International Conference on Intelligent Robots and Systems

Detroit, Michigan USA | October 1, 2023

## WORKSHOP: 08:30-17:30

# ASSEMBLING LARGE INFRASTRUCTURES IN SPACE USING INTELLIGENT ROBOTS

ORGANIZED BY:

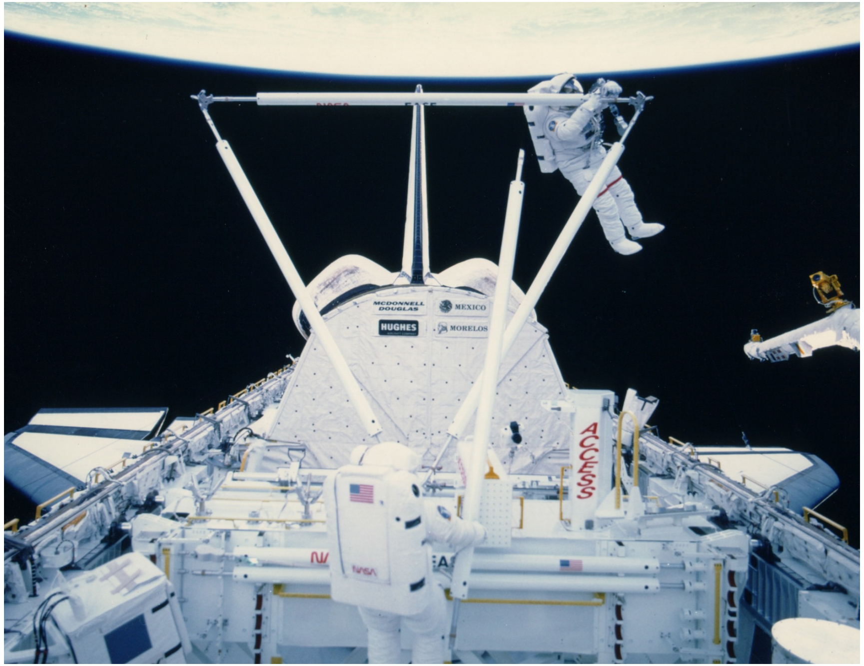

| | |
|---|---|
| Craig Carignan | University of Maryland, USA |
| Mini Rai | University of Lincoln, UK |
| Carol Martinez | University of Luxemburg |
| Giacomo Marani | West Virginia Robotics Technology Center |


IEEE Robotics & Automation Society

http://wvrtc.com/iros2023

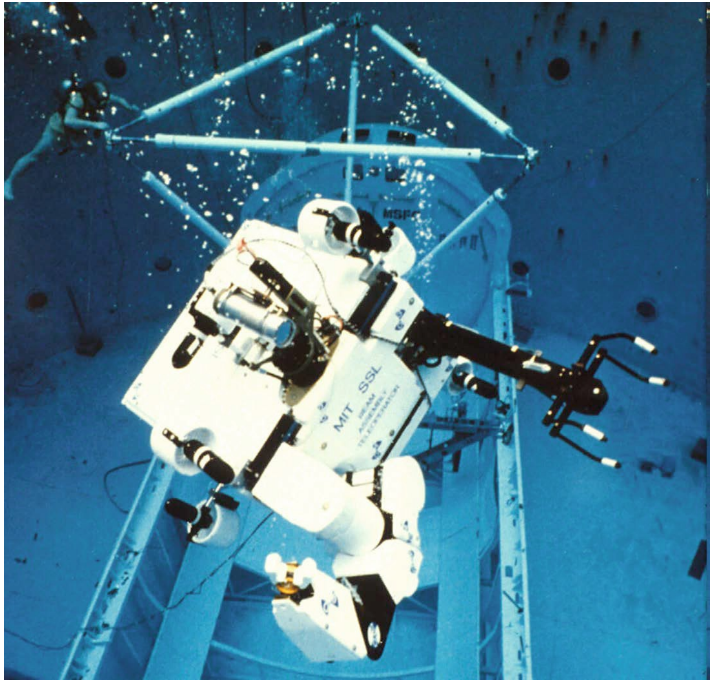
# Robotic and Human/Robotic Structural Assembly: Past Experiences, Future Promise

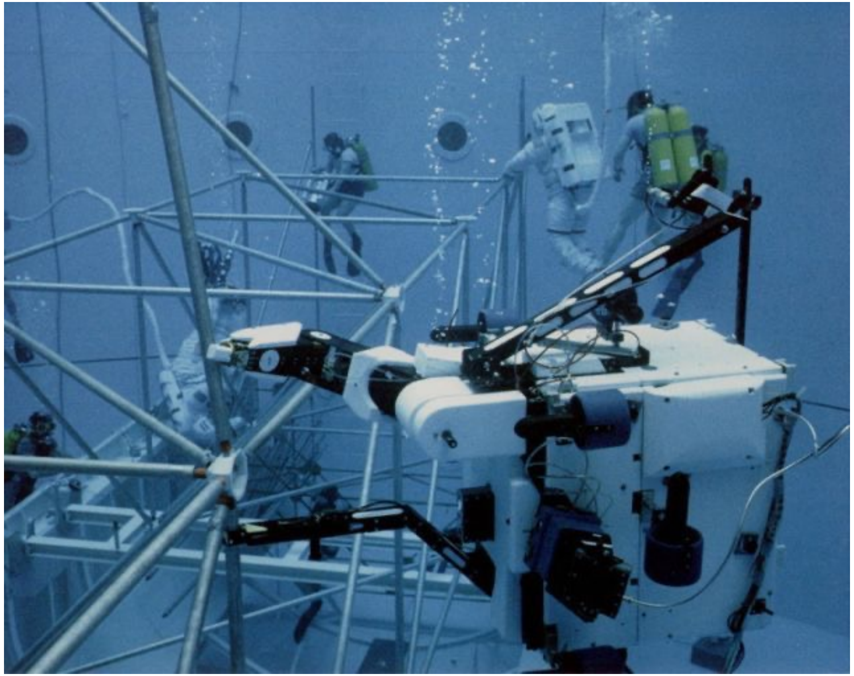
*David Akin*
*University of Maryland*
*Space Systems Laboratory*




Experimental Assembly of Structures in EVA (EASE) structure on STS 61-B (1985)

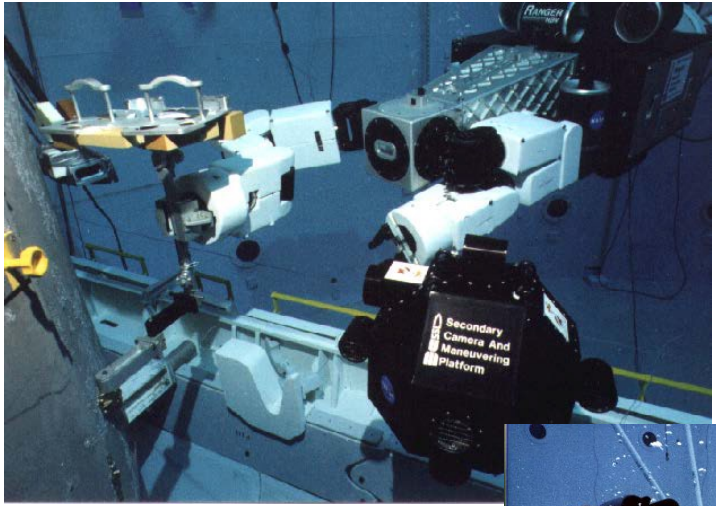
SPACE SYSTEMS LABORATORY
UNIVERSITY OF MARYLAND

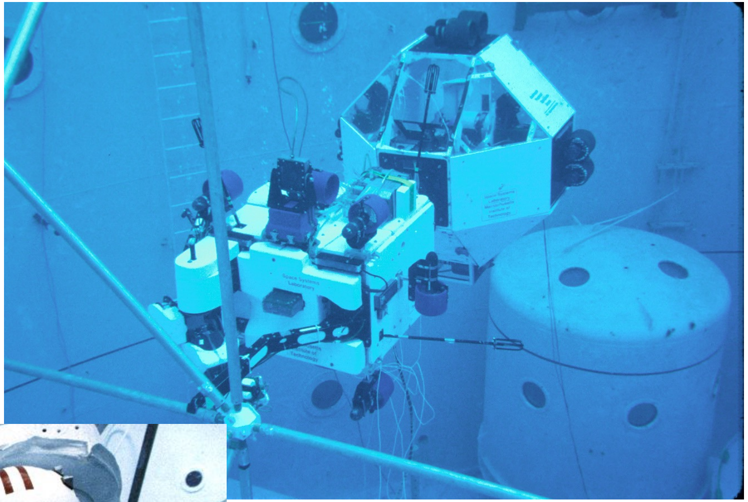


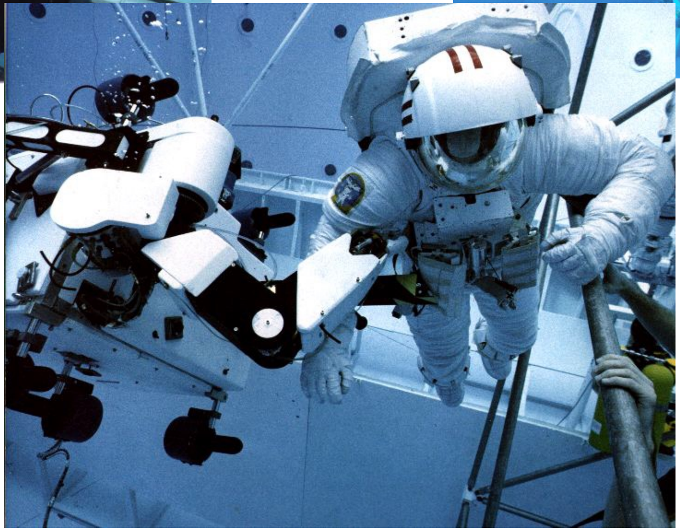


Robotic Assembly of EASE and other structures in neutral buoyancy.

# Multi-Agent Collaboration





Future Applications

2

# Human-Robot Collaborative Manipulation of Deformable Objects for In-Space Assembly

Burak Aksoy

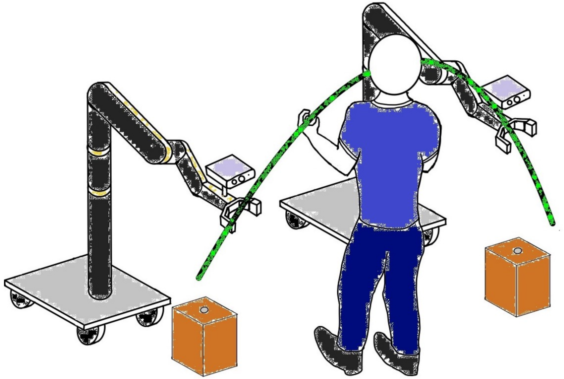
John T. Wen

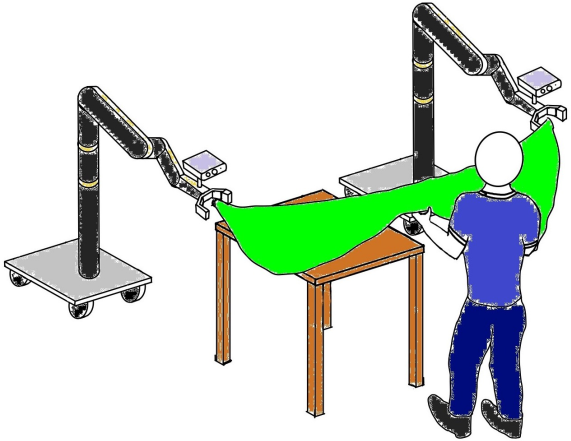
Rensselaer

why not change the world?®

# Collaboration for In-Space Assembly

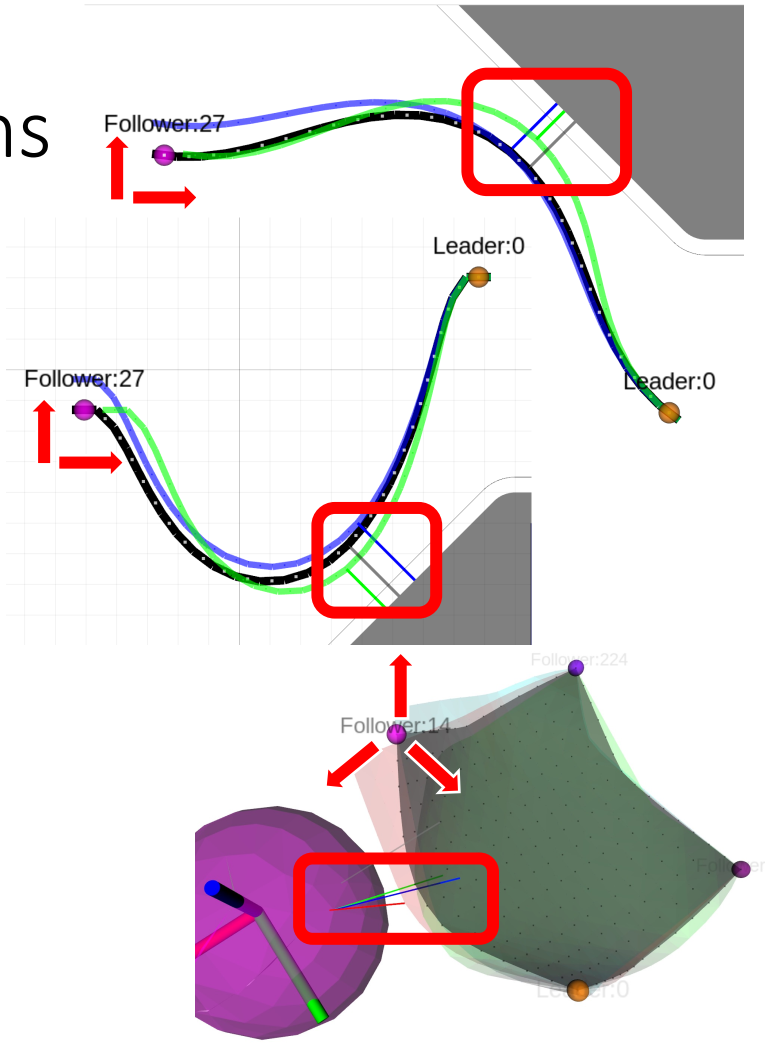
- Focus:
  - Deployable booms & Flexible sheets
- Challenges in Deformable Object Manipulation
  - Modeling, Diversity, Variable Stiffness
- Human Limitations:
  - Fatigue & Error
- DOM Complexity:
  - Ensuring Safety in High DoF
- **Solution:**
  **Merge Human Intelligence & Robotic Assistance**
  - Human Focus: Precision;
  - Robots: Prediction & Adjustment





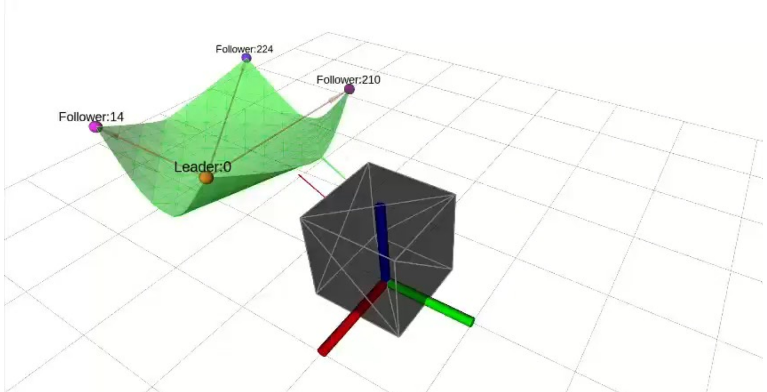
# Methodology & Contributions

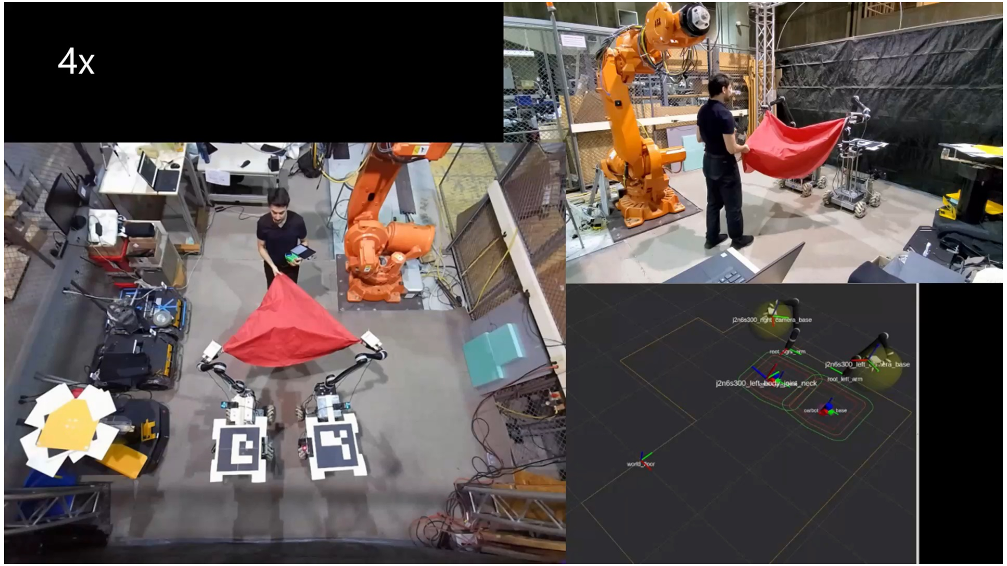
- Real-time Flexible Material Simulation
  - With Position-Based Dynamics (PBD) & ROS
- Safety:
  - Control Barrier Functions
  - Prevents Overstretching & Collisions
- Versatile:
  - 1D Beams/ropes & 2D Fabrics
- Input:
  - Human Position Tracking
  - Depth sensor
  - F/T sensors

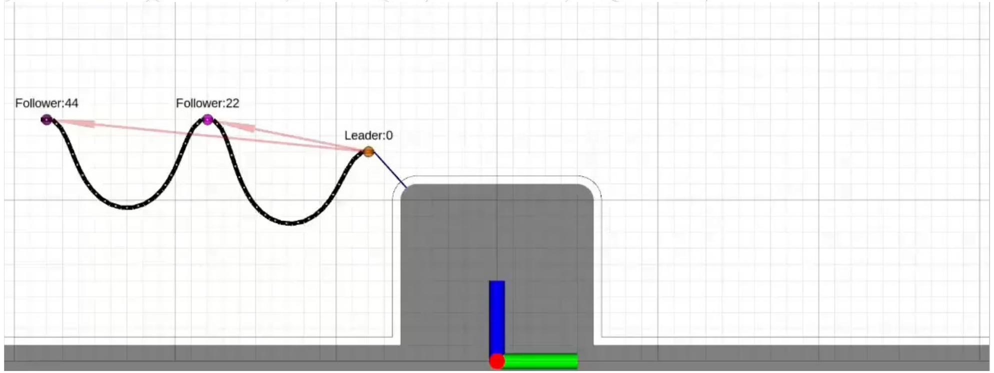


# Demonstrations

- Both Simulated & Real-world




3

# Effect of Orbital Dynamics on Fuel Use in Sampling-based Plans for Proximity Operations

Brandon Apodaca[1], Ella Atkins[2], Leia Stirling[1]
[1]University of Michigan, [2]Virginia Tech

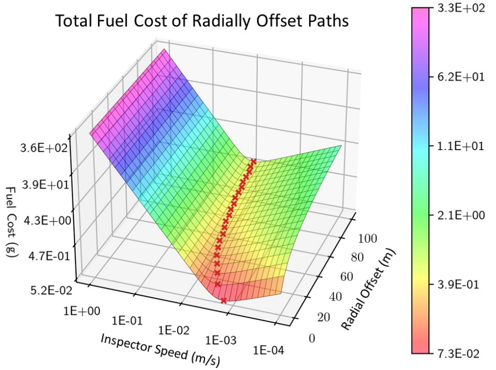
# Introduction and Background

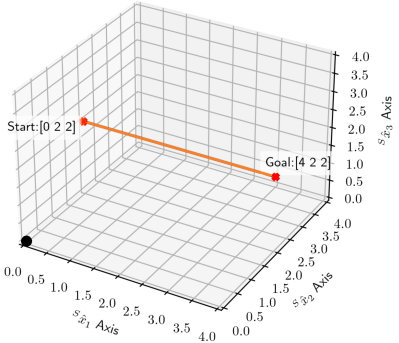
- There is a need for free-flyer inspections on the International Space Station [1].
- Motion planners for space proximity operations effectively **minimize costs** associated with orbital dynamics, however they struggle to optimize paths with **complex obstacle fields** [2,3].
- Robotics path planners are effective at **obstacle avoidance**, however they do not account for **orbital dynamics** [4,5].

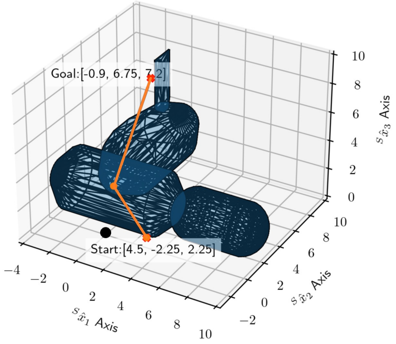
[1] R. Moore, “ISS Inspection Capabilities and Challenges,” presented at the In-Space Inspection Workshop, NASA Johnson Space Center, Jul. 2014. Accessed: May 17, 2023. [Online]. Available: https://mediaex-server.larc.nasa.gov/Academy/Play/09e01da677ed4f768d6d9f020e3fa4ec1d
[2] K. Berry et al., “OSIRIS-REx Touch-And-Go (TAG) Mission Design and Analysis,” presented at the 36th Annual AAS Guidance and Control Conference, Breckenridge, CO, Feb. 2013. Accessed: May 09, 2023. [Online]. Available: https://ntrs.nasa.gov/citations/20130013409
[3] M. Pyrak and J. Anderson, “Performance of Northrop Grumman’s Mission Extension Vehicle (MEV) RPO imagers at GEO,” in *Autonomous Systems: Sensors, Processing and Security for Ground, Air, Sea and Space Vehicles and Infrastructure 2022*, M. C. Dudzik, T. J. Axenson, and S. M. Jameson, Eds., Orlando, United States: SPIE, Jun. 2022, p. 28. doi: 10.1117/12.2631524.
[4] S. M. LaValle, “Rapidly-exploring random trees: A new tool for path planning,” Computer Science Department, Iowa State University, Technical Report TR 98-11, Oct. 1998. [Online]. Available: http://msl.cs.uiuc.edu/~lavalle/papers/Lav98c.pdf
[5] B. Apodaca, E. Atkins, and L. Stirling, “RRTZ: a Path Planner Designed for Zero Gravity,” IEEE Aerospace Conference, 2024, In press.

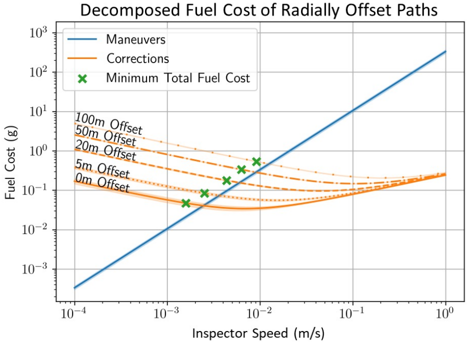
# Methods and Results

- Robotics planner RRTZ [5] was used to produce continuous trajectories on four different obstacle fields (two below).
- We leveraged Newtonian mechanics to estimate fuel cost using the Clohessy Wiltshire Equations [6] (right).




[5] B. Apodaca, E. Atkins, and L. Stirling, “RRTZ: a Path Planner Designed for Zero Gravity,” IEEE Aerospace Conference, 2024, In press.
[6] W. H. Clohessy and R. S. Wiltshire, “Terminal Guidance System for Satellite Rendezvous,” Journal of the Aerospace Sciences, vol. 27, no. 9, pp. 653–658, Sep. 1960, doi: 10.2514/8.8704.

4

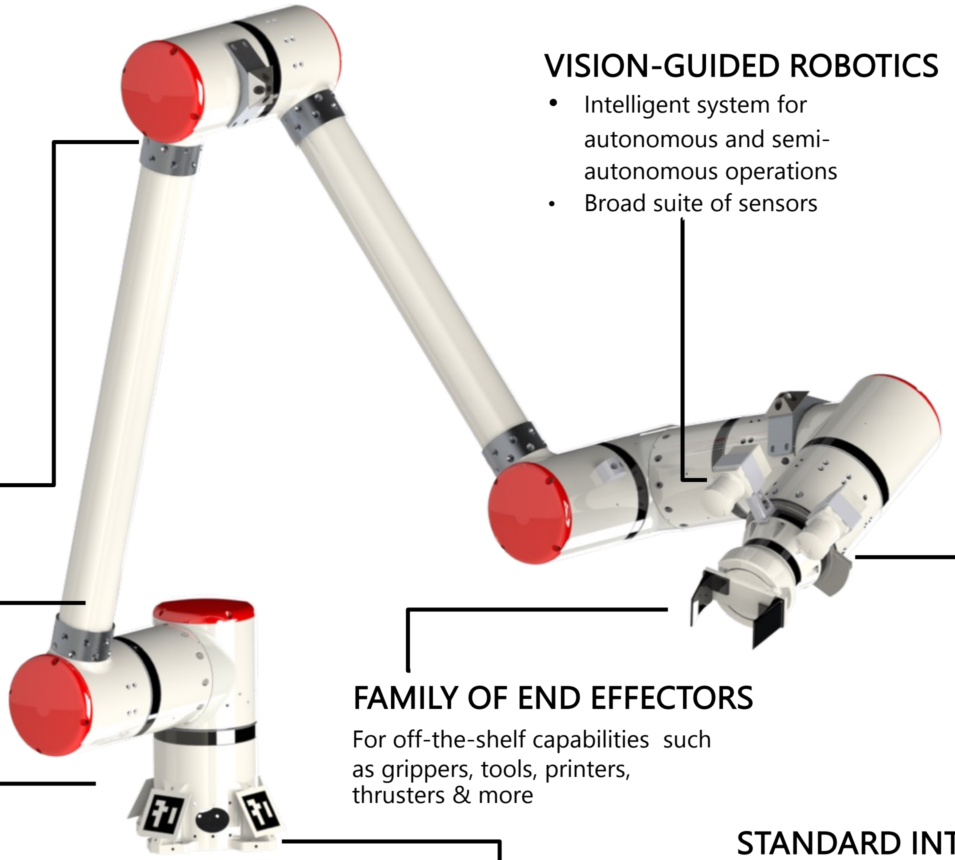
# STAARK Robotic Arm system

- System Overview

# Scalable in-space robotics

LUXEMBOURG SPACE AGENCY

esa



## VISION-GUIDED ROBOTICS

- Intelligent system for autonomous and semi-autonomous operations
- Broad suite of sensors

## SCALABLE AND MODULAR

- Customizable DOF
- Select best configuration & reach
- Adjust for optimal loads transfer
- New features can be installed

## FAMILY OF END EFFECTORS

For off-the-shelf capabilities such as grippers, tools, printers, thrusters & more

## OPTIMIZED

- Integrated avionics
- Easily programmable software
- Lightweight components
- High performing systems

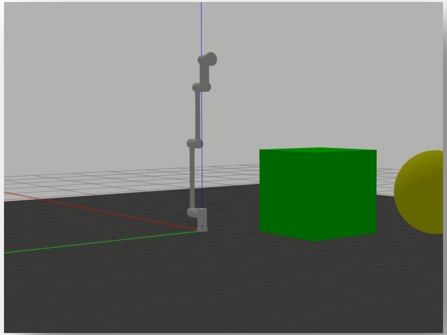
## STANDARD INTERFACES

Integration with spacecraft and connecting custom end-effectors

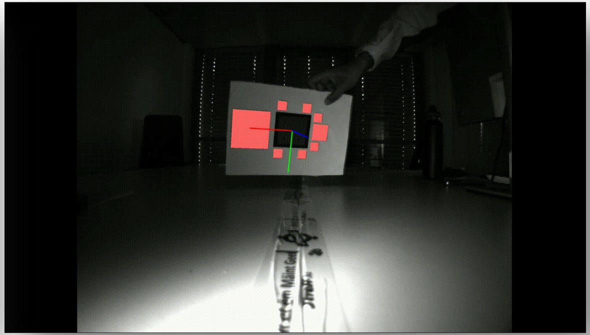
# Robotics Functions & Capabilities

- STAARK 6–DoF allows for a fully reachable dome-type workspace that allows for complex operations and trajectories

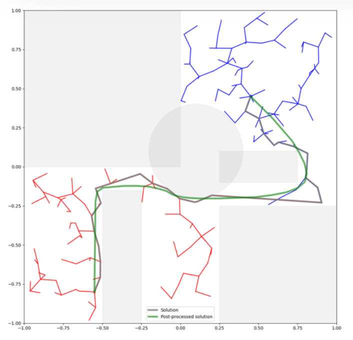
- **Robotic System equipped with MACOS (Manipulator Control Stack):**
  - Running onboard the RCU.
  - As a simulation instance on the ground station.
- **Robotics Capabilities include:**
  - Joint Space Control
  - Cartesian Pose Control
  - Static Environment Collision Detection
  - Static Environment Path Planning
  - Tool Based Operations Planning (static offset from tool flange)
  - Compliance Control (Coming 2024)
  - Visual servoing (Coming 2024)



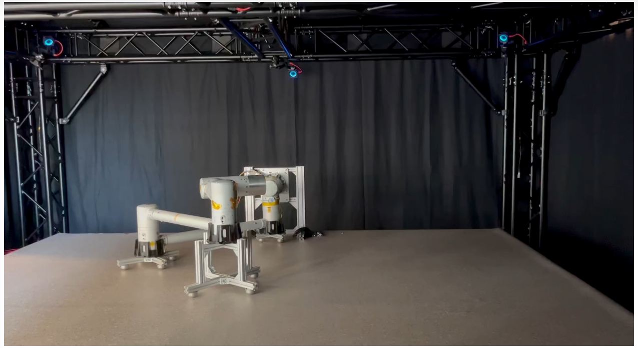
Collision Detection



Fiducial Marker Identification




Path Planning



Control

# 5 Efficient and Singularity-Aware Inverse Kinematics for 6-DOF and 7-DOF Revolute Manipulators

Alexander J. Elias and John T. Wen · Rensselaer Polytechnic Institute

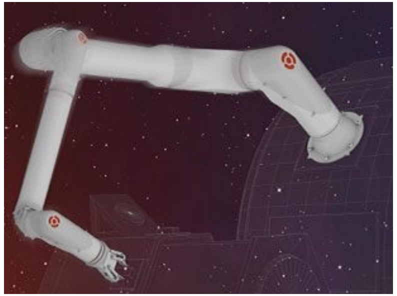
**Slide 2**: Canonical Subproblems for Robot Inverse Kinematics [1]

**Slide 3**: General, Conventional, and Stereographic SEW Angles for 7-DOF Arms [2]

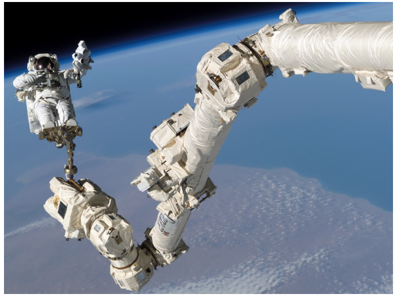
**Slide 4**: 6-DOF and 7-DOF IK using Subproblem Decomposition Method [1, 2]

linktr.ee/iros_ik
eliasa3@rpi.edu
github.com/rpiRobotics/ik-geo
github.com/rpiRobotics/stereo-sew

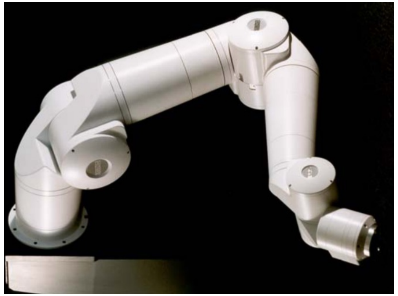
OSAM-1 (2R-2R-3R)



OSAM-2 (R-2R-2R-2R)



SSRMS (2R-3R||-2R)



RRC (General 7R)

[1] Alexander J. Elias and John T. Wen, "Canonical subproblems for robot inverse kinematics," *arXiv preprint arXiv:2211.05737, 2022*

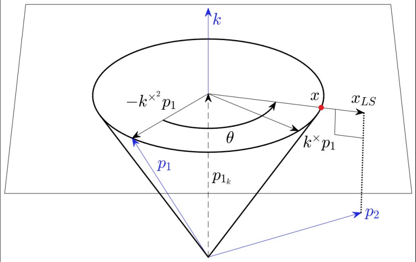
[2] —, "Redundancy parameterization and inverse kinematics of 7-DOF revolute manipulators," *arXiv preprint arXiv:2307.13122, 2023*

# Canonical Subproblems for Robot Inverse Kinematics

## Angle of intersection of circles with other geometric objects

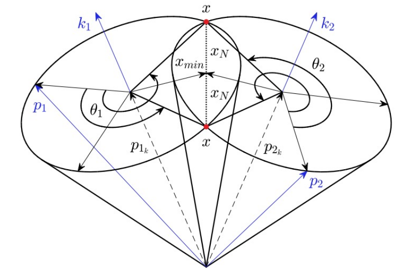
## Least-squares (1–4) and detect/resolve continuum of solutions

### 1: Circle and Point



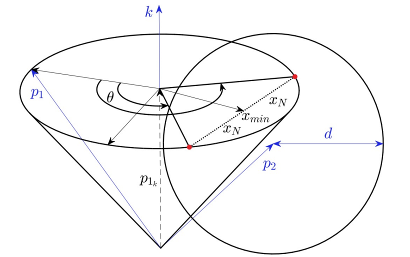

$\min \|R(k,\theta)p_1 - p_2\|$

### 2: Two Circles



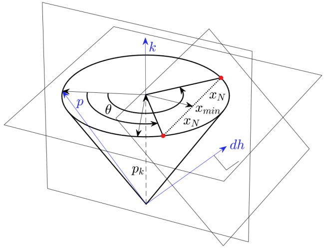

$\min \|R(k_1,\theta_1)p_1 - R(k_2,\theta_2)p_2\|$

### 3: Circle and Sphere



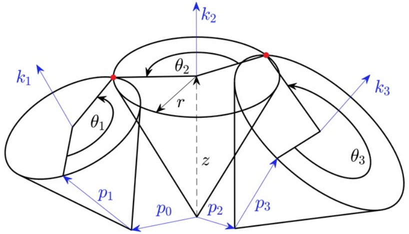

$\min \big|\|R(k,\theta)p_1 - p_2\| - d\big|$

### 4: Circle and Plane




$\min \left|h^T R(k,\theta)p - d\right|$

### 5: Three Circles




$$p_0 + R(k_1,\theta_1)p_1 = R(k_2,\theta_2)(p_2 + R(k_3,\theta_3)p_3)$$

### 6: Four Circles

$$\begin{cases} h_1^T R(k_1,\theta_1)p_1 + h_2^T R(k_2,\theta_2)p_2 = d_1 \\ h_3^T R(k_3,\theta_1)p_3 + h_4^T R(k_4,\theta_2)p_4 = d_2 \end{cases}$$

Solution method:

1. Write in terms of $x = \begin{bmatrix}\sin\theta \\ \cos\theta\end{bmatrix}$
2. Find unconstrained solutions
3. Add $\|x\| = 1$ constraint
4. Return $\theta = \text{atan2}(\sin\theta, \cos\theta)$

No arccos, arcsin, or $\tan(\theta/2)$

→ Robust to numerical issues

Solutions are fast with MATLAB and Rust

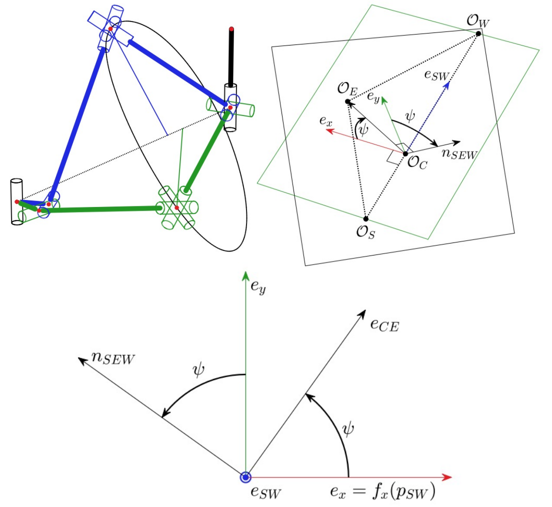
| | Mean Runtime (ns) | | |
|---|---|---|---|
| Subproblem | m-file | MEX | Rust |
| 1: Circle and Point | 13 517 | 36 | 59 |
| 2: Two Circles | 27 262 | 312 | 242 |
| 3: Circle and Sphere | 18 034 | 134 | 111 |
| 4: Circle and Plane | 17 669 | 105 | 115 |
| 5: Three Circles | 105 288 | 2 553 | 1 027 |
| 6: Four Circles | 116 750 | 3 110 | 1 436 |

# General, Conventional, and Stereographic SEW Angles for 7-DOF Arms

## Shoulder-Elbow-Wrist (SEW) angle parameterizes redundant DOF

### General SEW Angle

Parameterization with arbitrary reference direction function $e_x = f_x(p_{SW})$

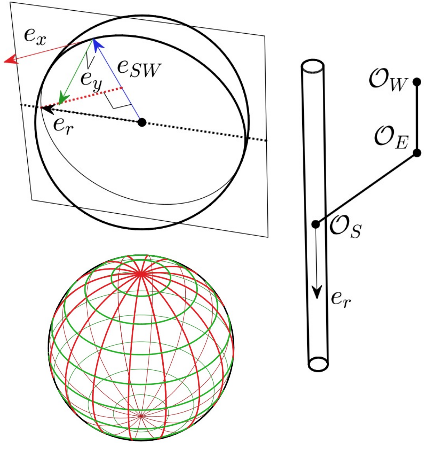



$$\psi = \arg\min_{\theta} \|\mathtt{R}(e_{SW}, \theta)e_x - p_{SE}\|$$

$$n_{SEW} = \mathtt{R}(e_{SW}, \psi)e_y$$

### Conventional SEW Angle

Singularity if wrist on line
May limit usable workspace



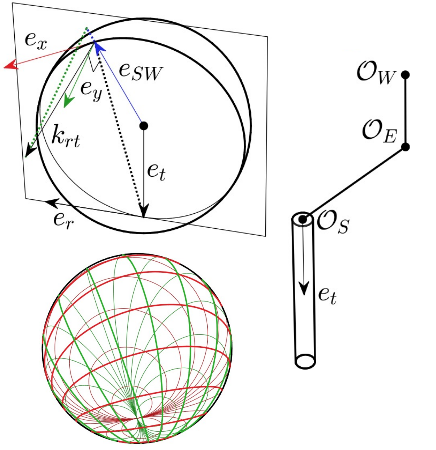

$$e_x = f_x(p_{SW}) = e_y^{\times} e_{SW},$$

$$e_y = \frac{k_y}{\|k_y\|},$$

$$k_y = p_{SW}^{\times} e_r.$$

### Stereographic SEW Angle

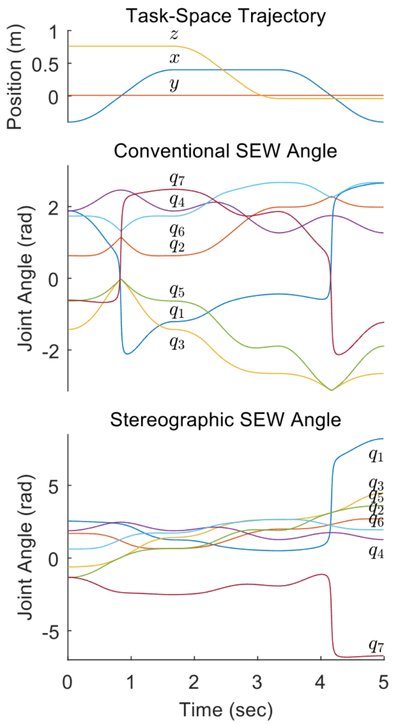
Singularity if wrist on half-line
Singularity can be out of reach




$$e_x = f_x(p_{SW}) = \frac{k_x}{\|k_x\|},$$

$$k_x = k_{rt}^{\times} p_{SW},$$

$$k_{rt} = (e_{SW} - e_t)^{\times} e_r.$$



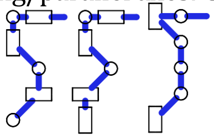
# 6-DOF and 7-DOF IK using Subproblems Decomposition Method

## Finds all solutions

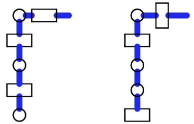
## Robust to internal and boundary singularities

### 6-DOF Inverse Kinematics

3 intersecting/parallel axes: Closed form

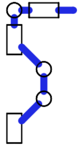


2 intersecting or parallel axes: 1D search

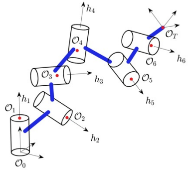


Example: Spherical wrist & two parallel axes

1. Find $q_1$ with SP 4
2. Find $q_3$ with SP 3
3. Find $q_2$ wth SP 1
4. Find $(q_4, q_5)$ with SP 2
5. Find $q_6$ with SP 1



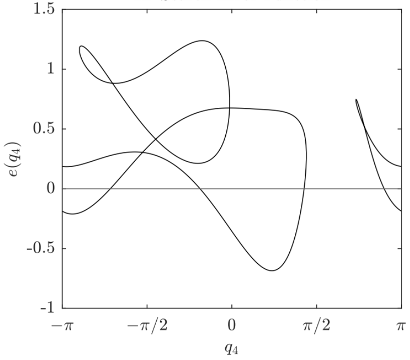
General 6R robot: 2D search




Subproblem decomposition is faster and more capable than IKFast and MATLAB Robotics Toolbox (Pieper method)

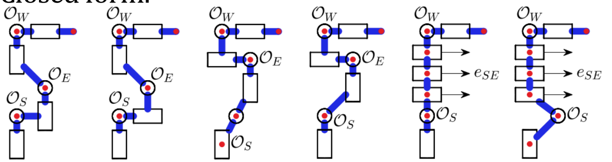
| | Mean Hardcoded Robot Runtime (μs) | | | |
|---|---|---|---|---|
| Robot Type | MEX | Rust | IKFast | MRT MEX |
| General 6R (2D search) | 20 741.535 | 16 026.010 | N/A[a] | N/A[a] |
| Two intersecting axes (1D search) | 199.194 | 114.552 | N/A[a] | N/A[a] |
| Two parallel axes (1D search) | 1 021.655 | 439.445 | N/A[a] | N/A[a] |
| Spherical wrist | 4.527 | 2.425 | 111.445 | 10.583 |
| and two intersecting axes | 4.991 | 3.688 | N/A[b] | N/A[a] |
| and two parallel axes | 2.991 | 3.183 | 4.417 | 13.318 |
| Three parallel axes | 5.345 | 4.339 | N/A[c] | N/A[a] |
| and two intersecting axes | 2.846 | 3.089 | 121.714 | N/A[a] |

[a] Did not generate code [b] Did not compile [c] Incorrect IK



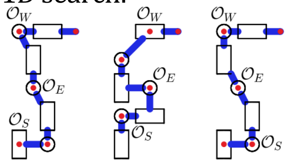

### 7-DOF Inverse Kinematics (Using General SEW Angle)

Closed form:



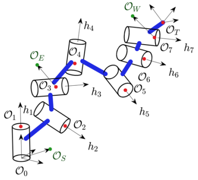

1. 2R-2R-3R. 2. 3R-R-3R. 3. R-R-3R$^E$-2R. 4. 2R-3R-2R. 5. 2R-3R||-2R. 6. R-R-3R||$^E$-2R.

1D search:




7. R-2R-2R$^E$-2R. 8. 3R-R$^E$-2R-R. 9. R-2R$^S$-R-3R.

General 7R robot: 2D Search

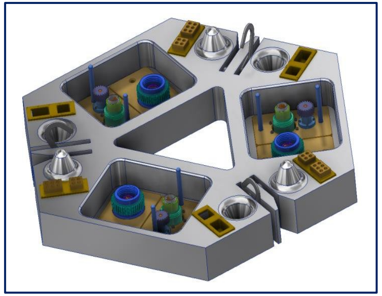


6

# OSAM-2 Technologies for Autonomous Construction of Large Structures on Orbit

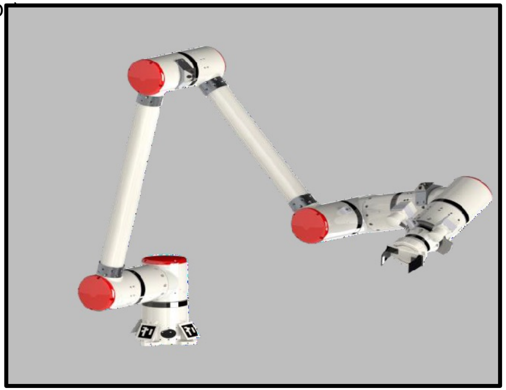
Dr. Daniel Hillsberry 10.01.23

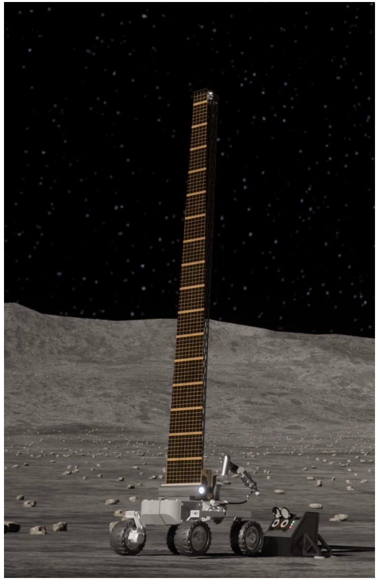
# OSAM-2 Technologies for Autonomous Construction of Large Structures on Orbit



## On the NASA OSAM-2 program, Redwire developed unique technologies required construct additively manufactured struc scales of 10s of meters on orbit:

- Extended Structure Additive Manufacturing Machine (ESAMM)
    - Leverages development from Additive Manufacturing Facility (AMF) and 3D Printing in Zero G (3D
    - Belongs to Redwire family of technologies for large structures into the open volume of space
    - Smaller parts like rover wheels on the surface of the Moon
- Redwire's robotic control algorithms running on computationally limited flight hardware
    - Enable precision manipulation
    - In-situ inspection
    - Safely interact and grasp components using compliance control
    - Precision movements with visual servoing,
    - Avoid undesirable configurations autonomously.
- Redwire modeled, simulated, and analyzed robotically constructed large structures
    - Simulation run on all phases of build through changing structural dynamics
    - Developed techniques to prevent excitation of low frequency structural modes
    - Developed structural monitoring and control systems





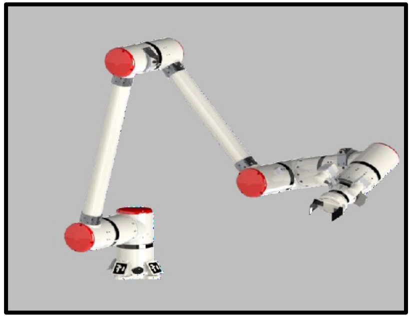
- This poster discusses these methods and terrestrial tests in the context of mission requirements.

# Enabling Technologies

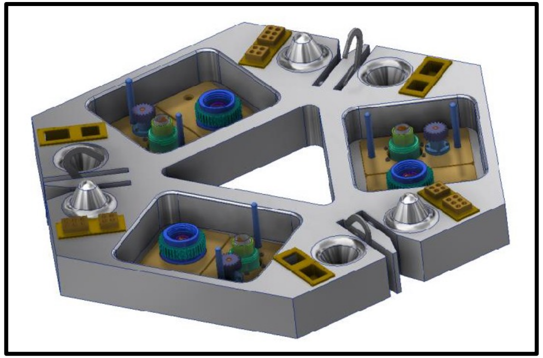
*End Effector*

*Standard Interface*

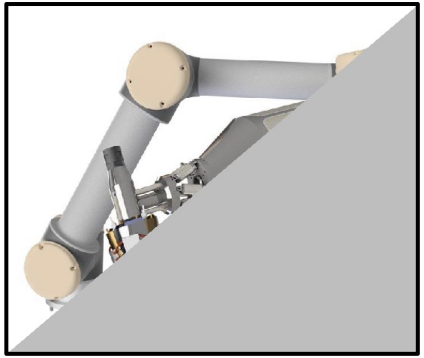
*Robotics*



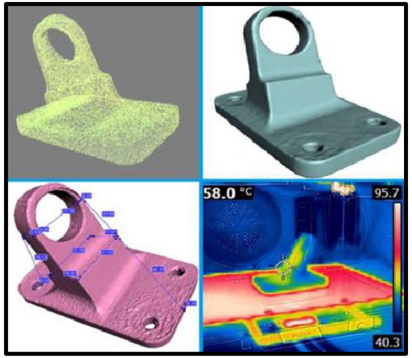
*Structures*



*Standard Interface*



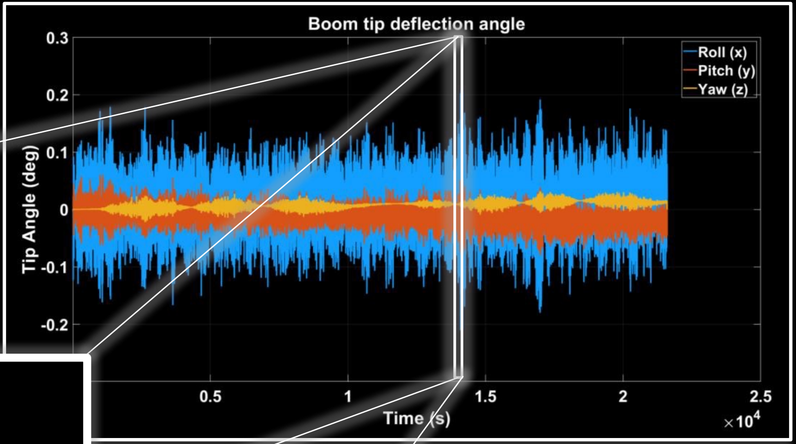
*Autonomy*

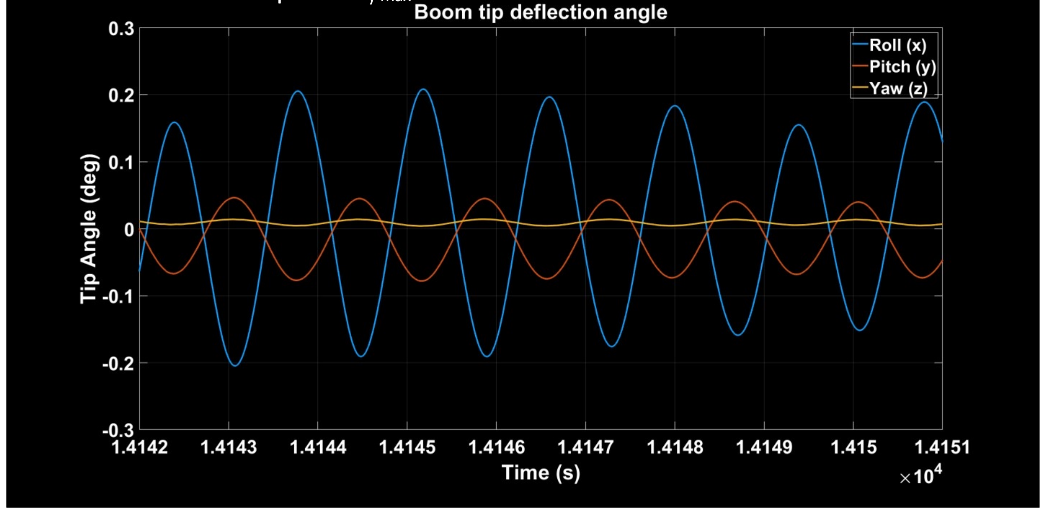



*In Situ Inspection*

# SSM Results: Beam Deflection

- Comparing the boom tip angles to the SV angles shows how the boom is deflecting with respect to the SV
- The largest deflection occurs around the X axis, or in the Y-Z plane, which matches the highest torque generated by the gantry moving along the Y axis
  - Max deflection in Y-Z plane: $\delta_{x\,max}$ = 27.5 mm
  - Max deflection in X-Z plane: $\delta_{y\,max}$ = 7.85 mm




Distributed Load $w = \frac{\theta_{max} * 6 * E * I}{L^3}$

Deflection $\delta_{max} = \frac{w * L^4}{8 * E * I}$

Moment $M_{max} = \frac{-w * L^2}{2}$

Stress $\sigma_{max} = \frac{M * y}{I}$

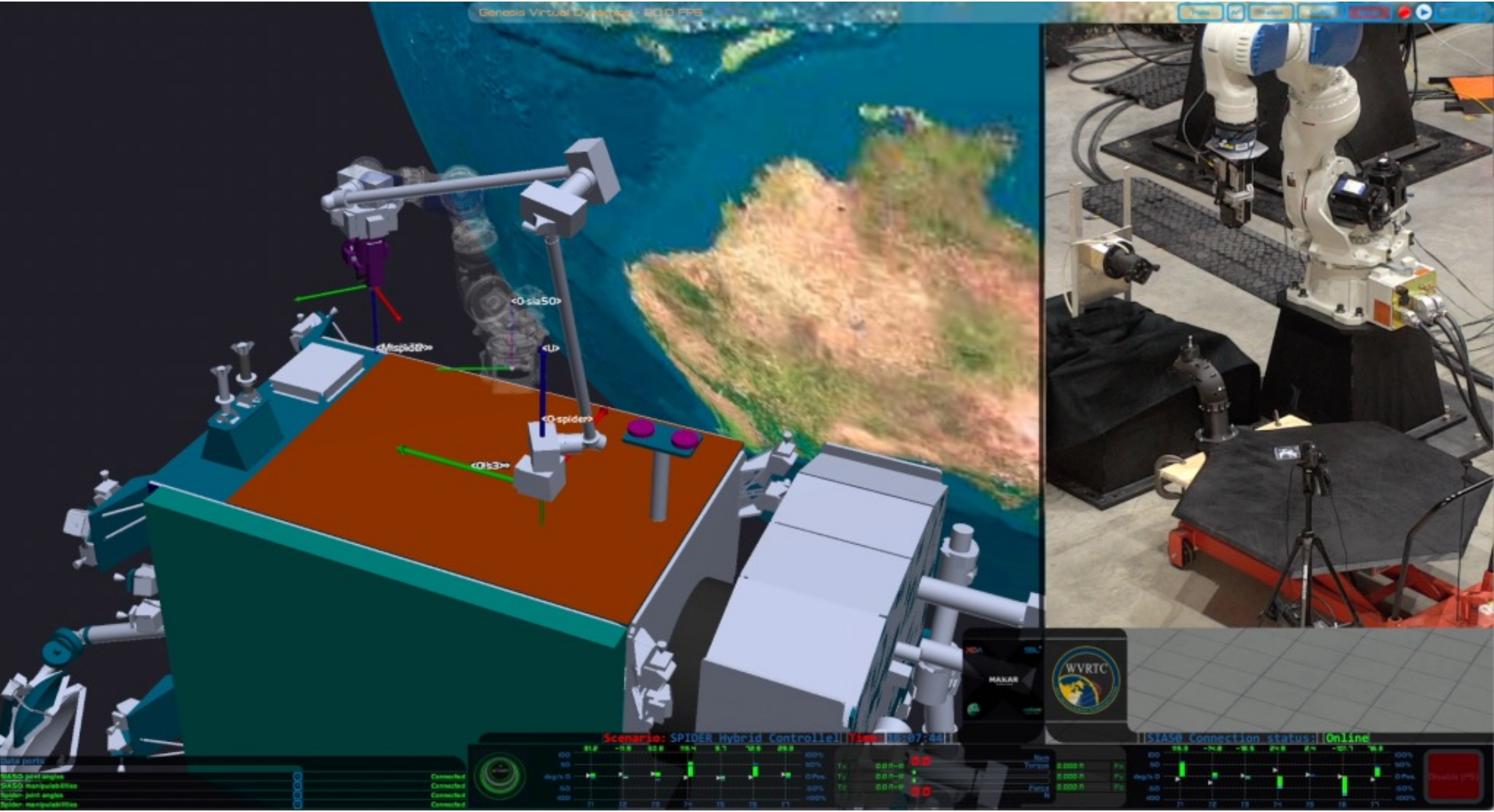
7

# Hardware-in-the-loop simulation of modular antenna assembly

*Alycia Gailey*
*Giacomo Marani*

*West Virginia Robotic Technology Center*

Robots are playing an increasing role in space exploration and in-space servicing. Robot arms are good for performing in-space tasks such as modular antenna assembly. The SPIDER arm (SPace Infrastructure Dexterous Robot) can perform assembly tasks in environmental conditions that would be dangerous for astronauts. Our work involves proof-of-principle testing of robot control systems on the ground using a hardware-in-the-loop (HIL) simulator, which simulates how the SPIDER robot end effector would move in space in response to externally applied forces from its environment. Using the HIL, we can test various robot control algorithms in a 1-G environment to see how well the robot system performs the different tasks that it would need to do in space.


Genesis Virtual Dynamics - 20.0 FPS
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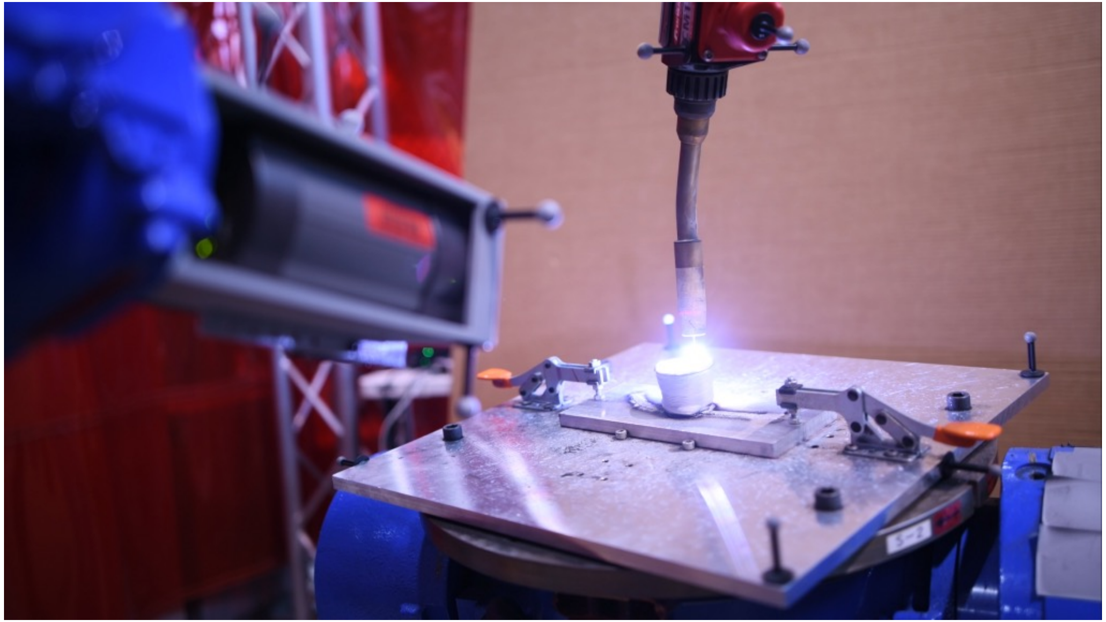
<U>
<0-spider>
WVRTC
MAKAR
Scenario: SPIDER Hybrid Controller
SIA50 Connection status: Online
Data ports
SIA50 joint angles
SIA50 manipulabilities
Spider joint angles
Spider manipulabilities
Connected
Connected
Connected
Connected

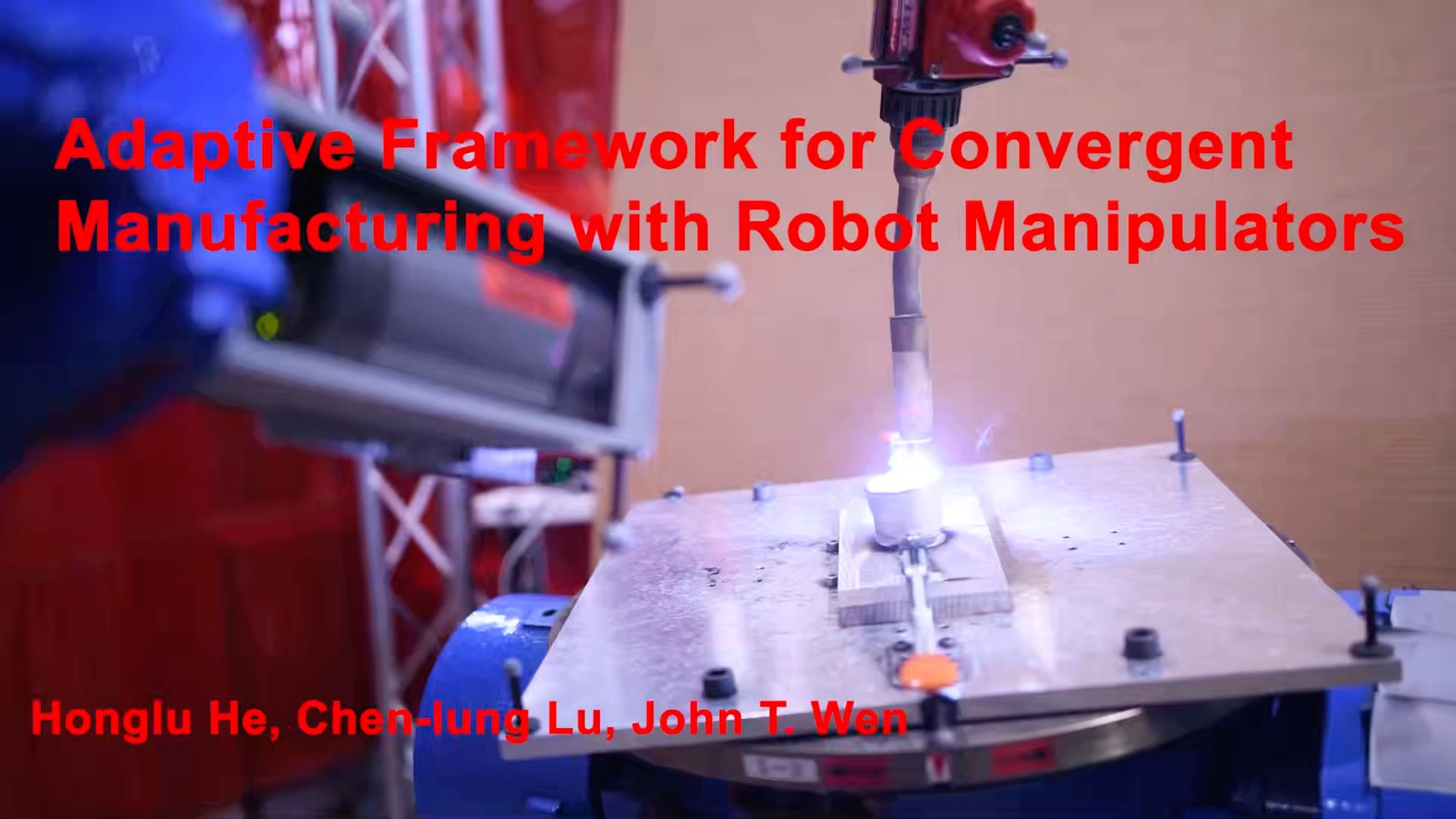
8

# Adaptive Framework for Convergent Manufacturing with Robot Manipulators

*Honglu He*
*Chen-lung Lu*
*John T. Wen*

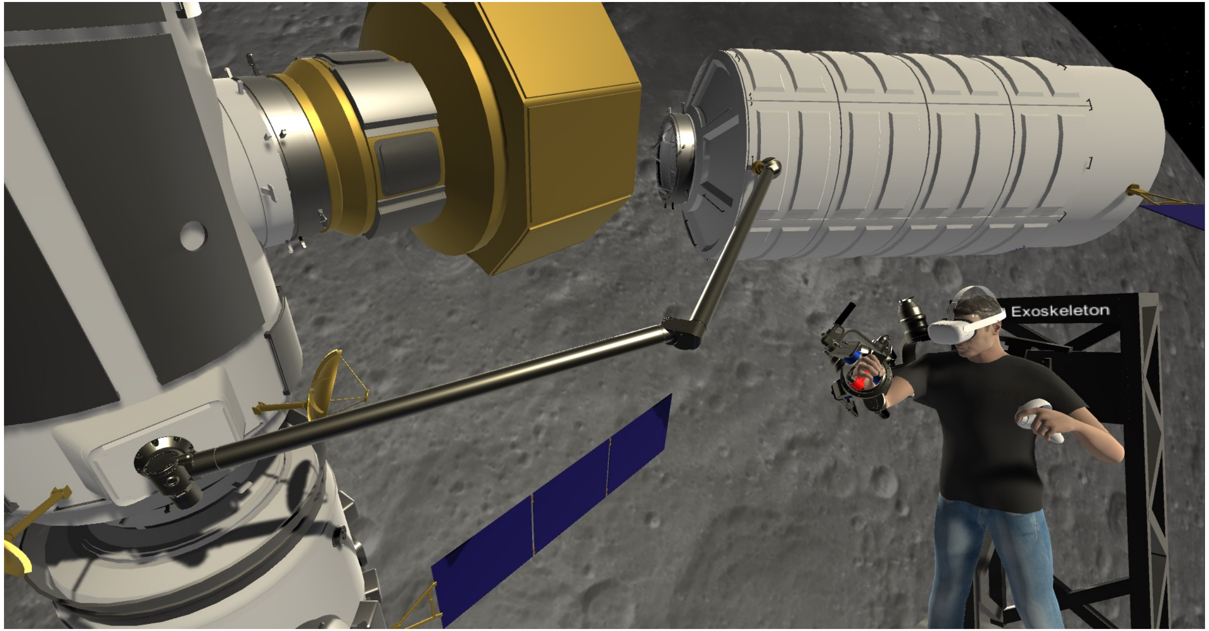
*Rensselaer Polytechnic Institute*




Adaptive Framework for Convergent
Manufacturing with Robot Manipulators
Honglu He, Chen-lung Lu, John T. Wen

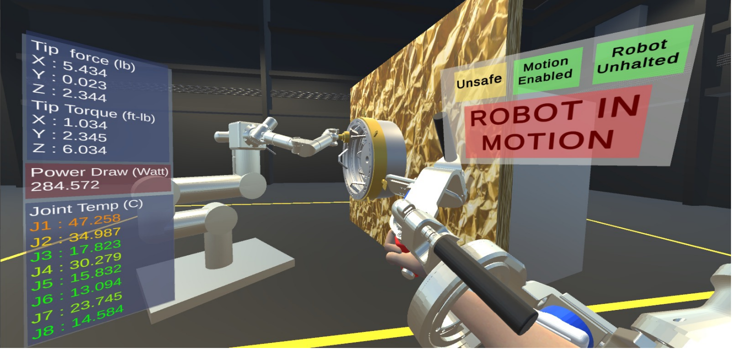
9

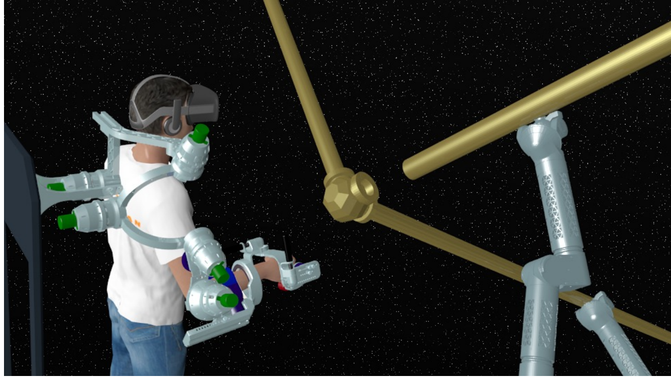
# Telerobotic Assembly of Structures in Space using an Exoskeleton-XR Interface



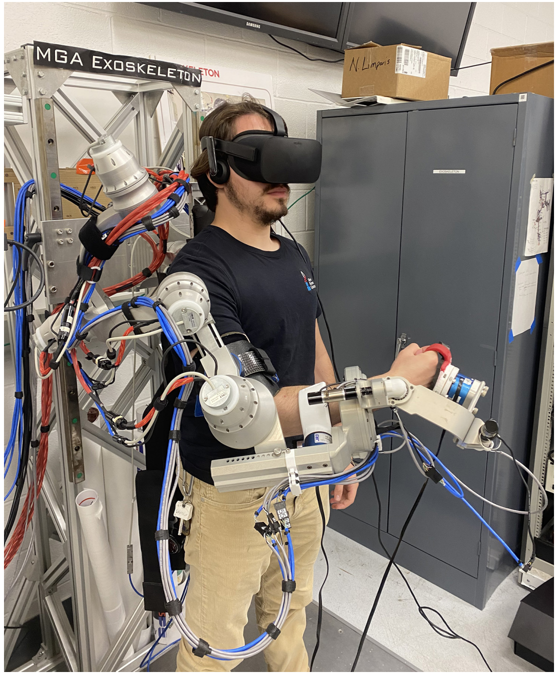

Romeo Perlstein, Daniil Gribook, Craig Carignan
University of Maryland

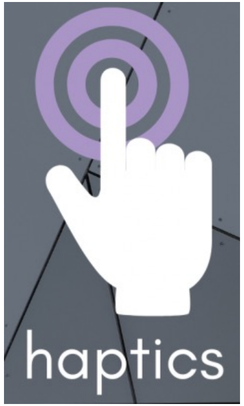
SPACE SYSTEMS LABORATORY
UNIVERSITY OF MARYLAND

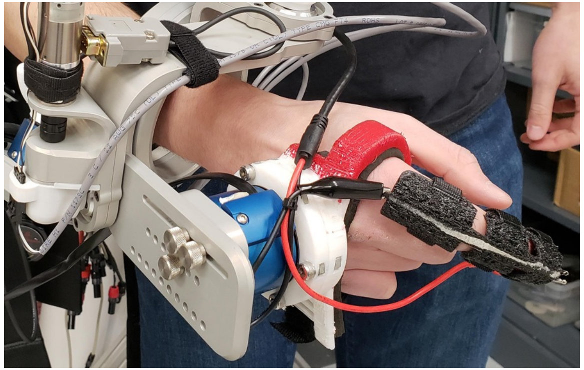

Tip force (lb)
X : 5.434
Y : 0.023
Z : 2.344
Tip Torque (ft-lb)
X : 1.034
Y : 2.345
Z : 6.034
Power Draw (Watt)
284.572
Joint Temp (C)
J1 : 47.258
J2 : 34.987
J3 : 17.823
J4 : 30.279
J5 : 15.832
J6 : 13.094
J7 : 23.745
J8 : 14.584
Unsafe
Motion Enabled
Robot Unhalted
ROBOT IN MOTION

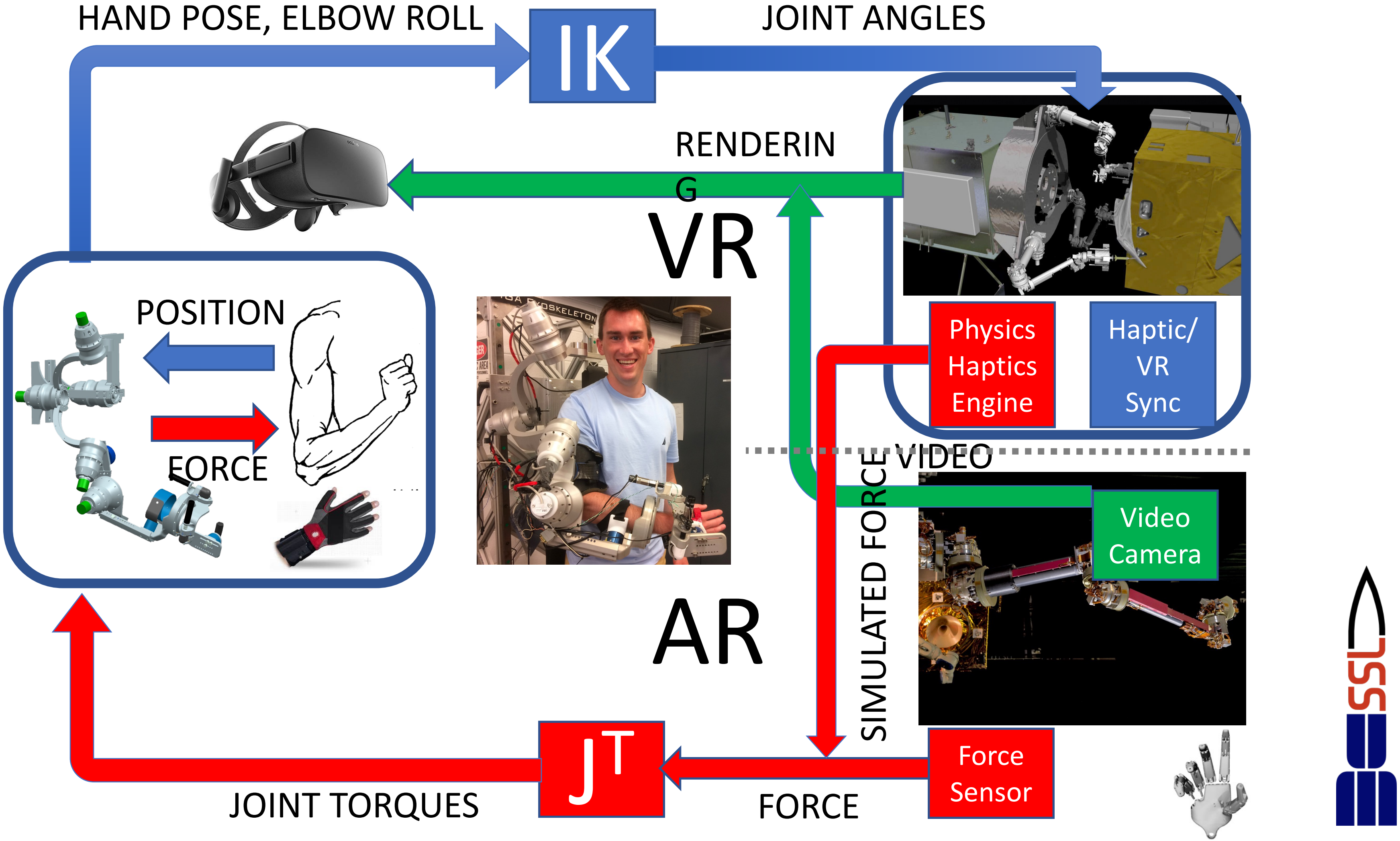



AR
VR
XR
MR


MGA EXOSKELETON


haptics




HAND POSE, ELBOW ROLL
IK
JOINT ANGLES
RENDERIN
G
VR
POSITION
FORCE
Physics
Haptics
Engine
Haptic/
VR
Sync
VIDEO
SIMULATED FORCE
Video
Camera
AR
JT
JOINT TORQUES
FORCE
Force
Sensor
SSL

10

# Deployable Lightweight Planar Antenna Technology Demonstration Mission

Keisuke WATANABE and Daisuke JODOI

Japan Aerospace Exploration Agency (JAXA)

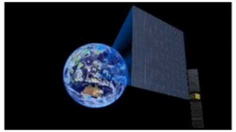
# Steps toward the SSPS (Space Solar Power Systems)

**Current level**

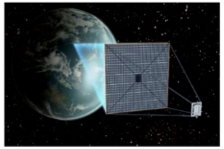
Planar antenna size: 10m x 3m

**Immediate target**

Construction of 30-m-class large planar antenna

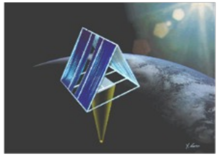


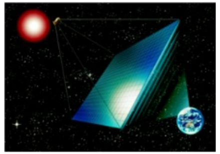
Construction of 100-m-class large space structure

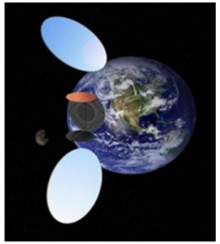


**Final target**

Construction of large space structures measuring several hundred meters or more in size



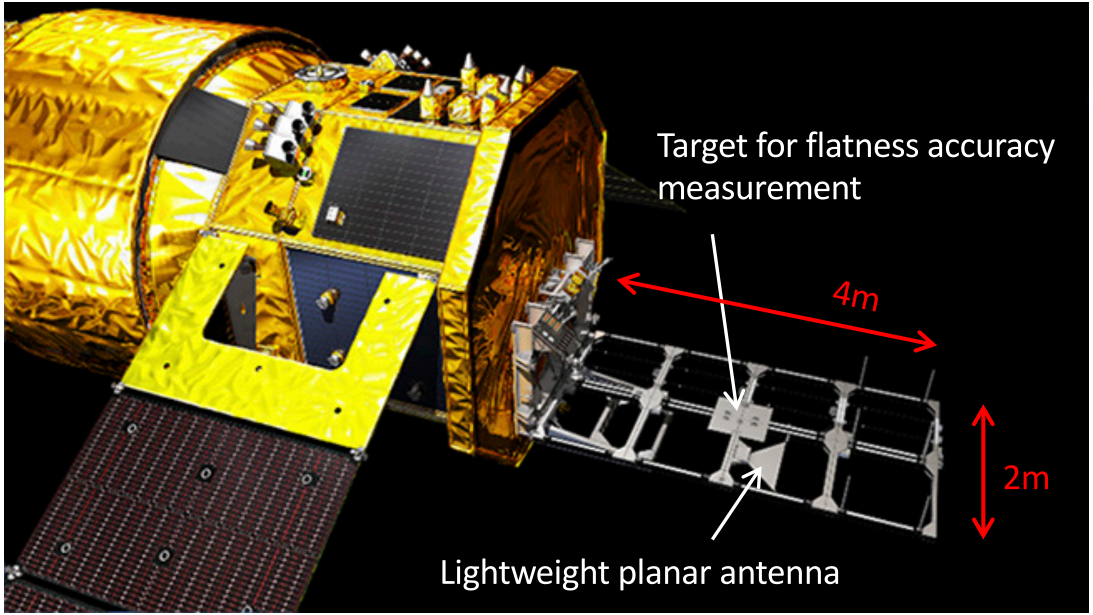




Realization of Geostationary Precipitation Radar (GPR)

- 100m-class structures and beyond will be constructed by combining 30m-class structures as a unit.
- Our current research goal is to build a 30m-class square planer antenna.

# DELIGHT

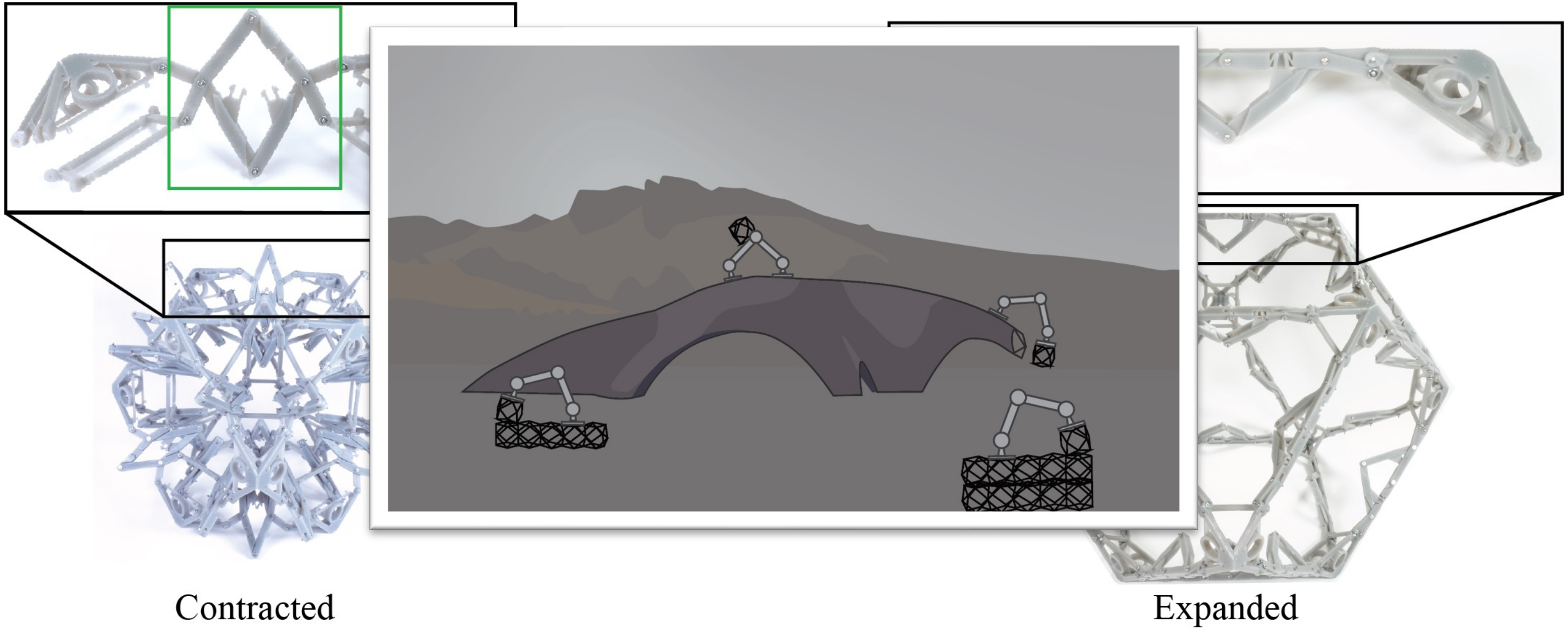



- Eight panels with deployment and connection mechanisms will be deployed row by row.
- Lightweight planar antenna will receive radio waves transmitted from the ground station.
- Dynamic behavior/flatness accuracy of the panels during/after deployment will be measured using cameras.

11

# Expanding subunits for deep space infrastructure

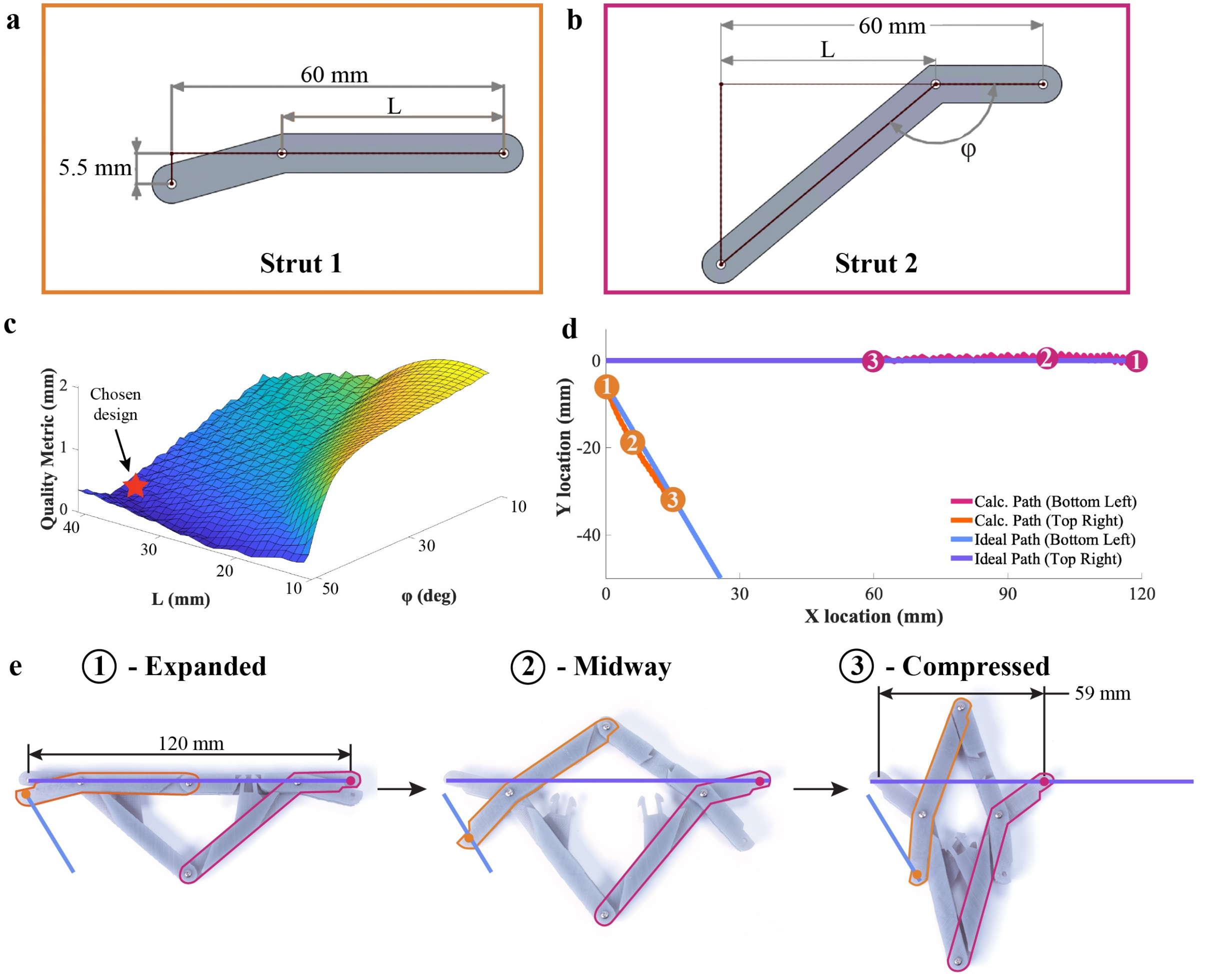
Stephanie Woodman[1], Alex Moore[1], Kenneth Cheung[2], and Rebecca Kramer-Bottiglio[1]
[1]*Mechanical Engineering and Materials Science, Yale University* [2]*NASA Ames Research Center*




Yale University

FABORATORY

# Principles of Hoberman sphere optimized for our shape




Yale University

FABORATORY