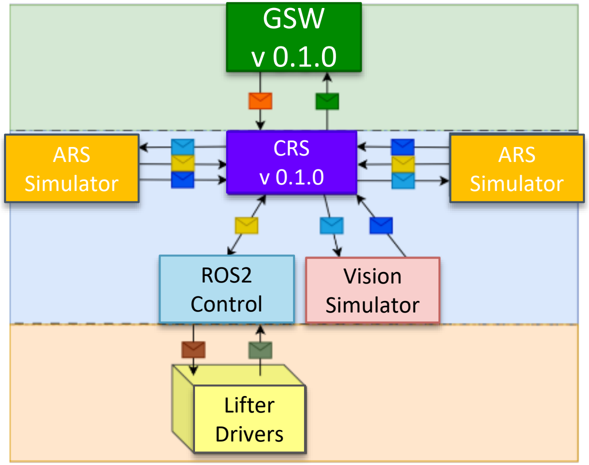
- Simulated localization and UR10e motion planning using teach pendant
- Software control of end effector through command line behaviors and ros2 messages
- Command response interaction with CRS simulated by operator

GSW (v0.1.0)

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

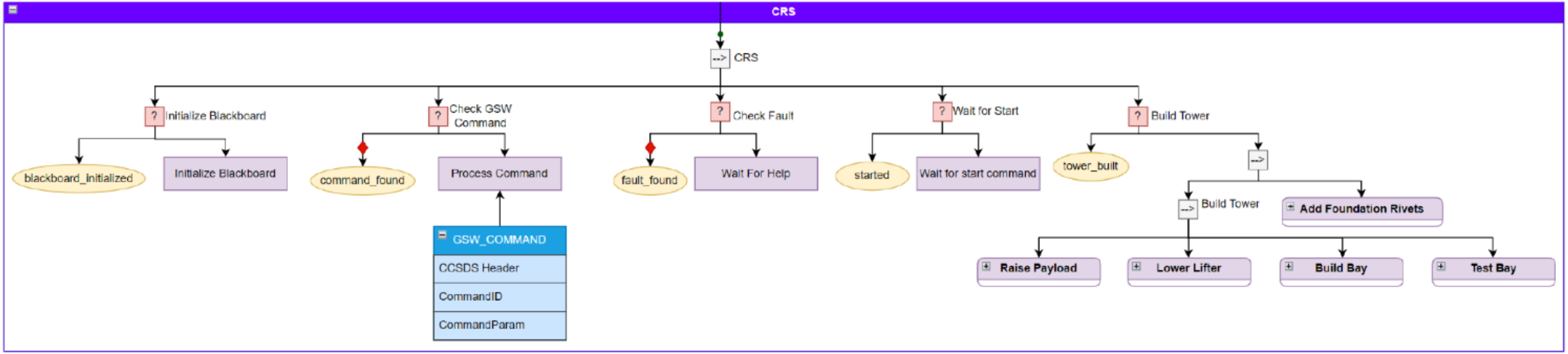
Vision (Simulated)

- Inspection command response interaction with CRS simulated by operator



CRS Configuration

CRS behavior tree for truss assembly implemented for supervised autonomous operation

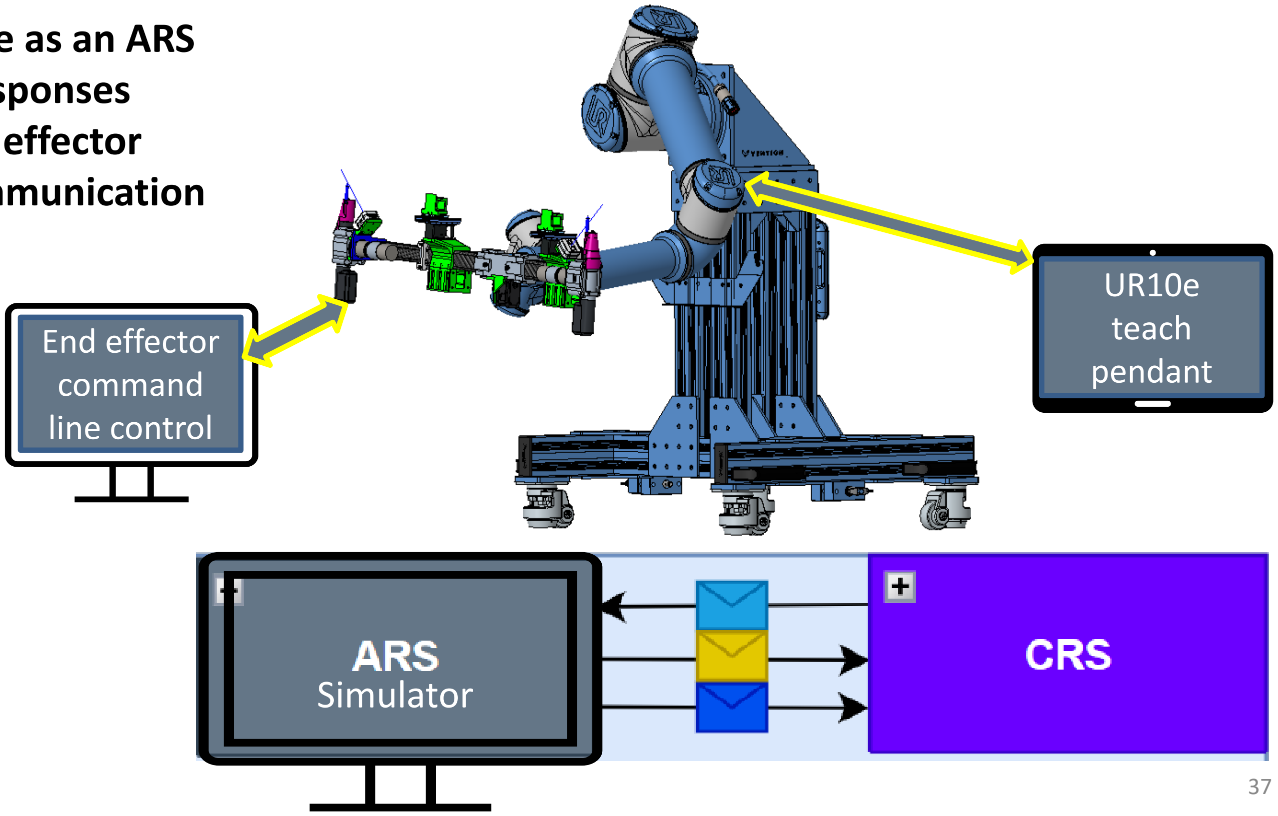


- **Tree pauses after every action completes and waits for operator to send a resume command**
- **Actuator control is managed by behavior tree nodes and ros2_control**
- **Tree state is saved on each tick and can be reloaded upon unexpected shutdown**

ARS Configuration

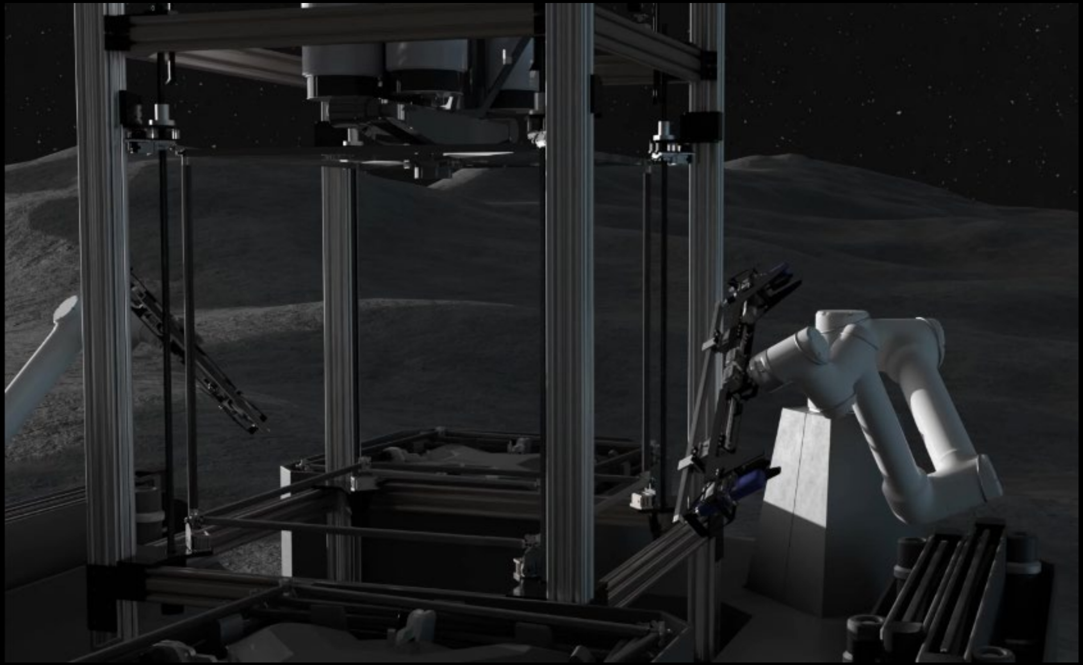
ARS behavior tree was simulated for testing and requires further development

- **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

- **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:

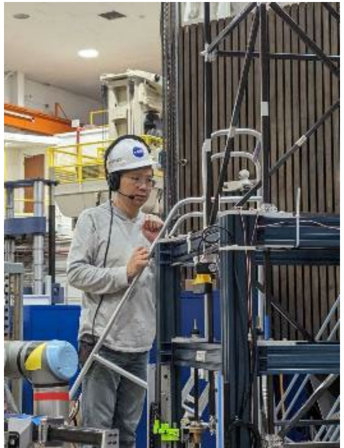
1. Demonstrate functional robotic tower assembly prototype
2. Demonstrate tower assembly process

- **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

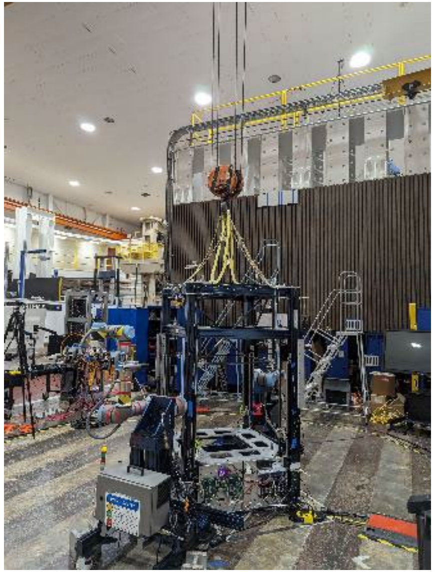
Demonstration Activities

- **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

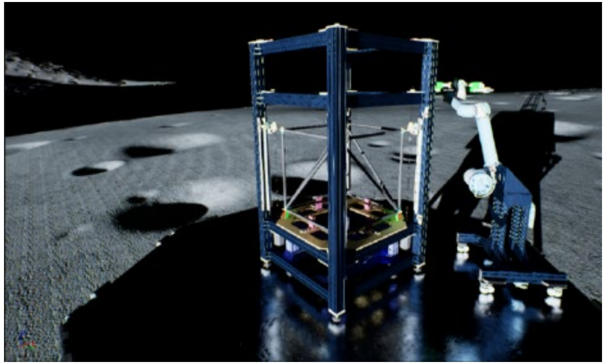
5 bays – Day 3

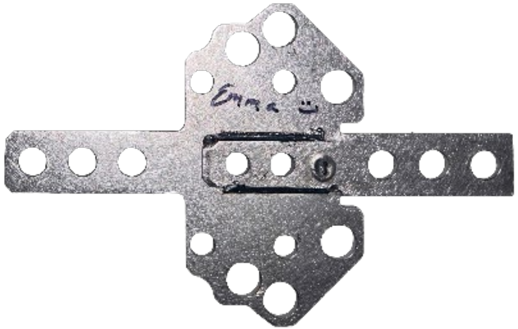
Demonstration Results

- **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





AIAA ASCEND 2023 Papers

- **Tall Lunar Towers: Systems Analysis of a Lunar-Surface-Assembled Power, Communication, and Navigation Infrastructure**
  – Dan Tiffin
- **Sizing, Buckling, and Thermal-Structural Analysis of Tall Lunar Tower**
  – Kyongchan Song
- **Software Design for the Supervised Autonomous Assembly of the Tall Lunar Tower**
  – Jacob Cassady
- **Scaling Climbing Collaborative Mobile Manipulators for Outfitting a Tall Lunar Tower and Truss Structures**
  – John Merila
- **Unreal Engine Testbed for Computer Vision of Tall Lunar Tower Assembly**
  – Brian Notosubagyo

Mission Analysis (PDF)

Structural Analysis (PDF)

Software Design (LaTeX)

Climbing Robots (PDF)

Lighting Simulation (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

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