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First Cobotic assisted string assembly of PIP-II SSR2 cavities at Fermilab

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TU1A005

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About myself

Mattia Parise – mparise@fnal.gov

Technical Lead and Control Account Manager

for the Single Spoke Resonator CryoModules - PIP-II Project at Fermilab, USA

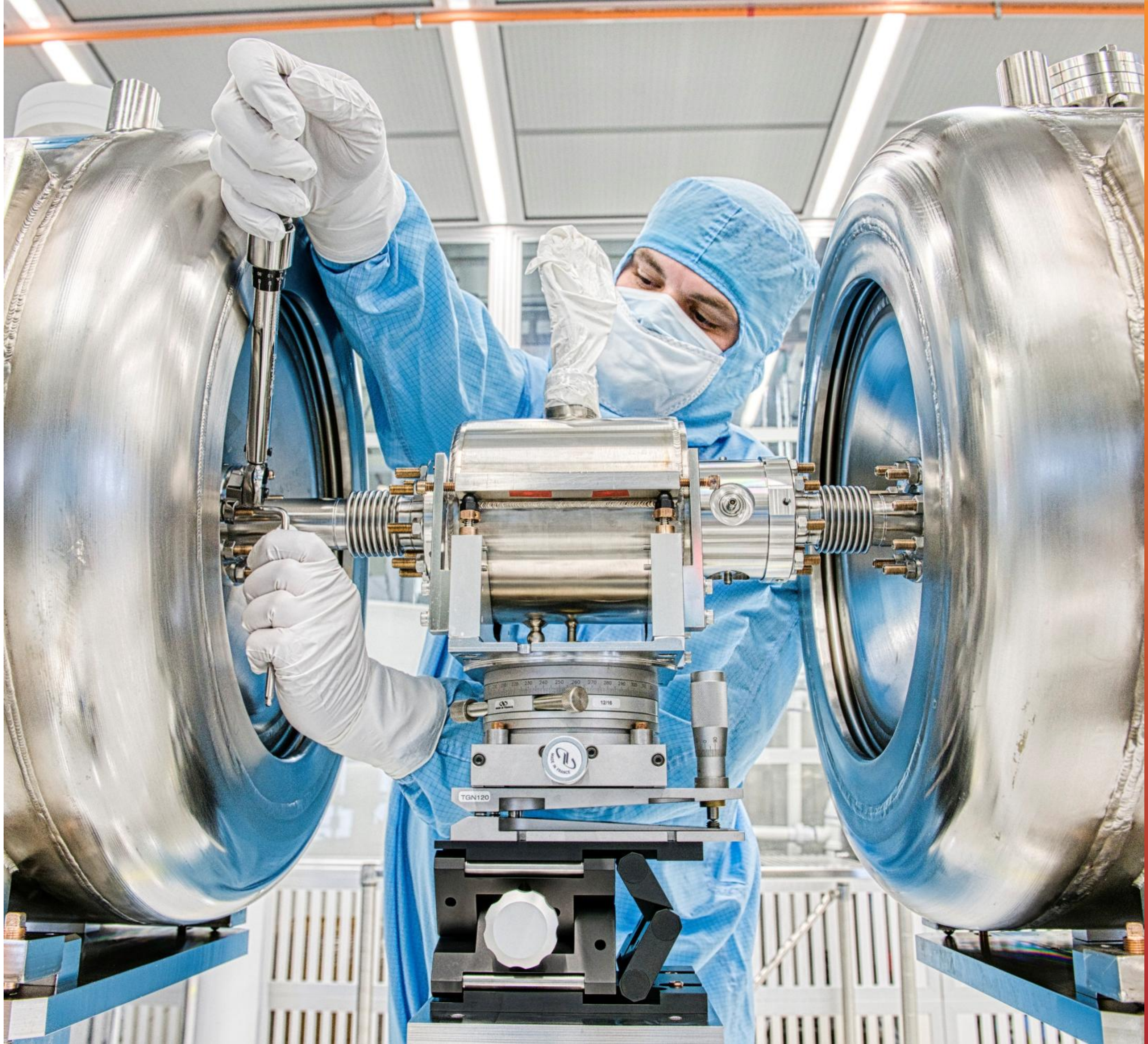
Senior Engineer, 11+ years of experience in SRF

Mechanical Engineer with experience in:

- SRF Cavities and Cryomodules Design, Fabrication and Testing
- Cleanroom assembly of SRF Cavities and Magnets Strings
- Assembly of Single Spoke Resonators Cryomodules
- Robotics and Automation for SRF Applications

Introduction

- Particulate contamination triggers field emission, local quenching, and degrades quality factor (Q_0) and accelerating gradients
- Cleanrooms maintain cleanliness by continuously flushing highly filtered air from the ceiling to the floor or sides
- Operator experience and tooling design are essential for successful SRF cavity string assembly



Introduction

Manual tooling for cleanroom assemblies is a double-edged sword:

- Flexible component positioning
- Eliminates operator weight-bearing
- Multi-part complexity (threaded/sliding connections)
- Steep 6-DOF learning curve requiring specialized training
- Rapid obsolescence when designs or projects change

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Robotic Arm

Universal Robotics 16e Cobot was chosen as the arm to begin developing

- First **Cobot** (UR16e) procured in late 2023
- **December 2023**: the first Cobotic installation of a vacuum-end high power coupler on an SSR2 cavity for PIP-II
  - **C. Narug, Robotic-Assisted Technology for Assembling PIP-II SRF Couplers onto Cavities in Cleanroom, TTC 2023, Fermilab**
- We procured two additional cobots: one **UR16e** and one **UR5e**
- Students from **University of Pisa** and **NIU** worked on development for cleanroom SRF applications
  - **C. Narug, Clean Room Protocols and Robotic Techniques for PIP-II, TTC 2025, Daejeon, South Korea**
  - **C. Narug, SRF Robotic Assembly Development at Fermilab, TTC 2026, Saclay, France**

Feature / Specification	Details
Axes	6
Payload Capacity	16 kg (35.3 lbs)
Reach	900 mm
Integrated Sensors	End effector load cell
Force Accuracy	±5.5 N
Torque Accuracy	±0.5 Nm
Cleanroom Rating (ISO 14644-1)	• Class 5 (at ≤ 40% speed)
Control System	PolyScope 5 pendant

01

The Road to the First Assembly

Road to first assembly

Design principles were established

- Use **open-source** options whenever possible
- Encourage **Collaboration** with **Universities**
- The initial goal was of being able to **align**, **approach** and **install** a **vacuum-end coupler**

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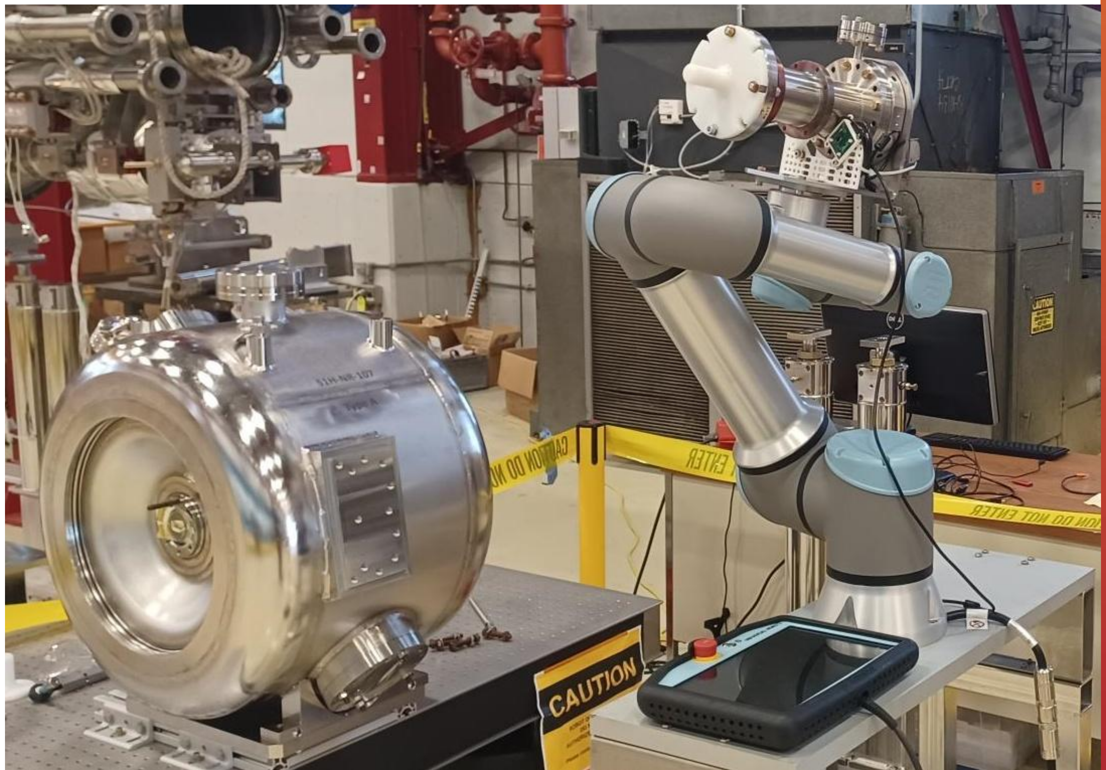
Development of robotic activities coincided with opportunities to assemble SSR2 Cavities

- To show that robotics were a viable path forward, initial test setup + successful coupler-cavity installation were needed



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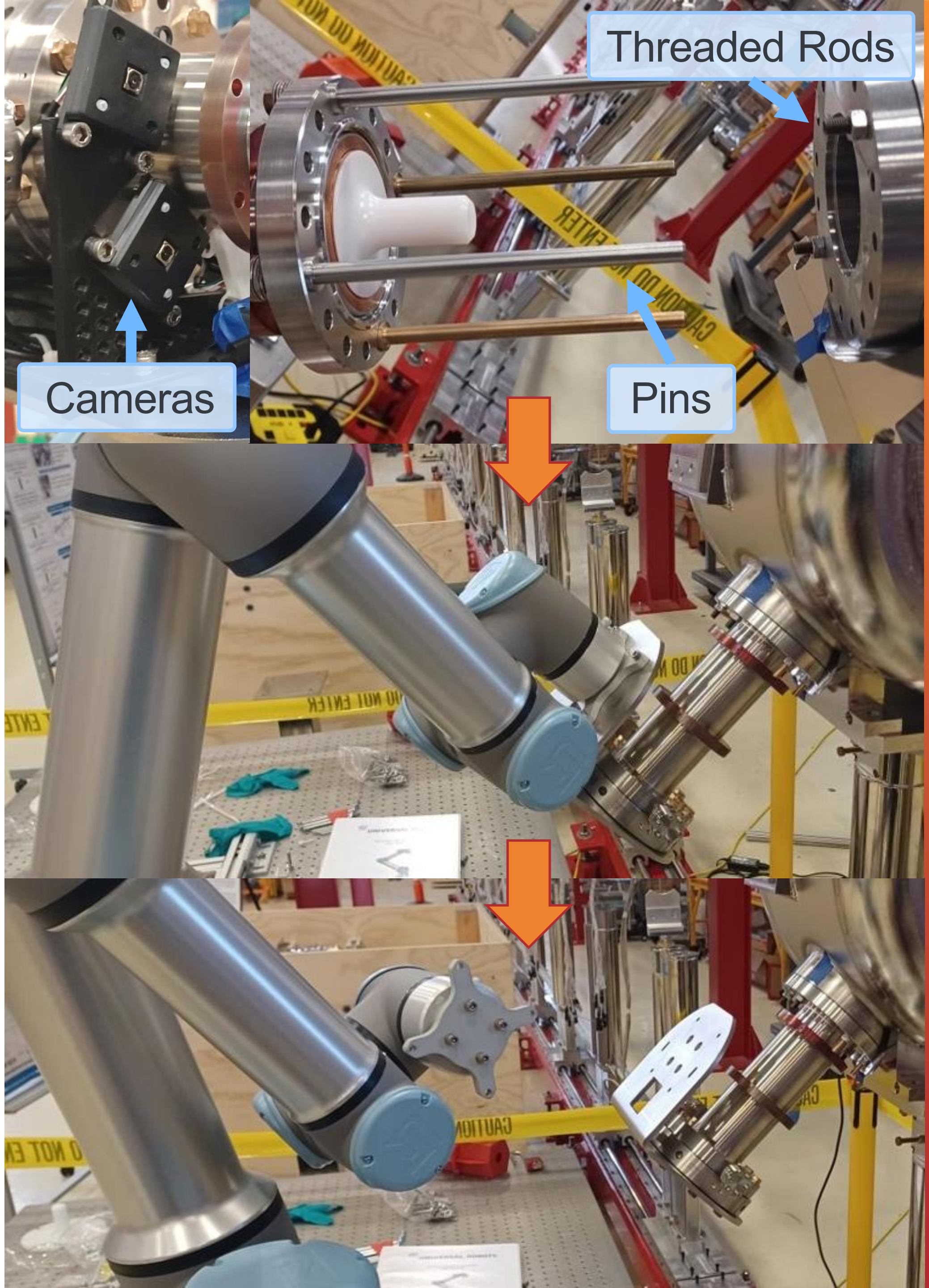
Four alignment processes were prepared

- Visual
- Camera system
- Alignment pins on coupler side
- Threaded rods on cavity side



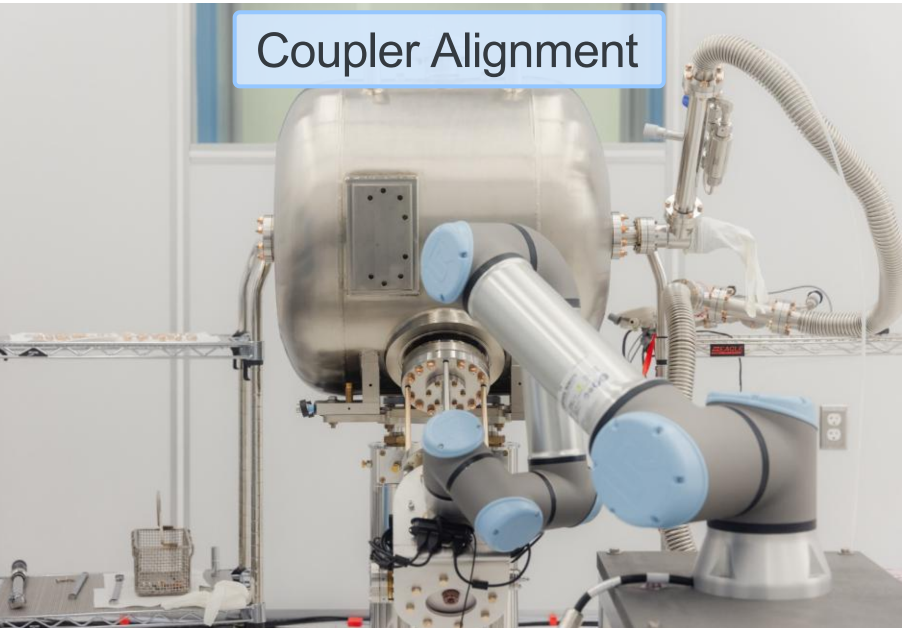
First Cleanroom Assembly

Cleanroom Setup

Positioning

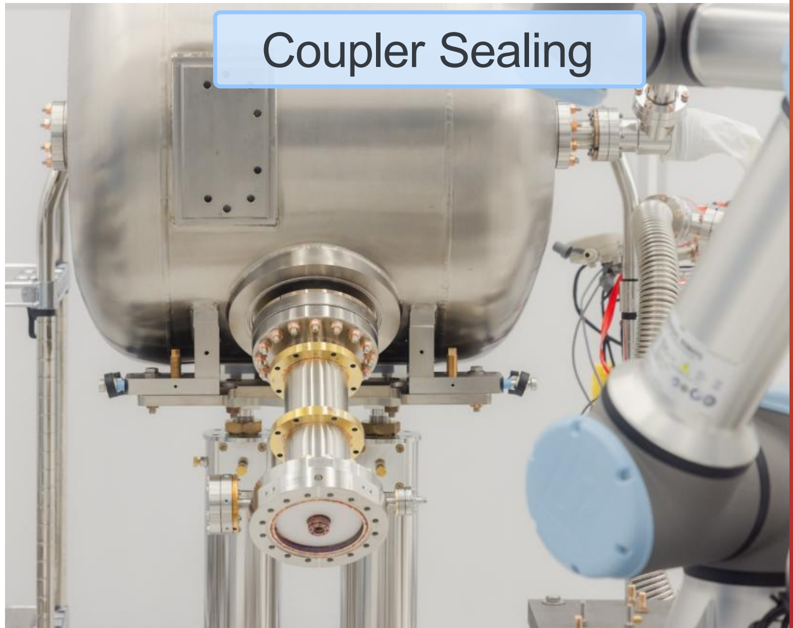
Pre-assembly Setup

Coupler Alignment



Coupler Sealing

Coupler Sealing



First Cleanroom Assembly

ROBERT KIRSCHBAUM
COLIN NARUG
DOMINIC SANTUCCI
TYLER FERMANICH

MATTIA PARISE

Outside the Cleanroom:

TOMMASO AIAZZI, DAMON BICE, TIM RING, JACOPO BERNARDINI, GENFA WU

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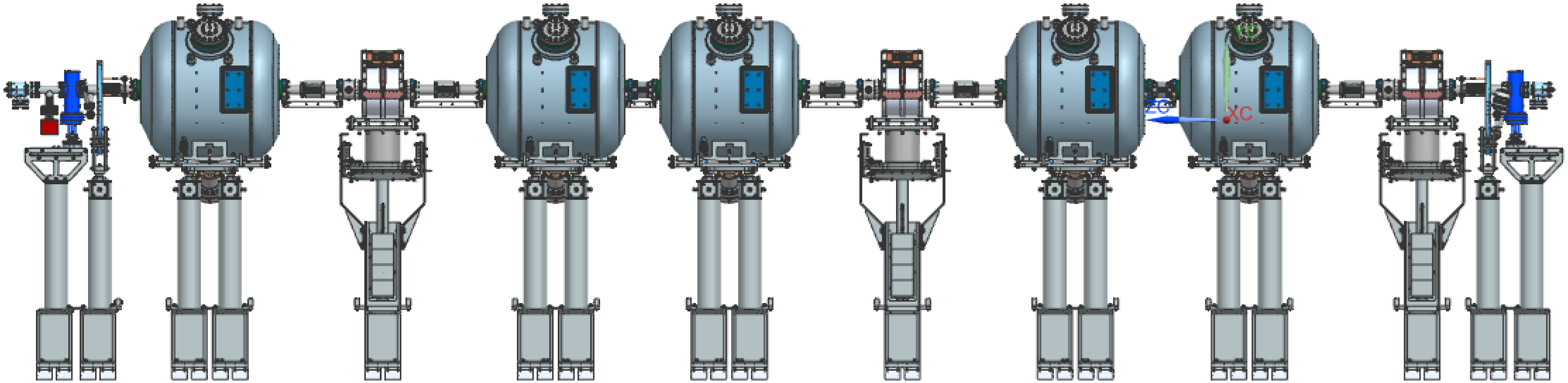
02

The String Assembly

The SSR2 String Assembly for PIP-II



To prepare for the string assembly, additional single cavity assemblies were performed

- Assembly missteps identified and excess equipment removed
  - Alignment pins used for final assembly process
- Bellows assembly and tooling processes developed
  - Using the development test station outside the cleanroom

Component	Quantities
Cavities	5
Magnets	3
Interconnecting Bellows	9
Gate Valves	2

The SSR2 String Assembly

In **September 2025**, first string Cobotic assisted was assembled

The SSR2 String Assembly

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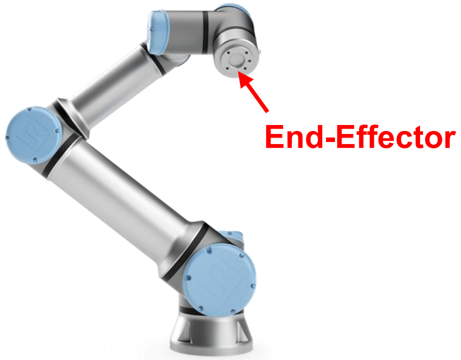
03

The Next Phase: Full Automation

The Hardware



UR16e

Basler a2A4508

Intel RealSense D435i

UR16e collaborative arm

- Carries the RF coupler on the tool flange; 16 kg payload covers coupler + camera bracket.

Intel RealSense D435i

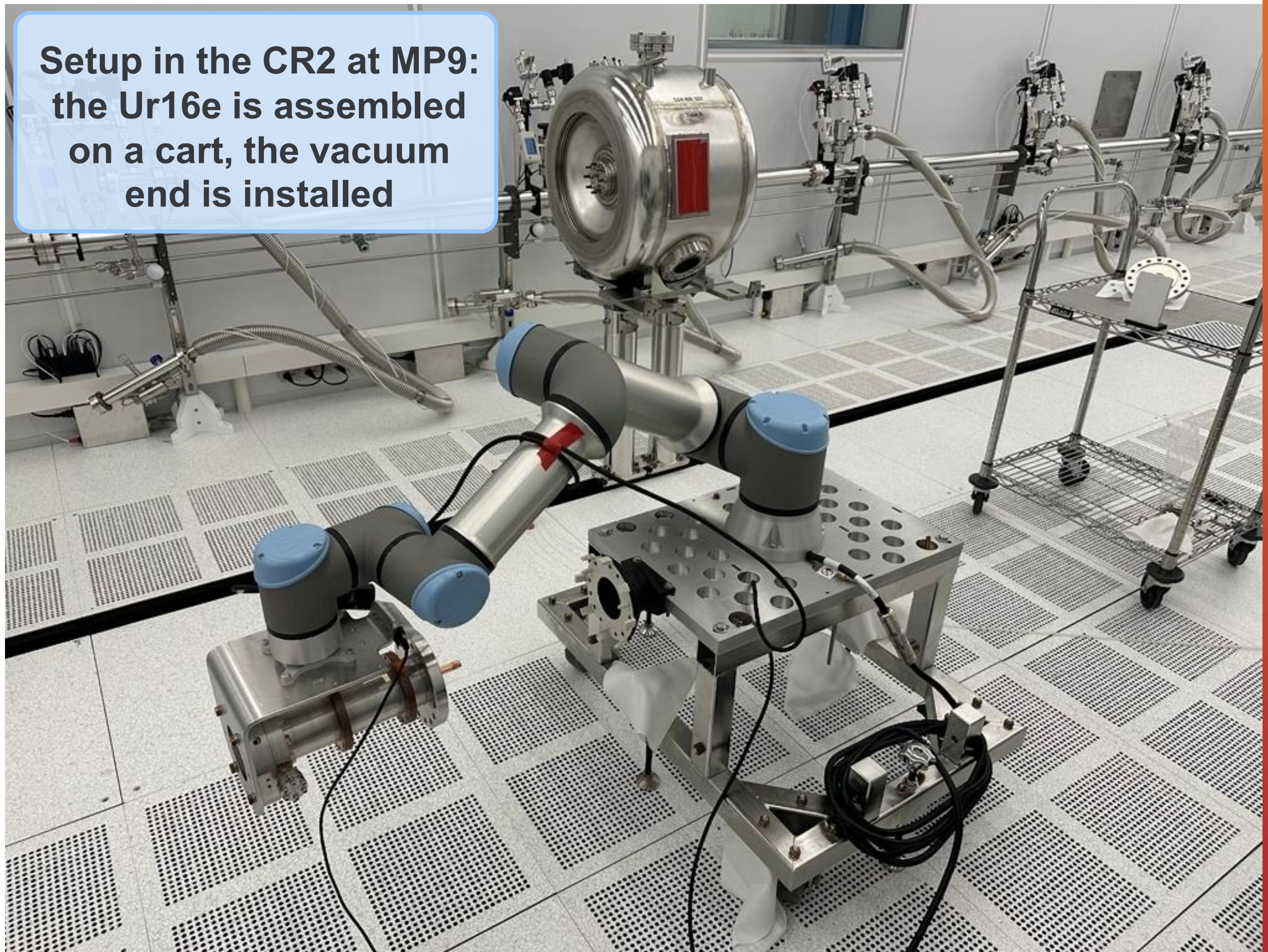
- 1920×1080, calibrated intrinsics.

Basler a2A4508 (18 MP) + Fujinon 16 mm

- Mounted next to the D435i on the wrist; dual-camera mode. Fixed-focus, low FPS, high resolution B&W camera.

Force sensing via the UR16e Cobot

- The cobot measure the force applied at the End-Effector



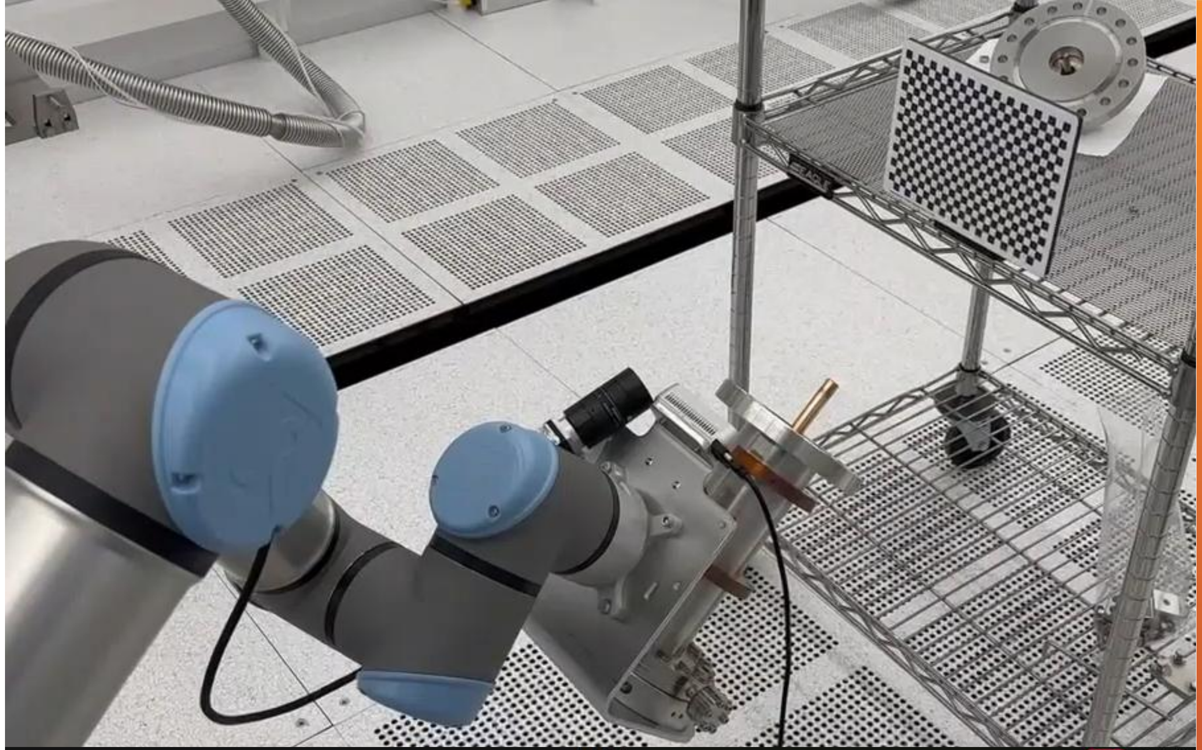
Setup in the CR2 at MP9: the Ur16e is assembled on a cart, the vacuum end is installed

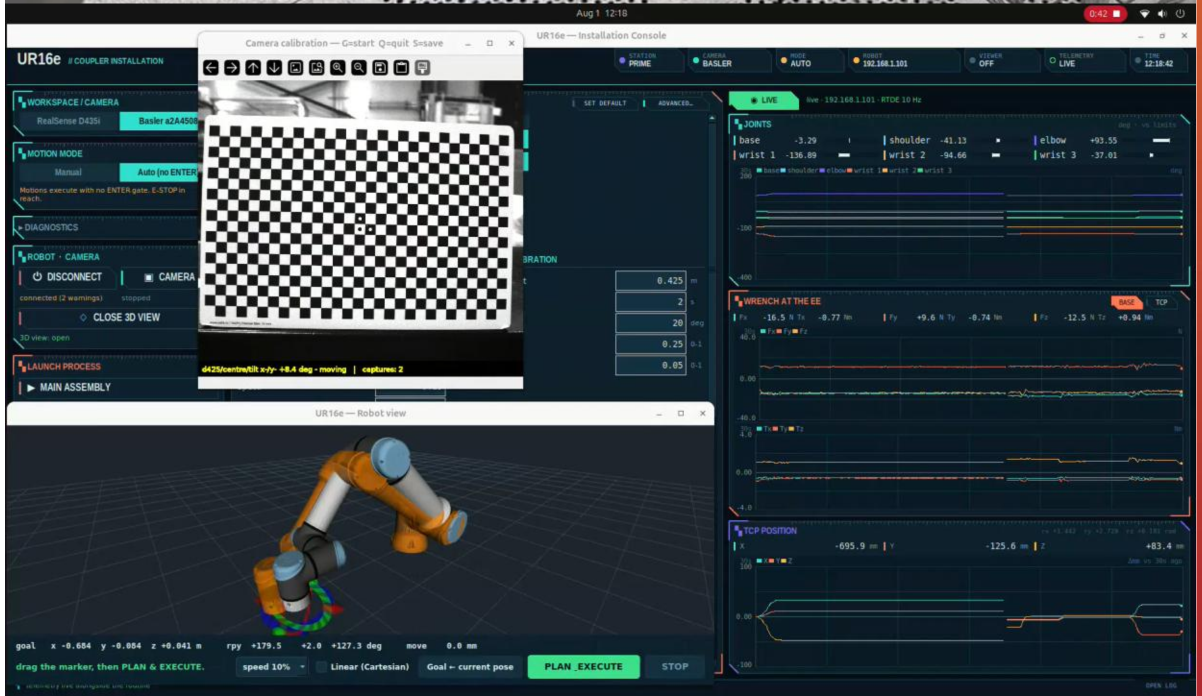
The Pipeline

1 Camera calibration

Intrinsics + hand–eye: fully automatic

- A fixed checkerboard is used to calibrate both the Intrinsics (Camera Distortion) and the Hand-Eye transformation (where the camera is with respect to the End-Effector)
- 54 photos of the checkerboard are automatically taken at different end-effector poses
- Required only once. Duration ~5 minutes.





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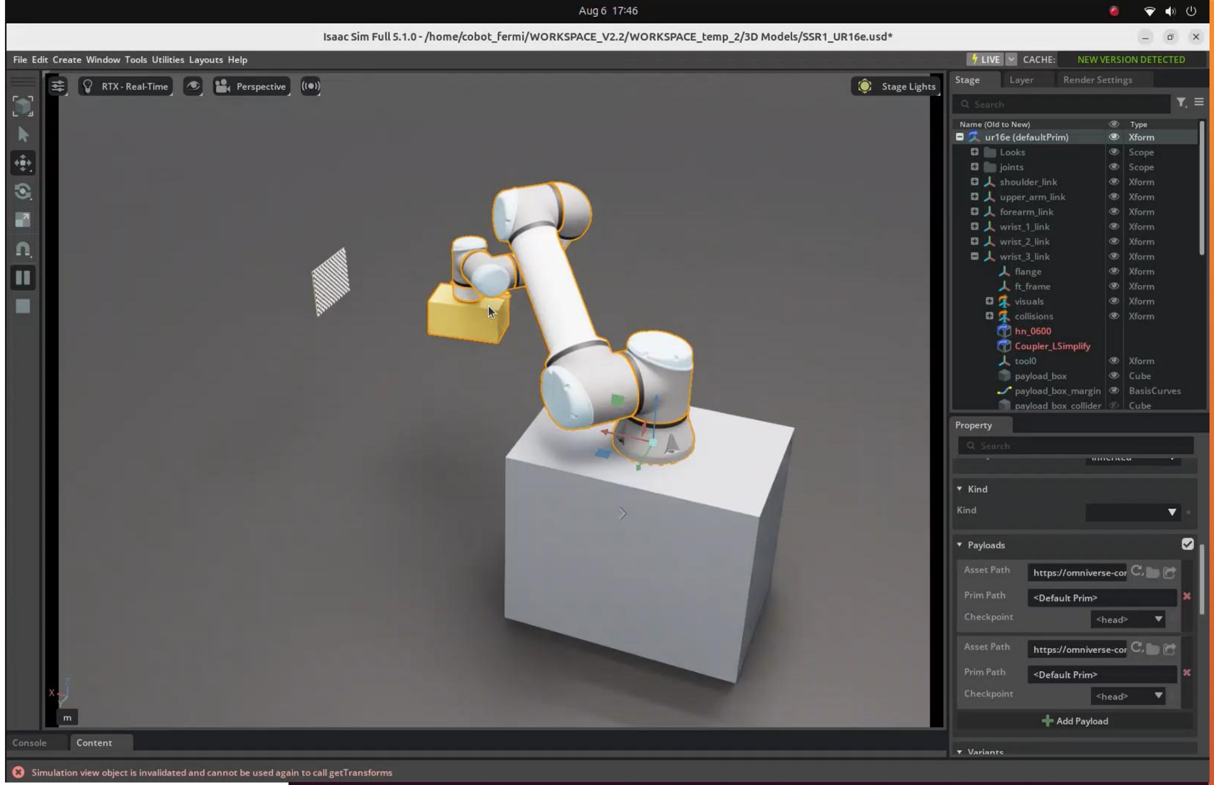


Leveraging Isaac Sim to ensure all 54 poses are reachable without collisions

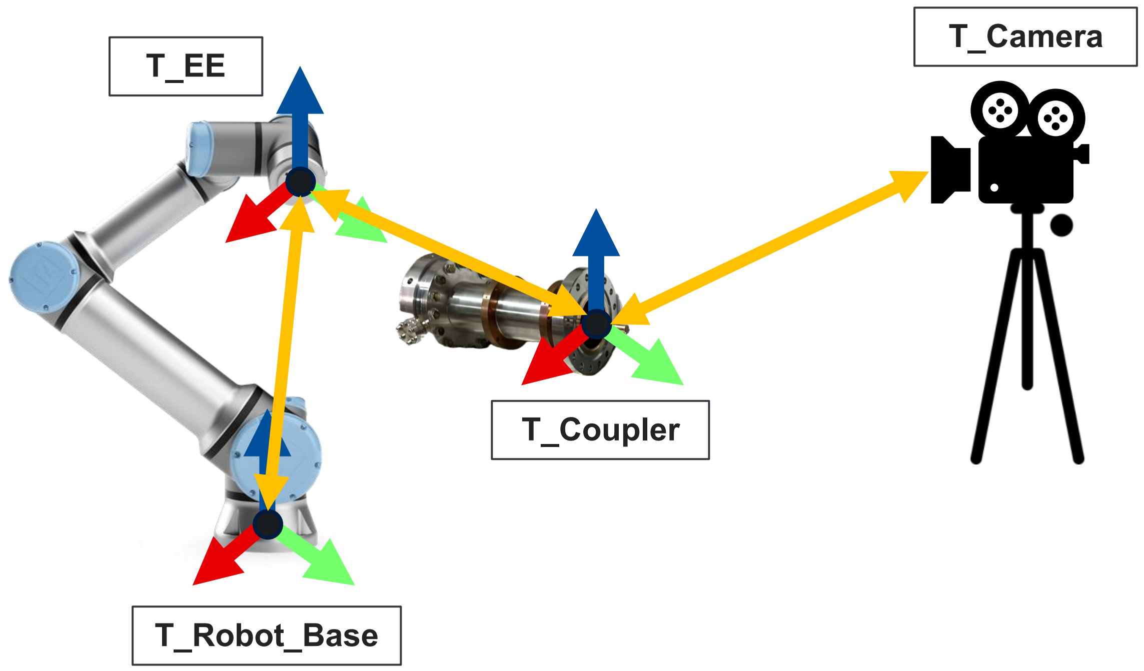
```
==============================================================================
ANSWER 1 — HOW MUCH TILT AND ROLL CAN YOU ASK FOR?
==============================================================================

  Scanned by re-planning the whole session at each value and scoring it
  from this same start pose. These two angles are what conditions the
  hand-eye solve (see pose_plan.py), so a headroom of zero is worth knowing
  and headroom you are not using is worth more.

  tilt  set to 30 deg -> 54/54 poses
        30 deg is the most that keeps every pose — it is already at the limit.
        the next rung, 35 deg, drops to 46/54.
        15:54/54  20:54/54  25:54/54  30:54/54  35:46/54  40:39/54  45:37/54

  roll  set to 60 deg -> 54/54 poses
        YOU CAN ASK FOR MORE: every pose still succeeds up to 75 deg.
        the next rung, 90 deg, drops to 50/54.
        15:54/54  30:54/54  45:54/54  60:54/54  75:54/54  90:50/54

  (each rung reads value:reached/planned. The pose COUNT changes with the
   angle because duplicate poses are dropped — that is the plan, not a bug.)

==============================================================================
ANSWER 2 — WHERE SHOULD THE BOARD GO?
==============================================================================

  THE BOARD IS FINE WHERE IT IS — every pose succeeds from this placement. Do not move it.

  (117 s)
==============================================================================
```

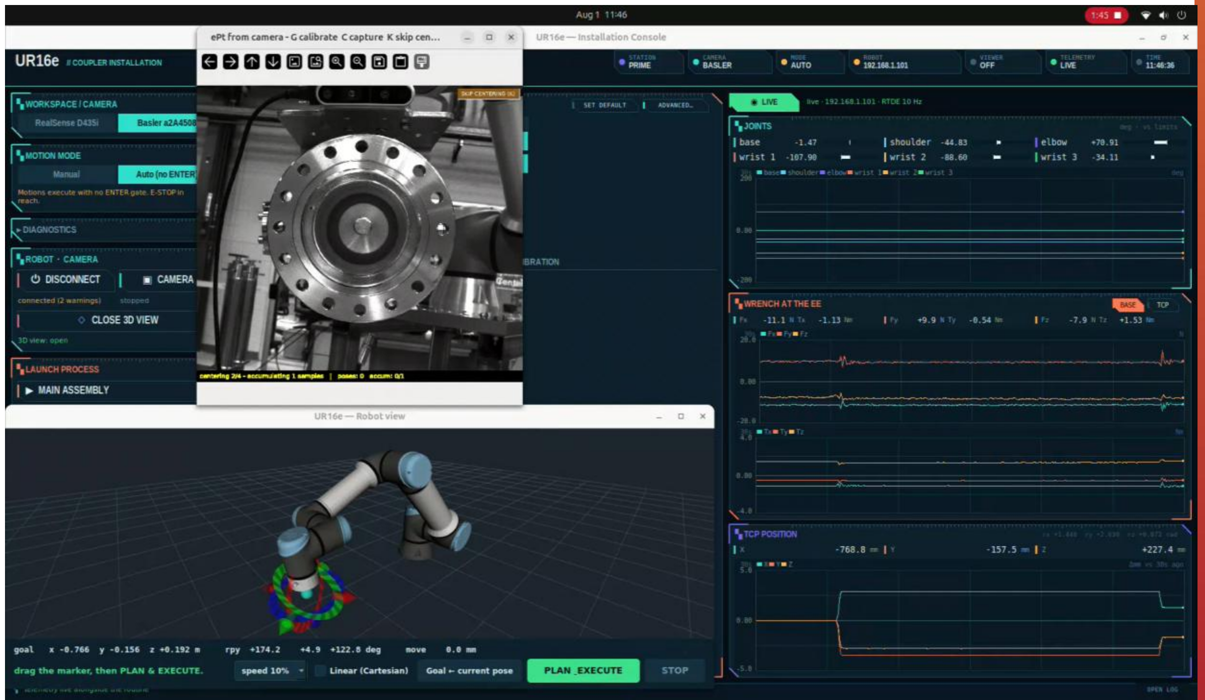
The Pipeline

2 Coupler calibration

Where is the coupler relative to the end-effector?

- Using a fixed camera, we detect the position and orientation of the coupler flange
- The cobot moves the coupler, and we collect several photos at different poses
- By solving Ax = yB we can reconstruct the position of the coupler with respect to the end-effector
- Required each assembly: ~5 minutes



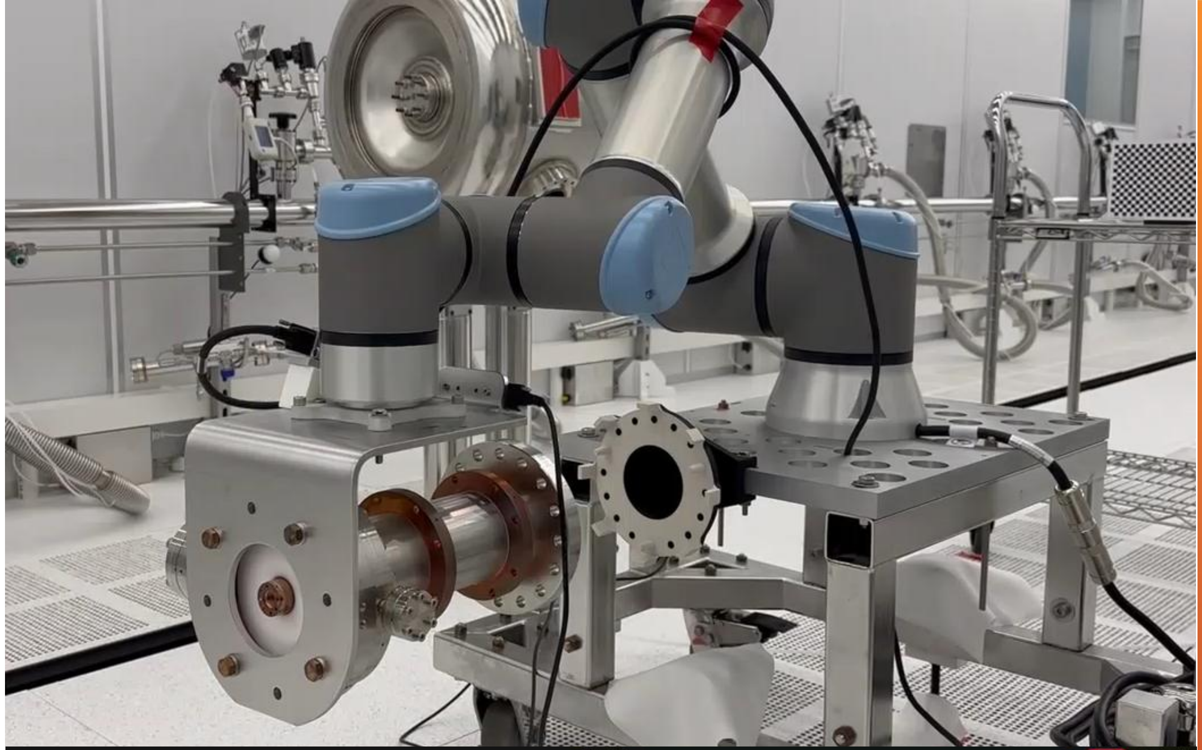


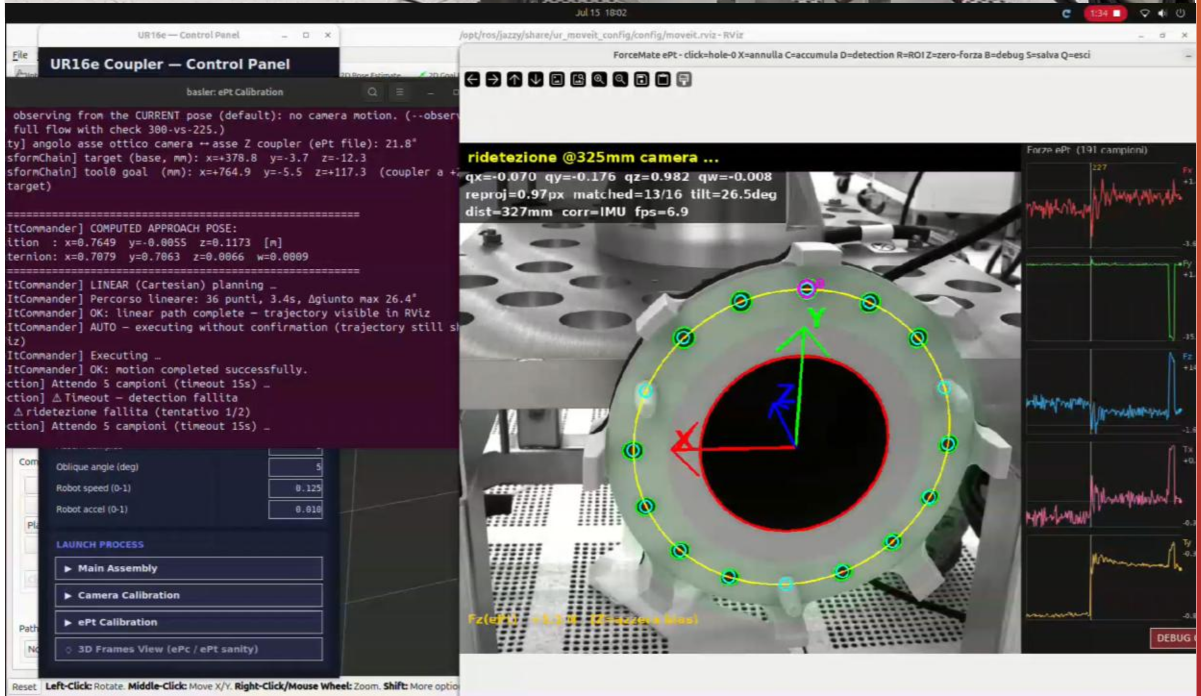
The Pipeline

2 Coupler calibration

Where is the coupler relative to the end-effector?

- Using the camera, we detect the position and orientation of a fixed calibration flange
- The cobot aligns the coupler to the calibration flange
- Fine tuning of the coupler position is performed
- The coupler position and orientation with respect to the end-effector are calculated
- Required each assembly: ~2 minutes





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- Using the camera we detect the position and orientation of a fixed calibration flange
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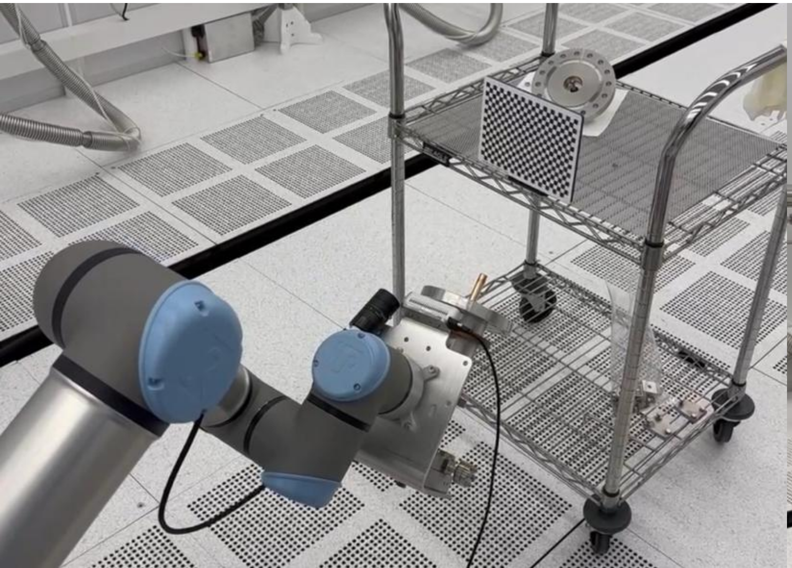
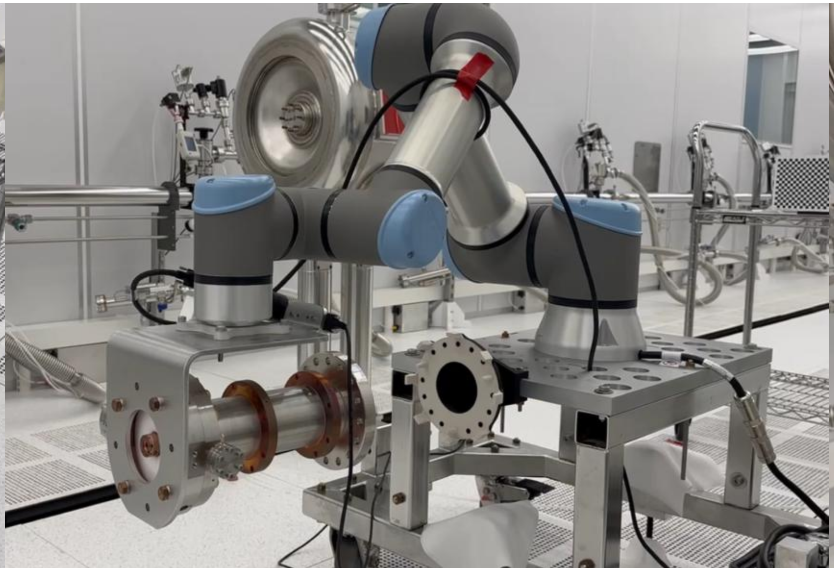
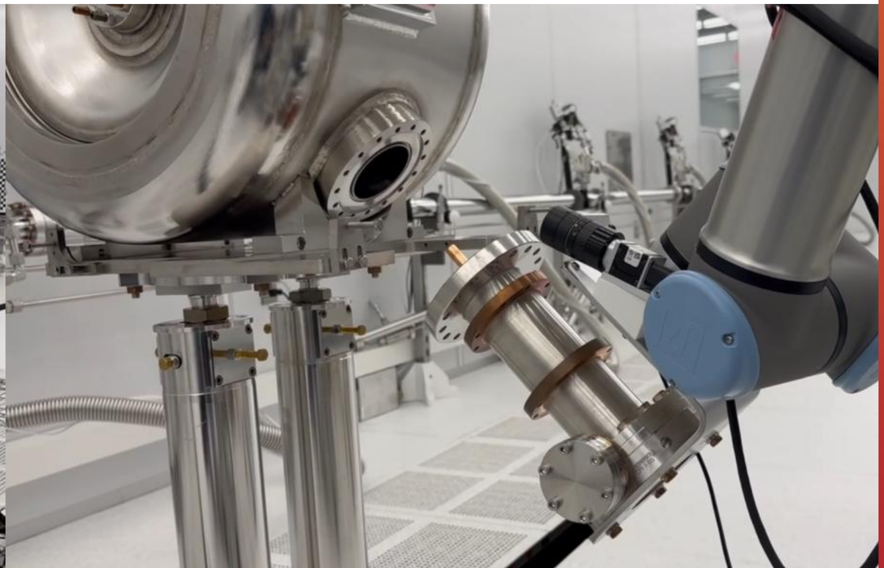
3 Main assembly

Coupler onto the SSR cavity flange

- Coaxial align at a distance, settle, accumulate
- 4 oblique orbits → fuse → frozen target
- Approach close position → 0 mm, one gate per step
- Force-seat: push tiny steps until Force goal is reached







The Detection

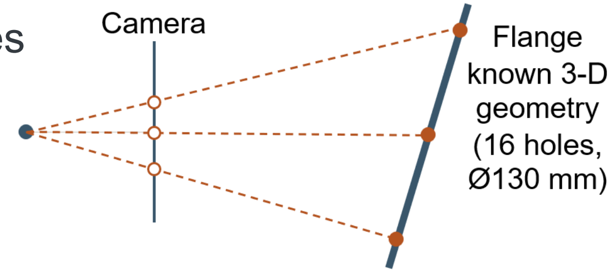
1) OWLv2 (Open-World Localization v2, released by Google research, 2023)

- Zero-shot local AI model: find the flange and crop it. Then it selects the holes inside the crop. Simple gate for size and aspect ratio filters out unwanted features.

2) SAM2 (Segment Anything Model 2”, Meta AI 2024, open weights)

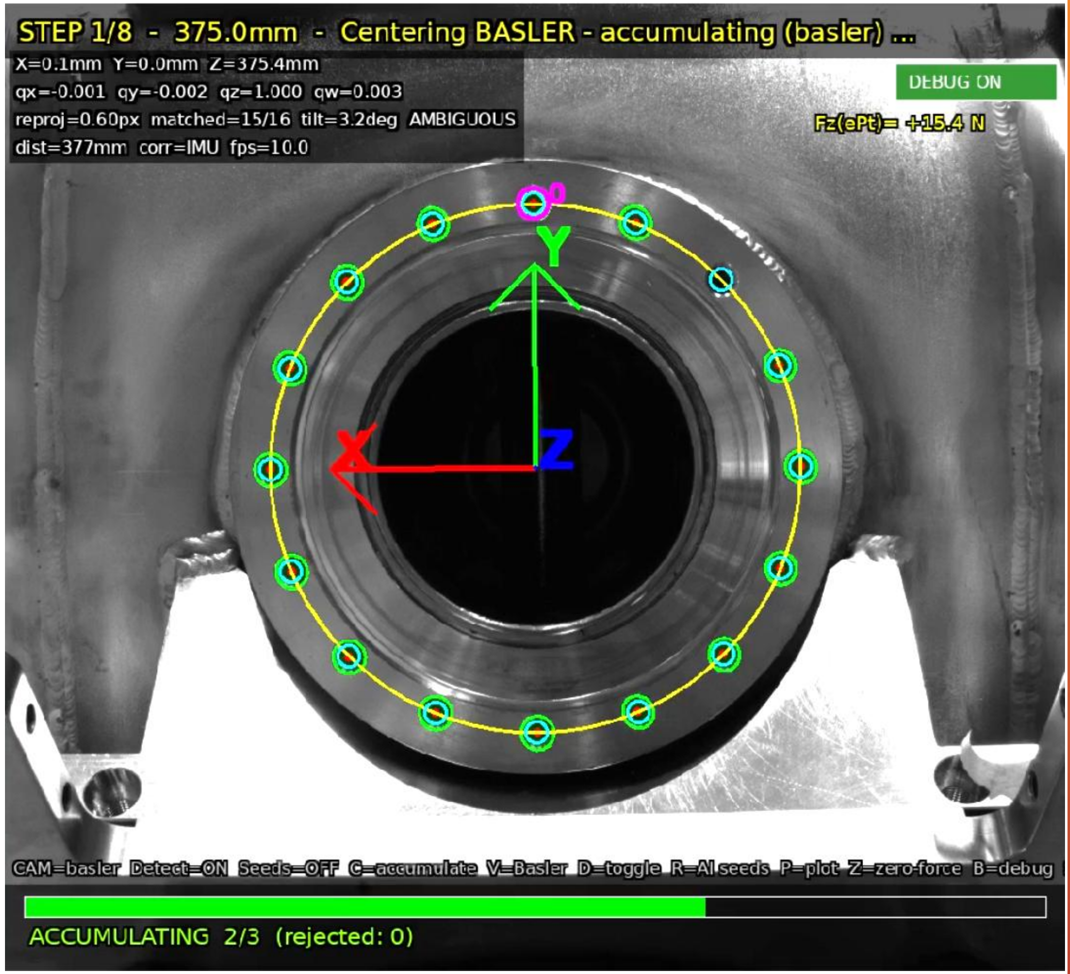
- SAM 2 is an AI tool that can instantly outline and track any object in both pictures and videos

- We create a mask of the image that exclude everything but the bolt holes and ellipses are fitted. The center point is computed onto the image



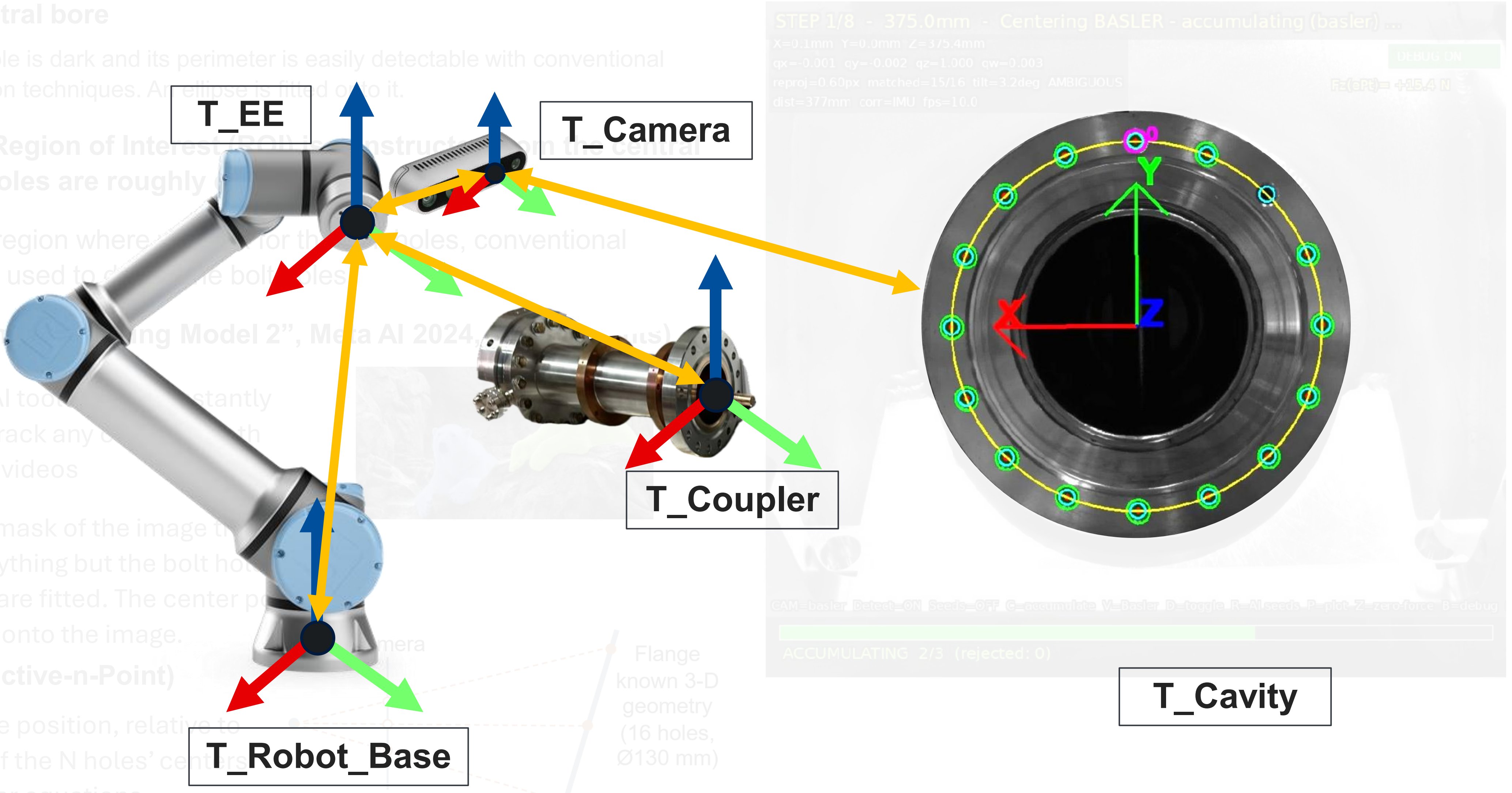
3) PnP (Perspective-n-Point)

- Calculates the position, relative to the camera, of the N holes’ centers solving N linear equations



Computer Machine Vision: holes are segmented and fitted with ellipses; centers are used to solve PnP problem resulting in the final pose computation

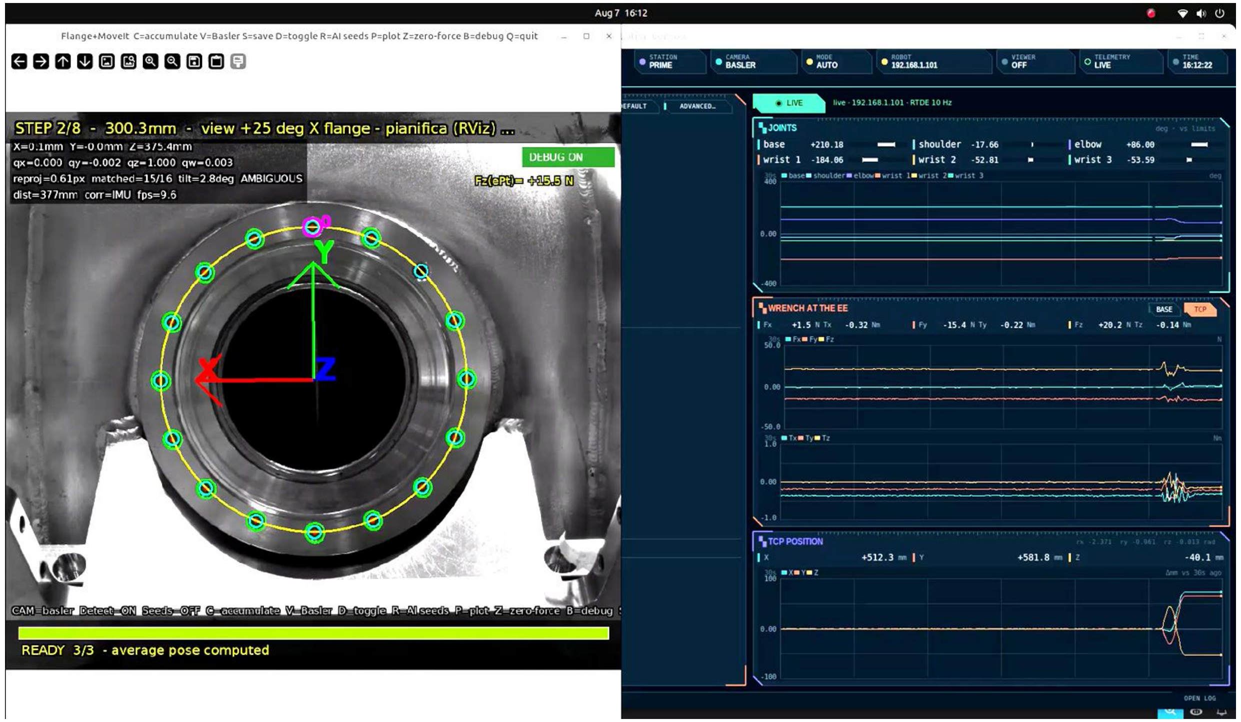
The Detection

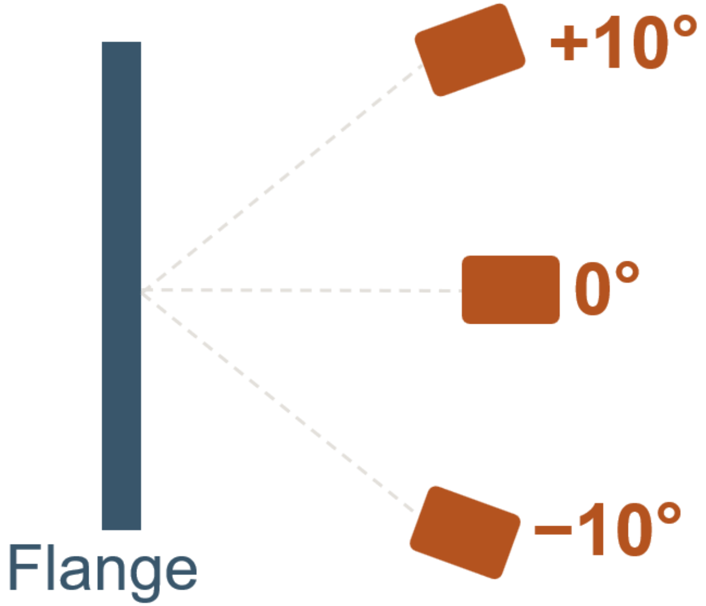


Multi-View Fusion

Single view is weak

- Using 1 image from 1 direction is not sensible enough to compute the pose (position and orientation) of the cavity flange with sub-mm/sub-degree precision
- Multi-View image fusion was exploited to reduce system complexity as it can be achieved using 1 camera only
- The camera is moved around the detected object and the estimated pose is "fused"*



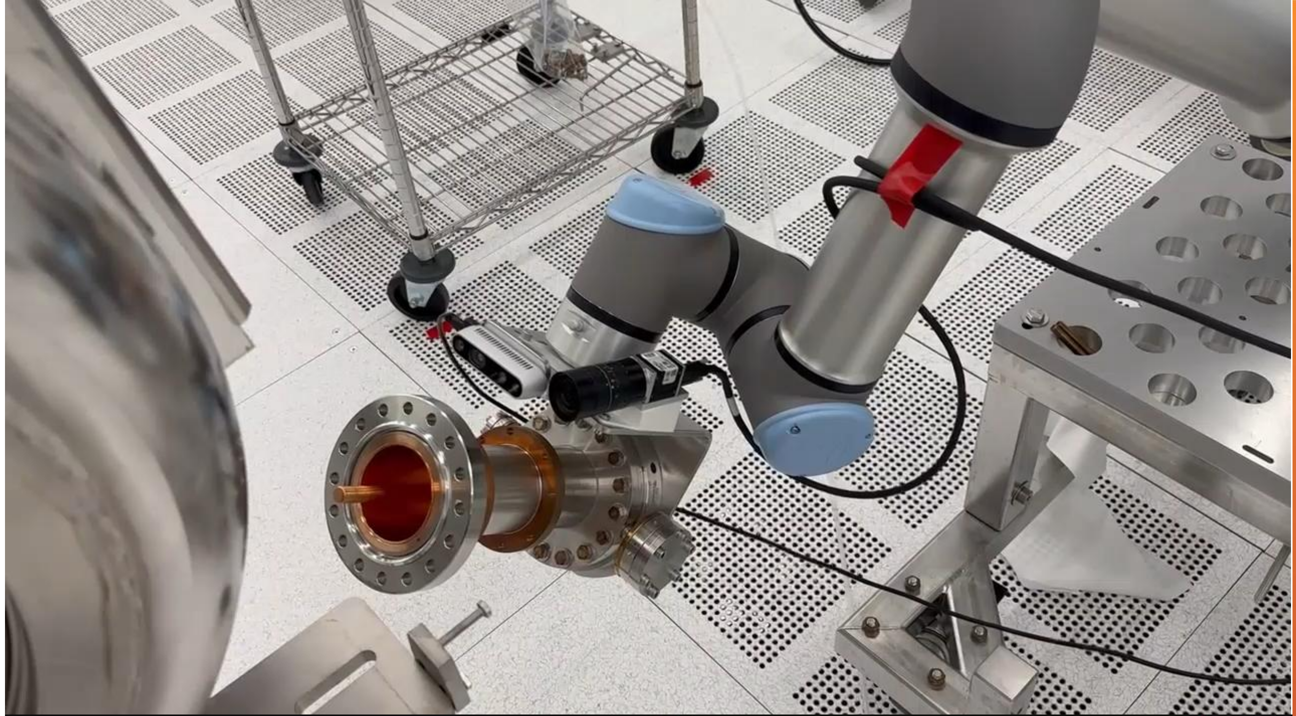


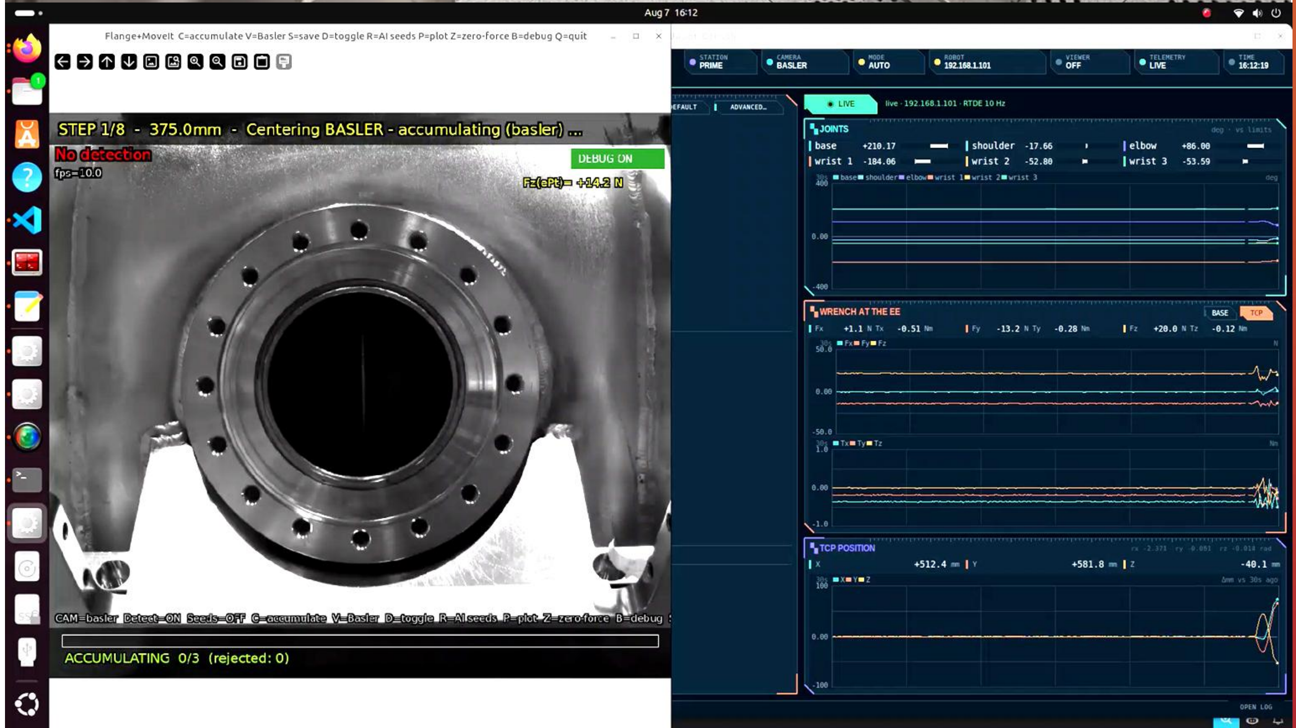
* F. L. Markley et al., Quaternion Averaging

Main assembly

Duration ~ 1 minute + manual fastener assembly

0. Detection initial accumulation on the flange
1. Coaxial alignment: coupler centred on the flange axis at a distance, settle 1-3 s
2. Frontal accumulation (5 samples) + 4 oblique orbits ±10-20° about flange X and Y (auto-fallback ±5° if a view sees < 10 holes)
3. Fusion of up to 5 estimates → final target; divergence gates stop the sequence on systematic error
4. Final approach with pose FROZEN: 200-100 mm → 0 mm, one plan-RViz-ENTER gate per step, straight-line Cartesian motion
5. Force-seat: while |Fz(ePt)| < 20-100 N advance 0.5 mm along the target axis, up to 10 mm past the estimated plane then STOP with a warning





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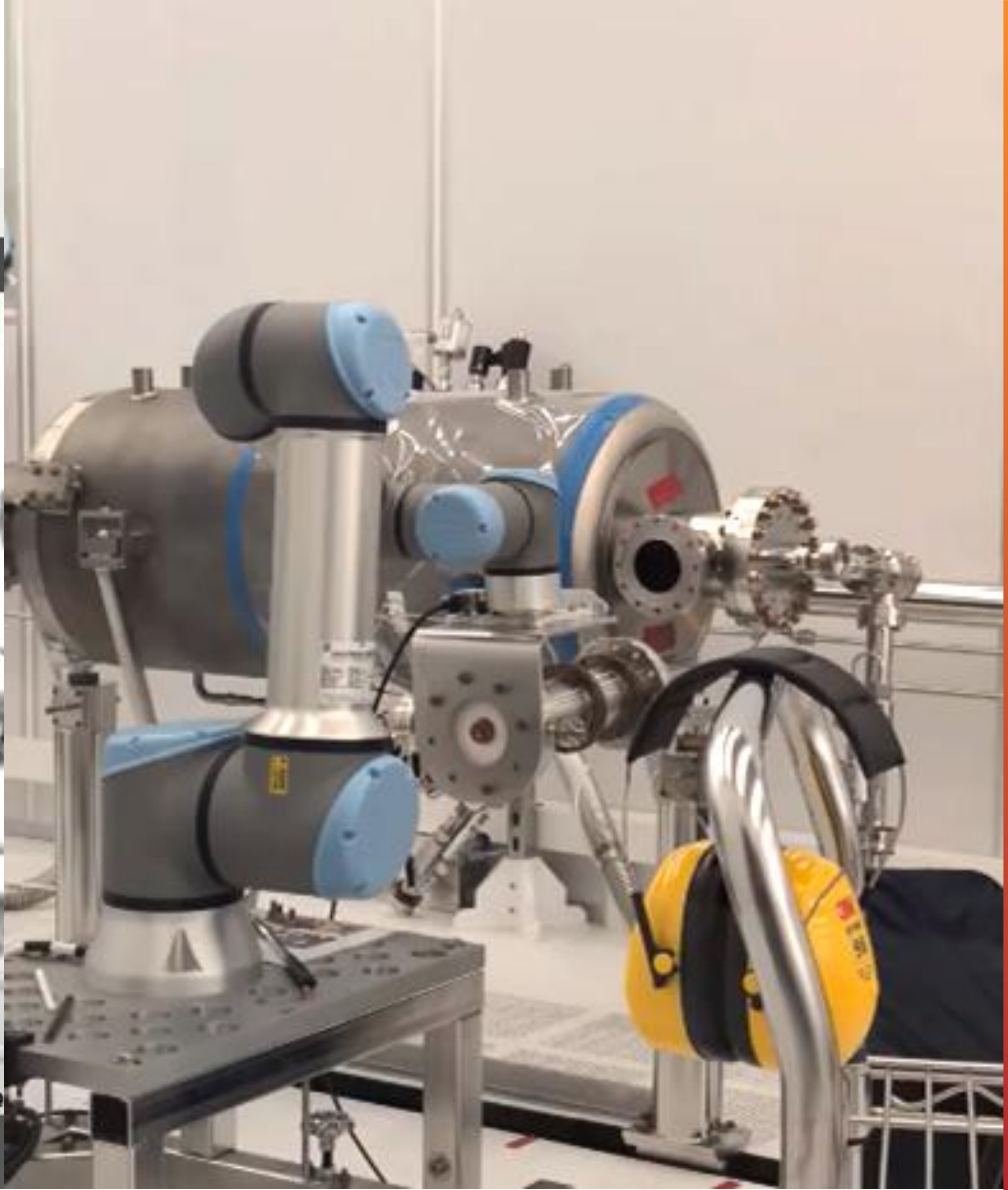
HB 650 MHz Assembly

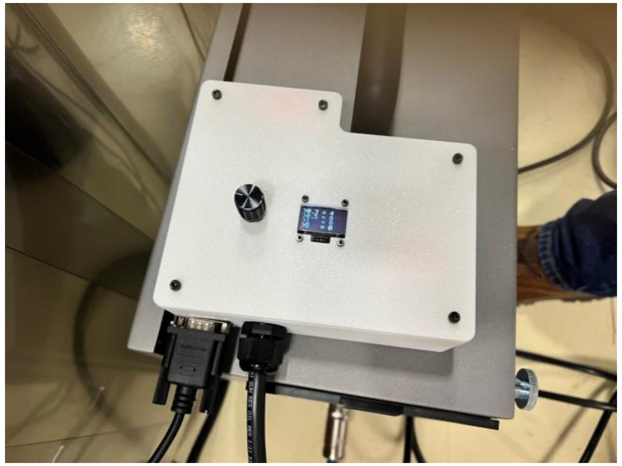


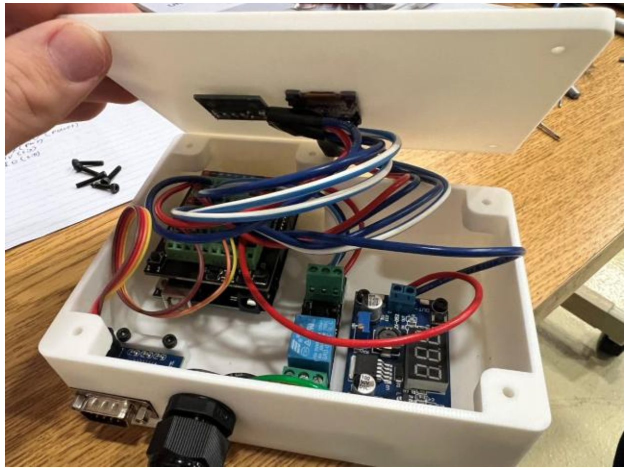
Hardware Cleaning

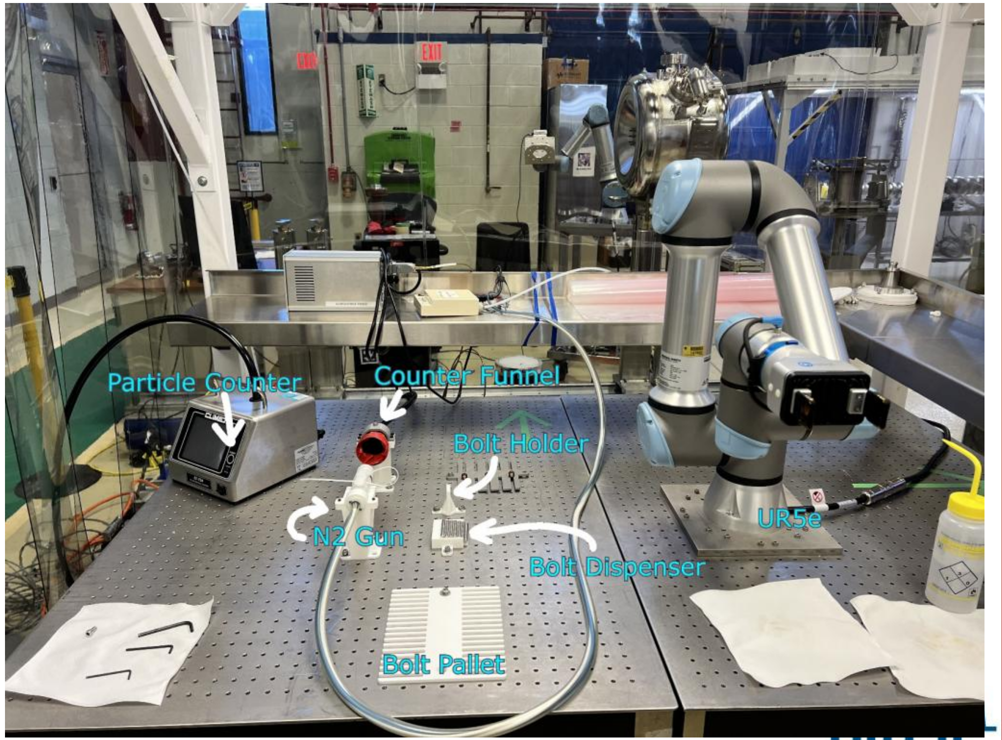
System designed by B. Whitlock of NIU

Before assembling cavities in cleanroom, hardware must be cleaned.

- Cleaning hardware is a time-consuming process, but is relatively simple process
  - Complications in cleaning come from human error
  - Biggest barrier for automation is reading Particle Counter
- Custom control box made to read Particle Counter
- Parts have been able to be cleaned in test setup

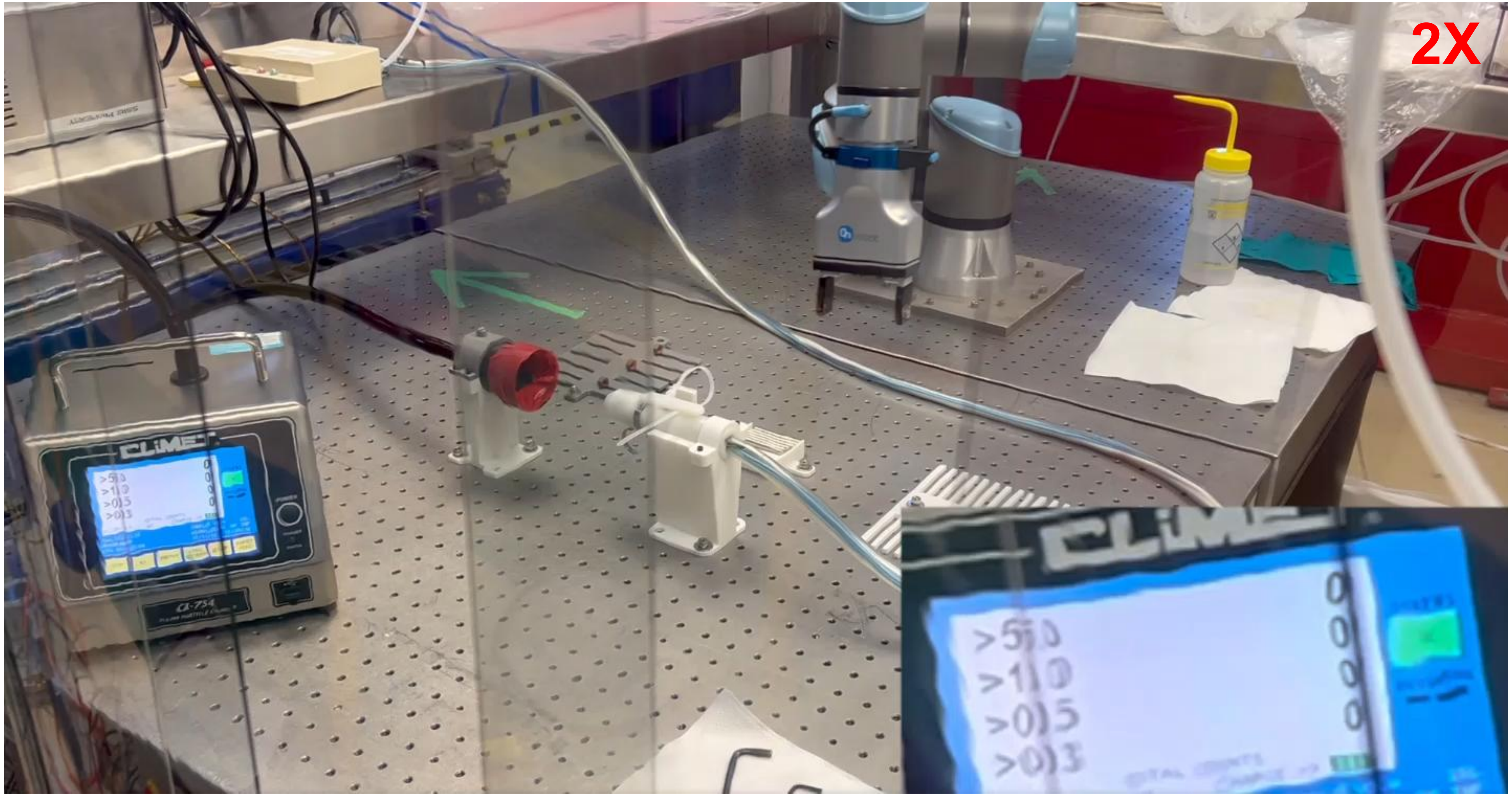






Hardware Cleaning – Prototype Setup

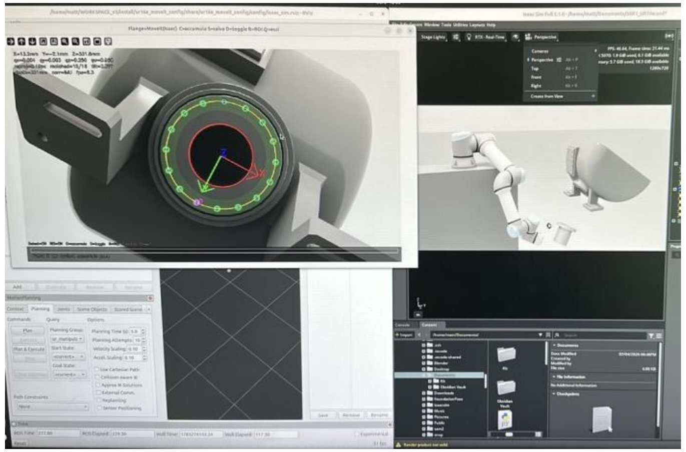
Prototype system works in cleaning hardware

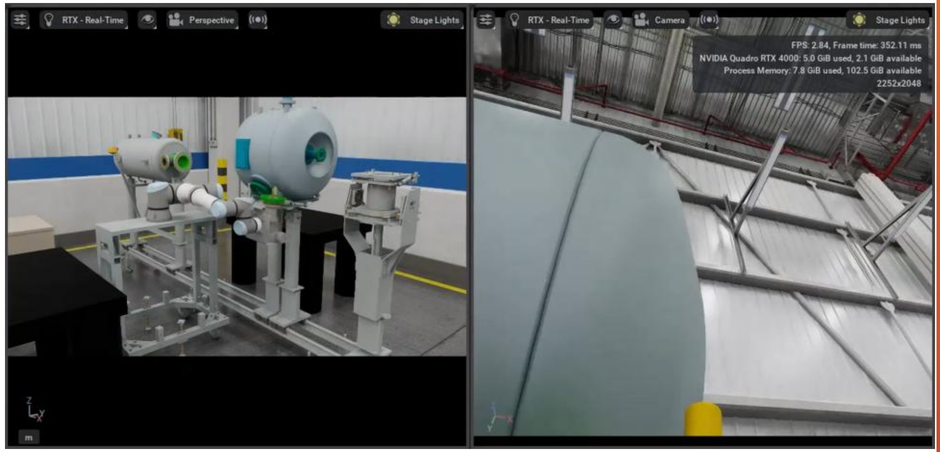


Conclusions

- Leveraging 3 years of platform development, we have pioneered a novel, markerless coupler-to-cavity alignment and assembly system. This breakthrough eliminates physical targets, setting an unprecedented standard for, precision, and contamination-free cleanroom assembly.

- All the processes and techniques presented today have been successfully replicated in **NVIDIA Isaac Sim**. We are now ready to deploy **AI training** models to further optimize and refine these assembly procedures.





- We are setting the new standard for **SRF cobotic cleanroom assembly**. Because we develop **custom**, tailored **automation architectures** instead of relying on rigid, turn-key industrial products, we have **zero technical limitations**. Owning this proprietary methodology allows us to seamlessly adapt, customize, and deploy our cutting-edge workflows to any high-precision task requiring cobotically assisted **inspection**, **ultra-clean assembly**, or **automated quality control**.

Special Thanks

Work presented was a result of a large collaboration between many groups

Engineers/Scientists

- **T. Aiazzi, C. Narug, D. Passarelli**, **G. Wu**, **J. Bernardini**

Cleanroom Team and Machinists

- **D. Bice**, **R. Kirschbaum**, **T. Fermanich**, **M. Battistoni**, **M. Chlebek**, **T. Ring, D. Santucci**
- University Partners
- **A. Ciaramella**, **A. Vivai** [UniPi]
- **N. Giffen**, **J. Imburgia, B. Whitlock, C. Denton, I. Salehina, J. Ryu** [NIU]

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