Fermilab | U.S. DEPARTMENT OF ENERGY | Office of Science

Computer Vision solutions for Robot-assisted technology in SRF assembly at Fermilab

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Outline

Automation for SRF application

- Identified technologies – existing R&D
- Roadmap
- Industry survey

Ongoing activities at Fermilab, APS-TD

- Reverse engineering using touchless techniques
- HBCAM for alignment monitoring

Why automation for SRF applications?

Manual operations in cleanroom

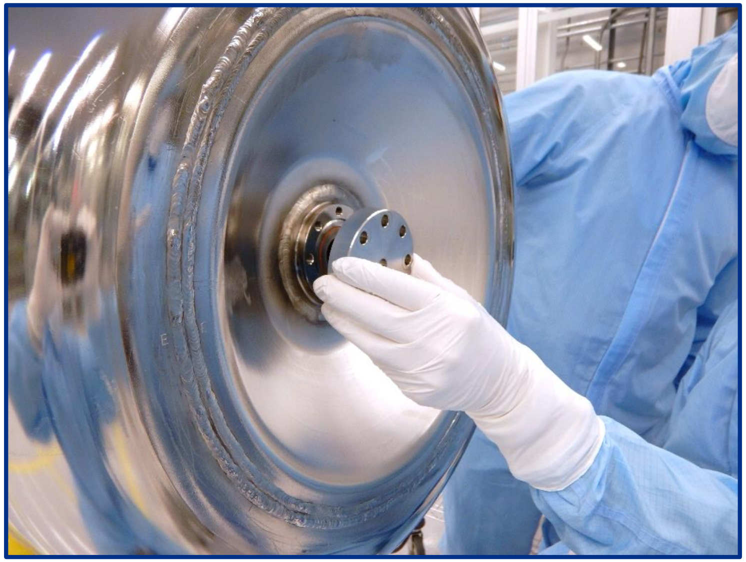
- Operators are among the main sources of contamination
- Performances highly depend on operator ability, experience and commitment

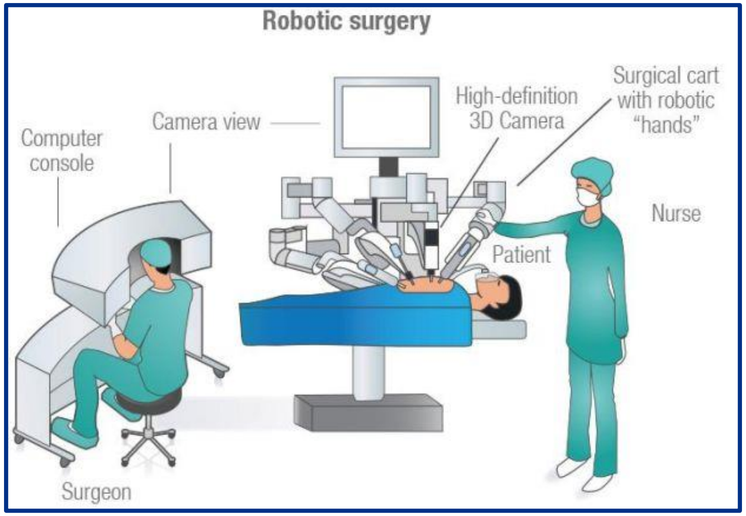
Robotically assisted operations

- Reduce the risk of chemical and particulate contamination during critical assembly steps
  - Handling and positioning components in proximity of beamline aperture
- **Make the assembly process more efficient and systematic, in order to obtain repeatability in SRF performances**

"People or systems? To blame is human. The fix is to engineer"

R.J. Holden





Roadmap

Implement automation and robotically assisted operations in the frame of SRF assemblies

- Identify technologies available on the market
  - Computer vision techniques
  - Manipulation, positioning
- SRF activities breakdown and technology implementation
  - Identify the ones that are suitable to be automated
  - Adapt identified techniques to selected activities
- Demonstrate effectiveness of Robot-assisted technology
  - Preparation and assembly of a single SRF unit
  - Scale it up to a more complex system

Identify technologies available on the market

Government and Research
Low volume
ISO 4-6
µm and mm precision
1 ~ 250kg payloads.
Custom solutions:
- NASA, Telescope alignment
- CERN, Cavity alignment, rel-time monitoring in the LHC
- SACLAY, cleanroom robot

Photovoltaic
High volume, Highly automated
ISO 6-8
0.1 ~ 1 mm accuracy
1 ~ 250kg payloads
Automated with:
Cartesian, Scara , Delta and Articulated arm

Biotech and Pharmaceutical
High volume, Highly automated
ISO 4-7
~ 1 mm accuracy
Range of payloads
Automated production cells
Fully automated camera inspection

Nanotech, Semiconductor
High volume, Highly automated
ISO 1-3
nm ~ µm accuracy
<<1kg payloads
Ultra-high precision alignment (piezoactuators) and positioning(interferometer) system

Optics (lens alignment)
High volume
ISO 2-4
0.01 ~ 1kg Payloads
µm and sub- µm precision
Highly automated, active alignment technology
High precision positioning system

Aereospace
High volume
ISO 5-9
Industrial applications that require cleanroom, robots, turbine, satellite assembly
Wide range of payloads
µm and mm precision

Identified technologies – Positioning

Positioning systems

- **Robotic arms**
  - Joints actuated by step motors
- **Precision motions**
  - Hexapod – parallel 6DOF motion
  - Translation stages

Robotic arm installing mirror segments for the James Webb Space Telescope - NASA

This is a mature technology with several commercial products available, also cleanroom compatible

Identified technologies – Computer Vision

Target based

- **6D pose estimation**
  - Array of 1D magnetometers that are triangulated by magnets in the 3D space
- **Optical systems**
  - Cameras equipped with laser light source to detect the position of reflective targets – HBCAM
  - Motion Capture System (MOCAP),
  - **TARGETS**
    - High reflective index glass balls, Stickers, Projected light

Target free – touchless optical systems

- Non contact inspection
  - Structured light
  - Point clouds
- Model reconstruction
  - Comparing the 2D or 3D model with the ideal CAD

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To be verified if compatible with cleanroom

Cleanroom compatible

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HBCAM for position monitoring

To be verified if compatible with cleanroom

Cleanroom compatible

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Existing R&D references

6D Pose estimation

Deep ChArUco: Dark ChArUco Marker Pose Estimation

Benchmarking 6D Object Pose Estimation for Robotics

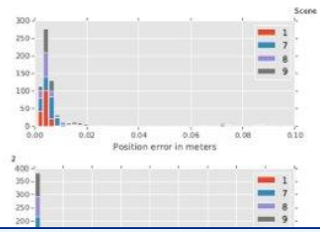
DenseFusion: 6D Object Pose Estimation by Iterative Dense Fusion

PoseCNN: A Convolutional Neural Network for 6D Object Pose Estimation in Cluttered Scenes

6DoF Pose Estimation for Industrial Manipulation based on Synthetic Data

Does Vision Work Well Enough for Industry?

https://pdfs.semanticscholar.org/ab8a/3fa39ef0aa2643511aa4bd8e9ade817bef7b.pdf

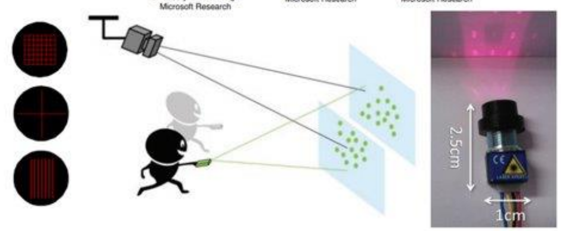


German Aerospace Center
Institute for Artificial Intelligence, University of Breme

Projected pattern for 6 DOF reconstruction

Kinectrack: Agile 6-DoF Tracking Using a Projected Dot Pattern

Paul McIlroy (University of Cambridge, Microsoft Research) · Shahram Izadi (Microsoft Research) · Andrew Fitzgibbon (Microsoft Research)

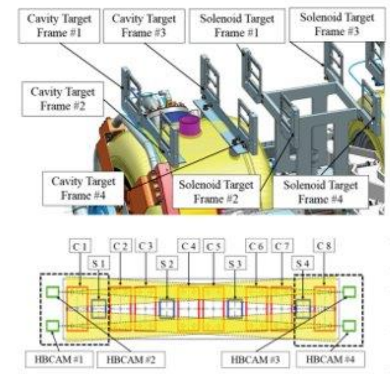


6.2 Comparison to Vicon

In figure 8 we show a 140-frame test sequence of Kinectrack compared to the Vicon tracking system, which is taken as ground truth. Translation accuracy was found to be 1.86 cm RMS error, with RMS error in rotation of 1.29°. This shows that at a greatly reduced cost, setup time, and with only a single camera, adequate tracking can be achieved when compared to a commercially available and expensive multi-camera system.

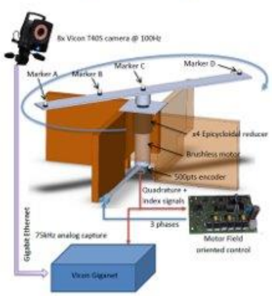
University of Cambridge,
Microsoft Research, UK

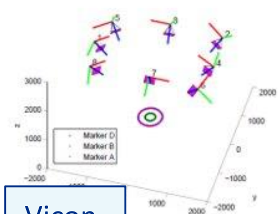
Alignment with BCAM



CERN, Fermilab

Motion capture system



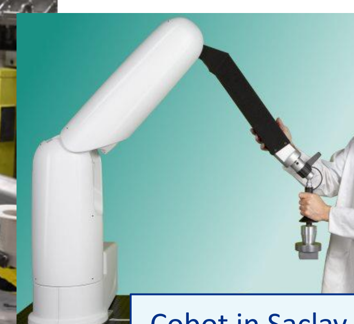


Vicon

3. Results for Static Experiments

Figure 3 shows the Vicon markers represented in the Robot frame thanks to the transformation *H* found with the Least-square method explained in Section 2.1. It can be seen that both point clouds perfectly align. The transformation is properly estimated with a mean squared error of 0.224 mm after frame alignment. In Figure 4, it can be seen [illegible] projection error is less than 0.255 mm for all markers. The Mean Average Error (MAE) is 0.153 mm and Root Mean Squared Error (RMSE) is 0.154 mm.

TIM Robot
CERN



Cobot in Saclay

THE NEW CLIC MAIN LINAC INSTALLATION AND ALIGNMENT STRATEGY

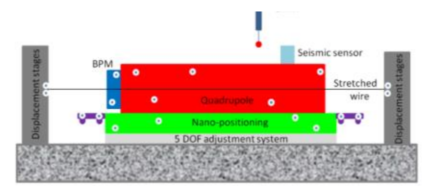
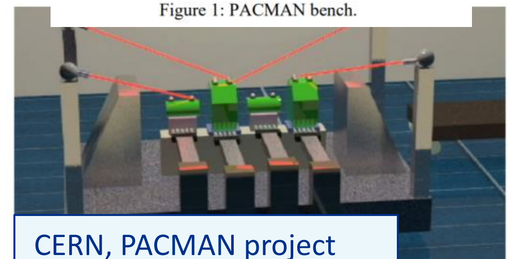


Figure 1: PACMAN bench.



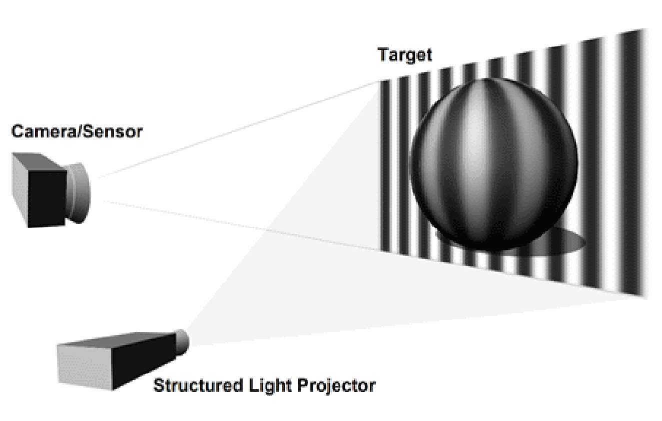
CERN, PACMAN project

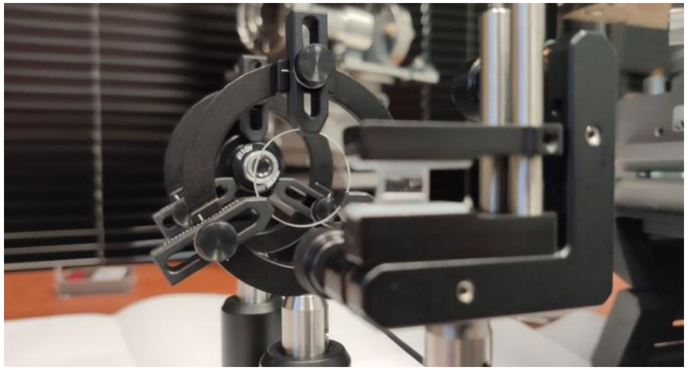
Ongoing activities at Fermilab, APS-TD

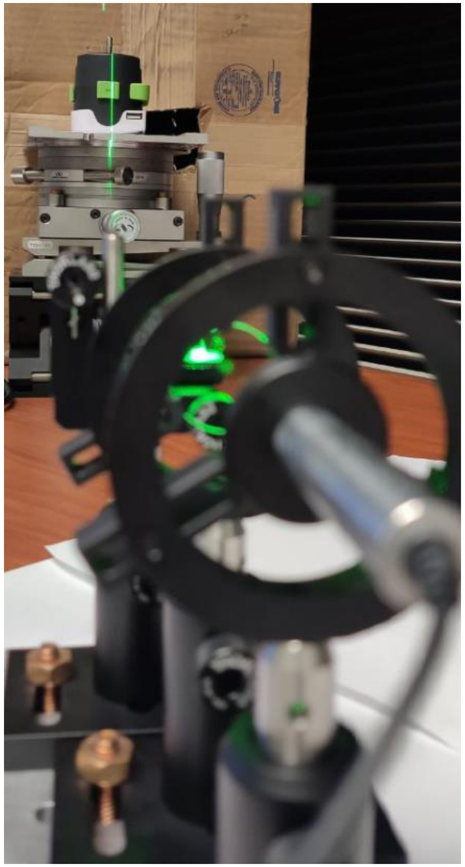
- **Target-less computer vision** compatible with cleanroom
- **HCBAM for position monitoring:** an example of computer vision applied to SRF

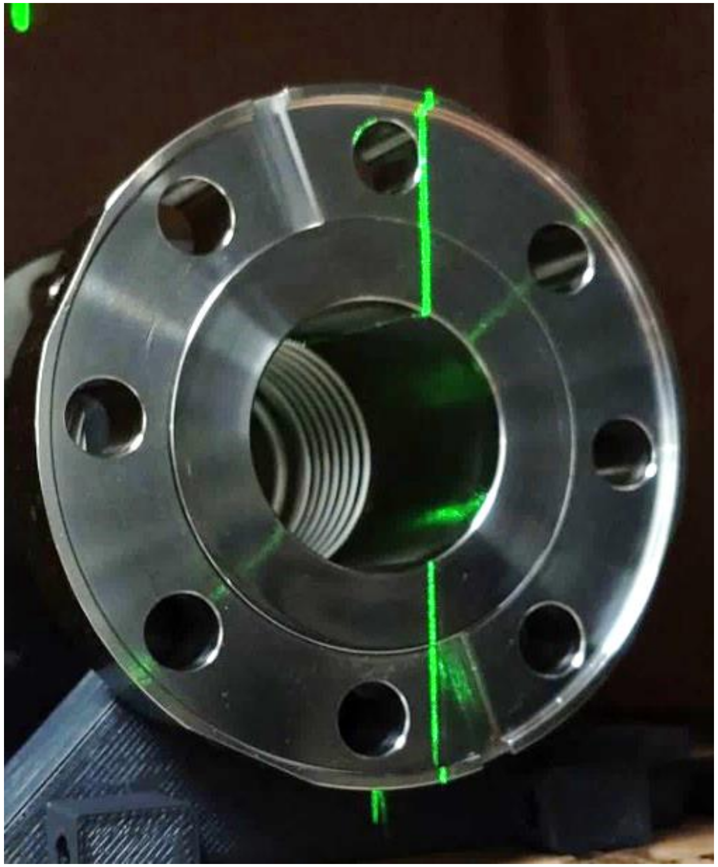
Structured light and stereo camera

- XYZ positioning of a bellow
- A green 5mw laser projector
- An optical setups to focus and modify the shape of the laser combined with a stereo camera

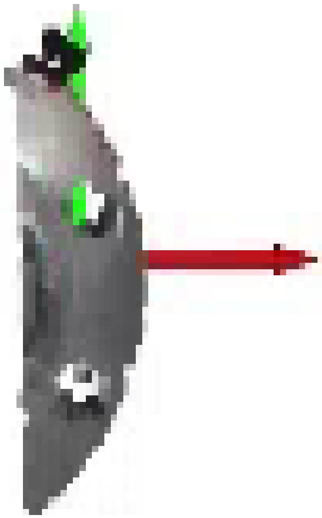




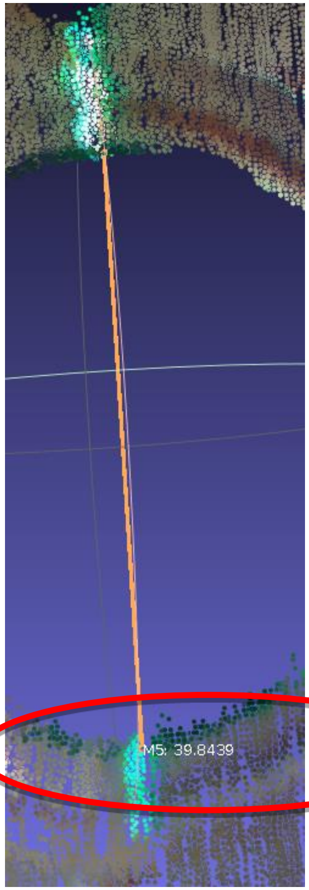


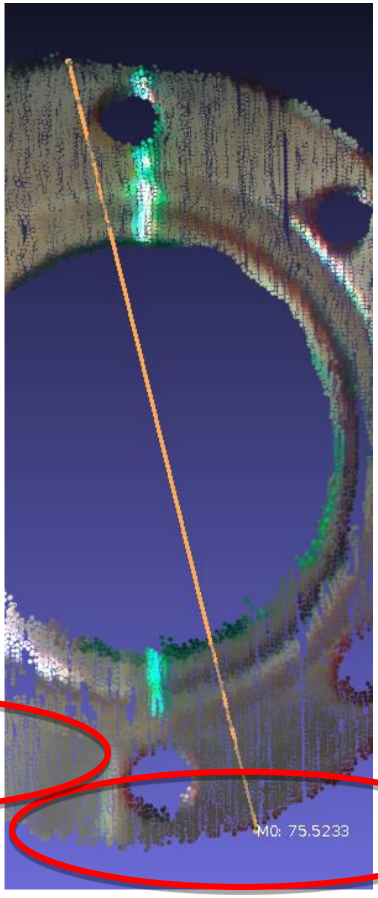


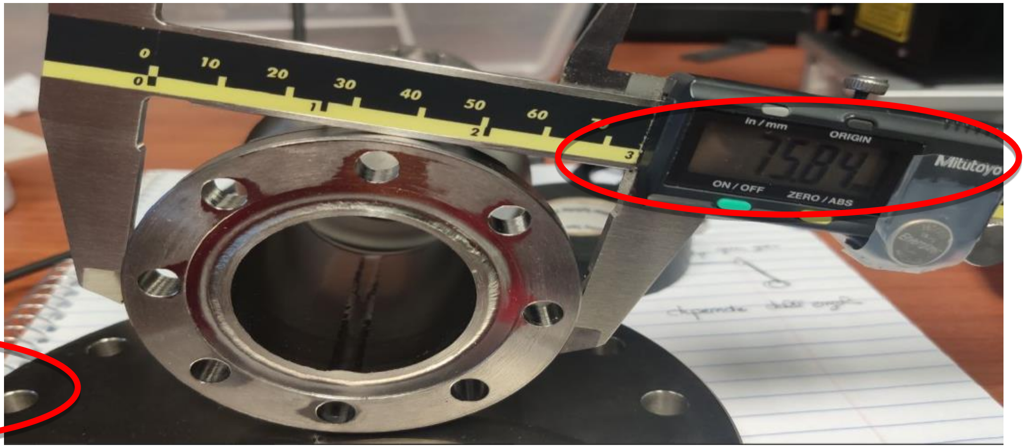
Structured light – Real time image reconstruction



Structured light – Quality assurance applications



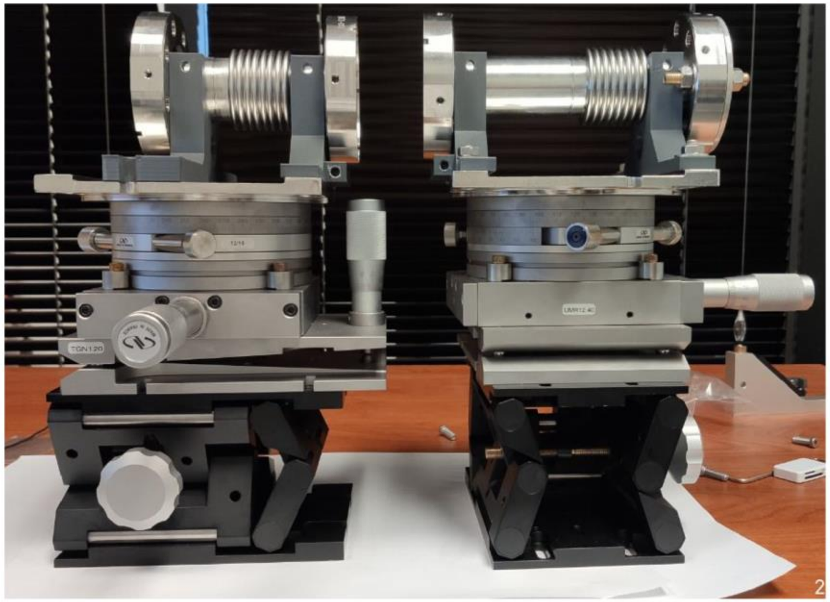


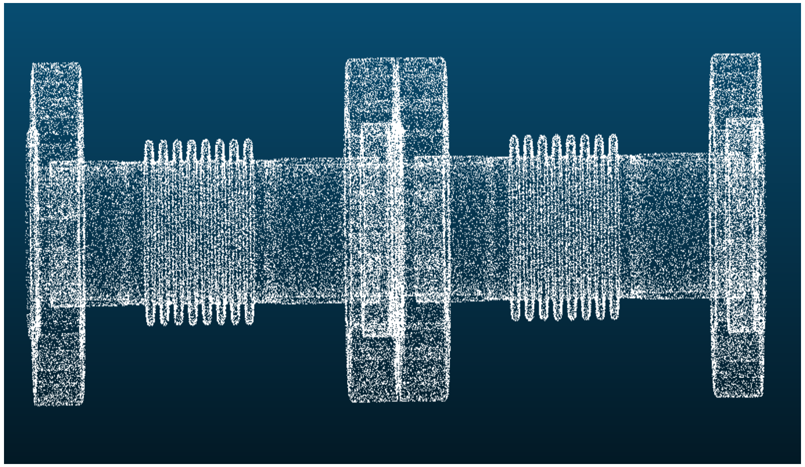


Pose reconstruction with point clouds - laser

Point cloud technique combined with pose reconstruction

- The output of the stereo sheet of light technique is a point cloud
  - 3D scanning for model reconstructions
- Reproduce a real time point cloud of the object
- Compute the transformation to align the bellows





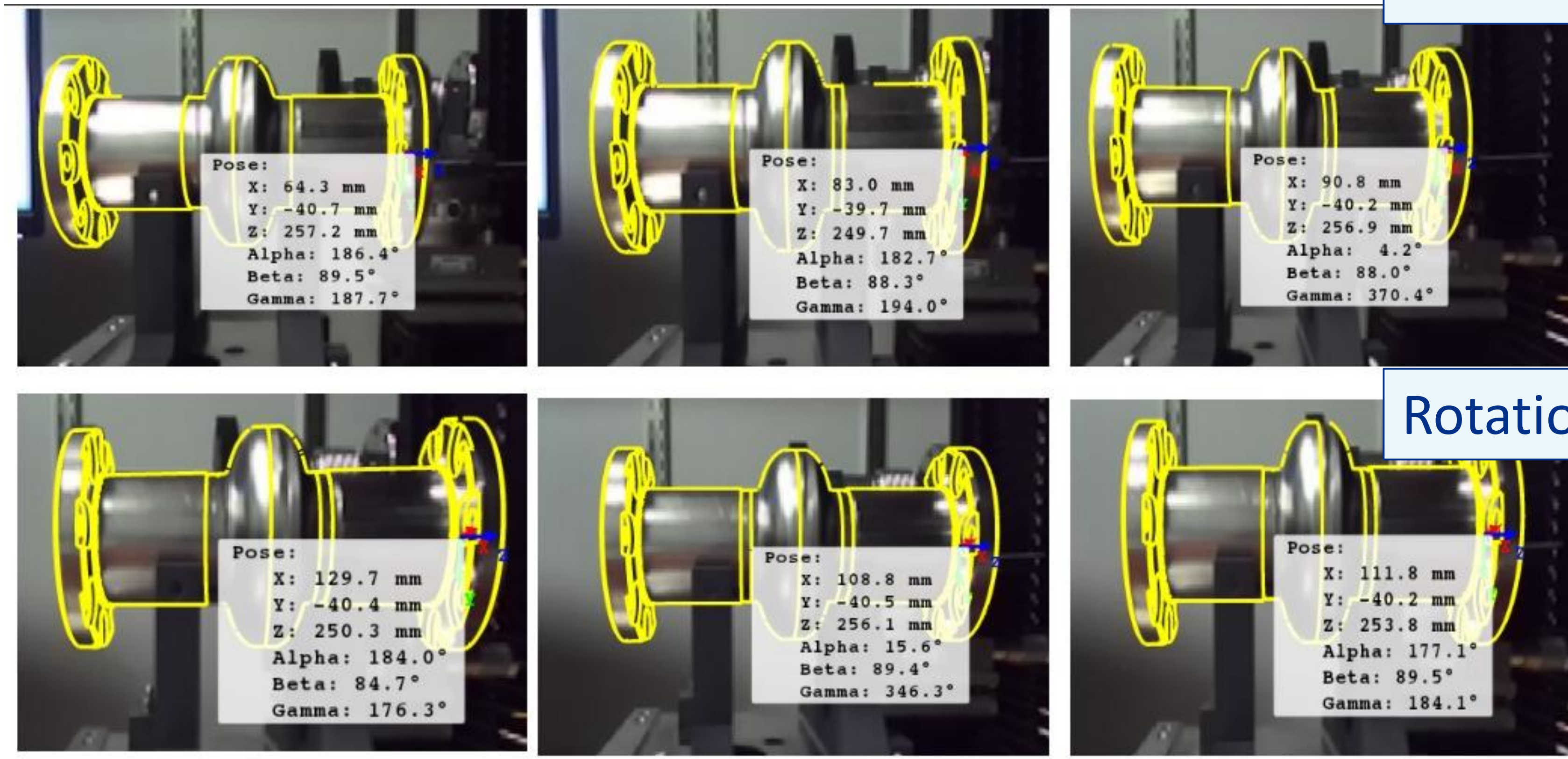
Next step: Close the loop between pose estimation and alignment

Pose reconstruction with point clouds - image

Performance evaluation

- The cavity is mounted on translation stages to validate the position monitoring
- Sub-micrometric accuracy for the translations

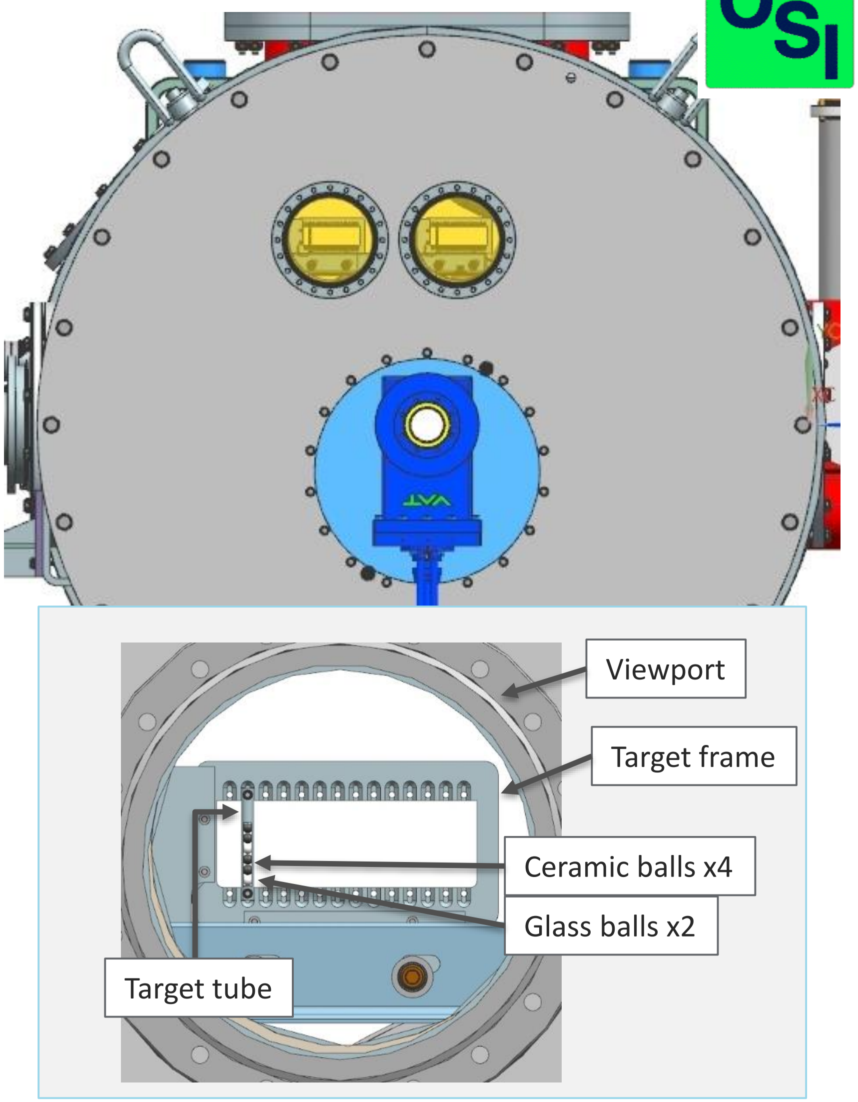
Translation



Rotation

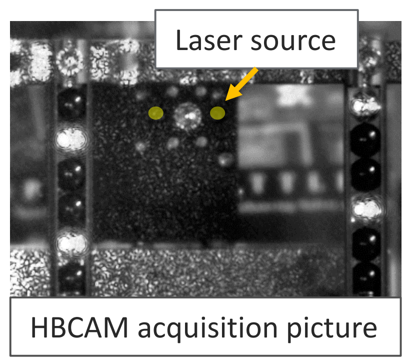
Fermilab

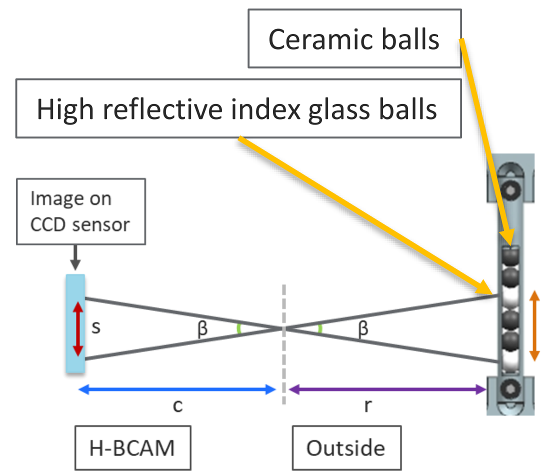
Alignment monitoring strategy for PIP-II cryomodules



The H-BCAM is an optical instrument designed to monitor the geometry of large structures

- Each target frame includes one target tube, in which two glass balls
- The glass balls have a high reflective index to act as a retro-reflector for the HBCAM device
- A laser source from the camera is flashed on the targets, the images are acquired on CCD sensors and the position in pixel points is found by scanning the luminosity peaks in the picture.

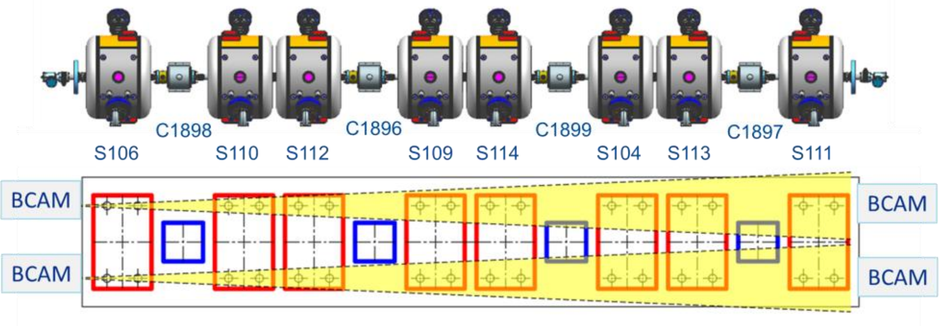


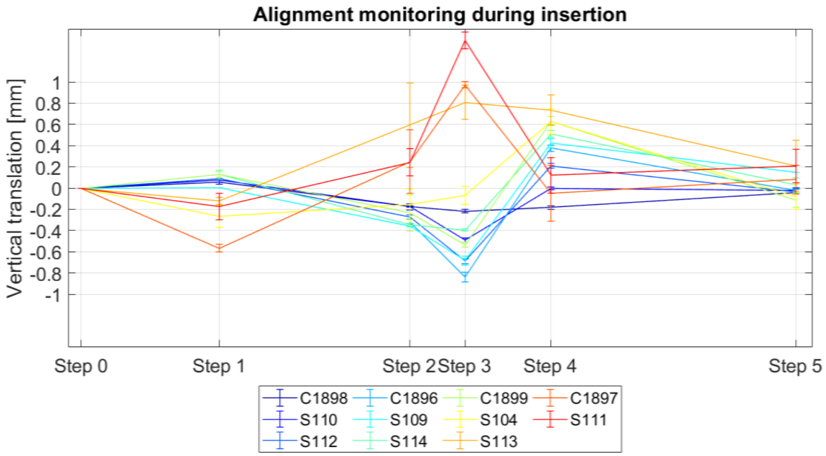


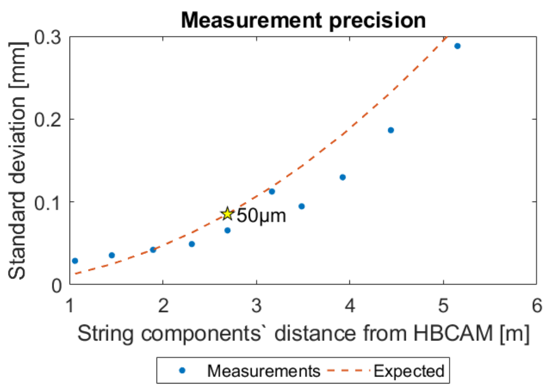
Coldmass insertion

Position monitoring during insertion

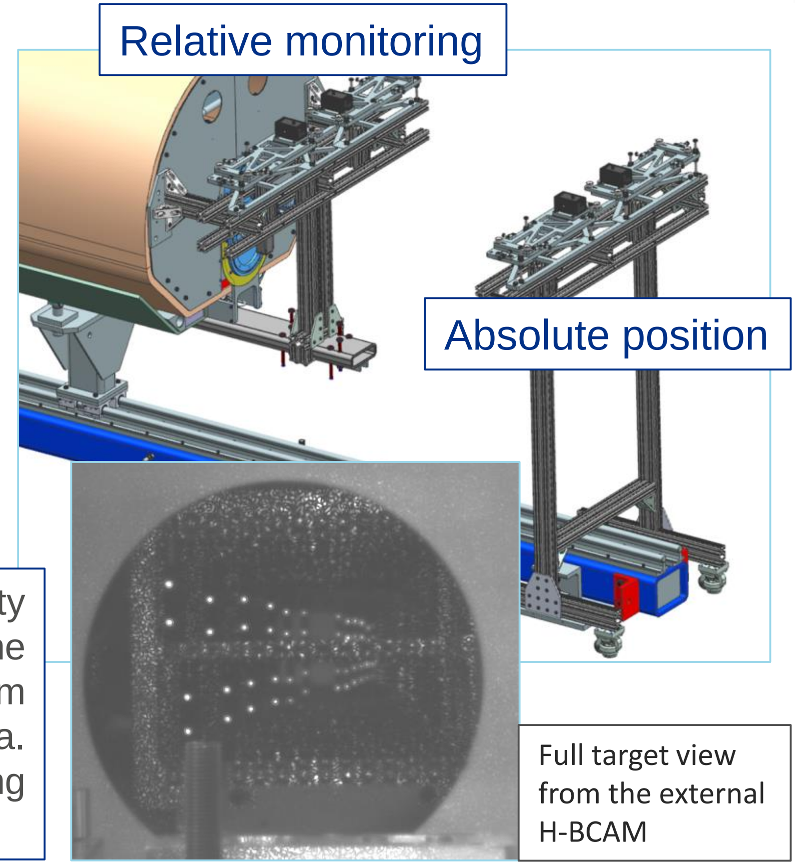
- Two cameras attached on the thermal shielding
- Two cameras installed at the ground and used as a reference







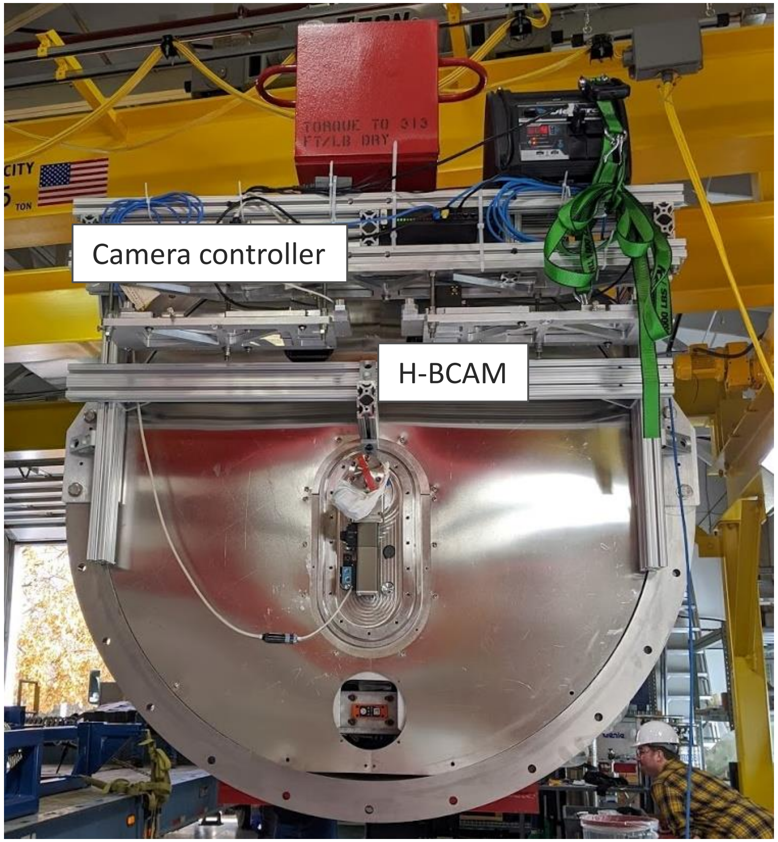
The measurement uncertainty for each component in the string assembly depends from the distance to the camera. Acquired data are matching with the expected precision.

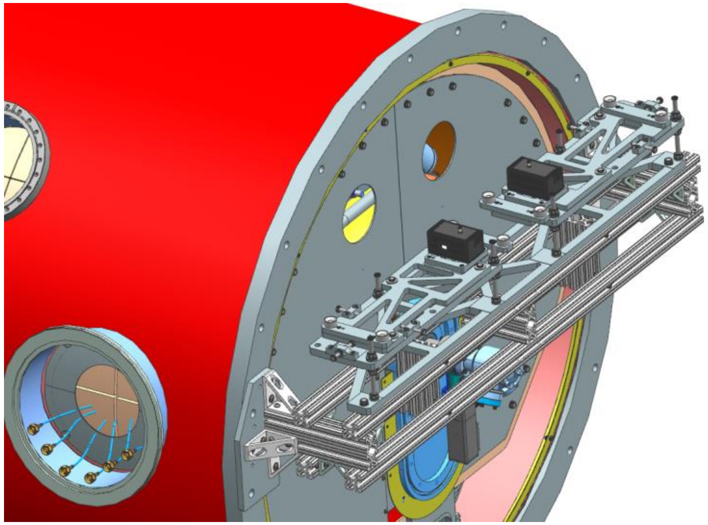


Fermilab

Transportation and cooldown

- Connection on the vacuum vessel
- Focus on a single cavity and monitor slow vibrations < 30 Hz
- Monitor the cavity position during cooldown, monitor position vs. T





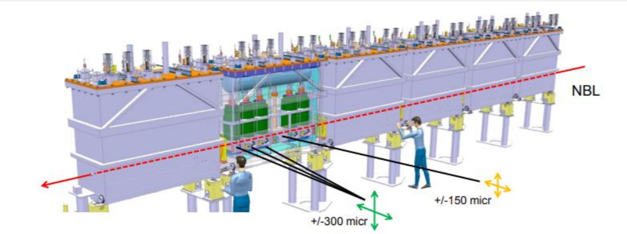


Figure 1: The HIE-ISOLDE linac

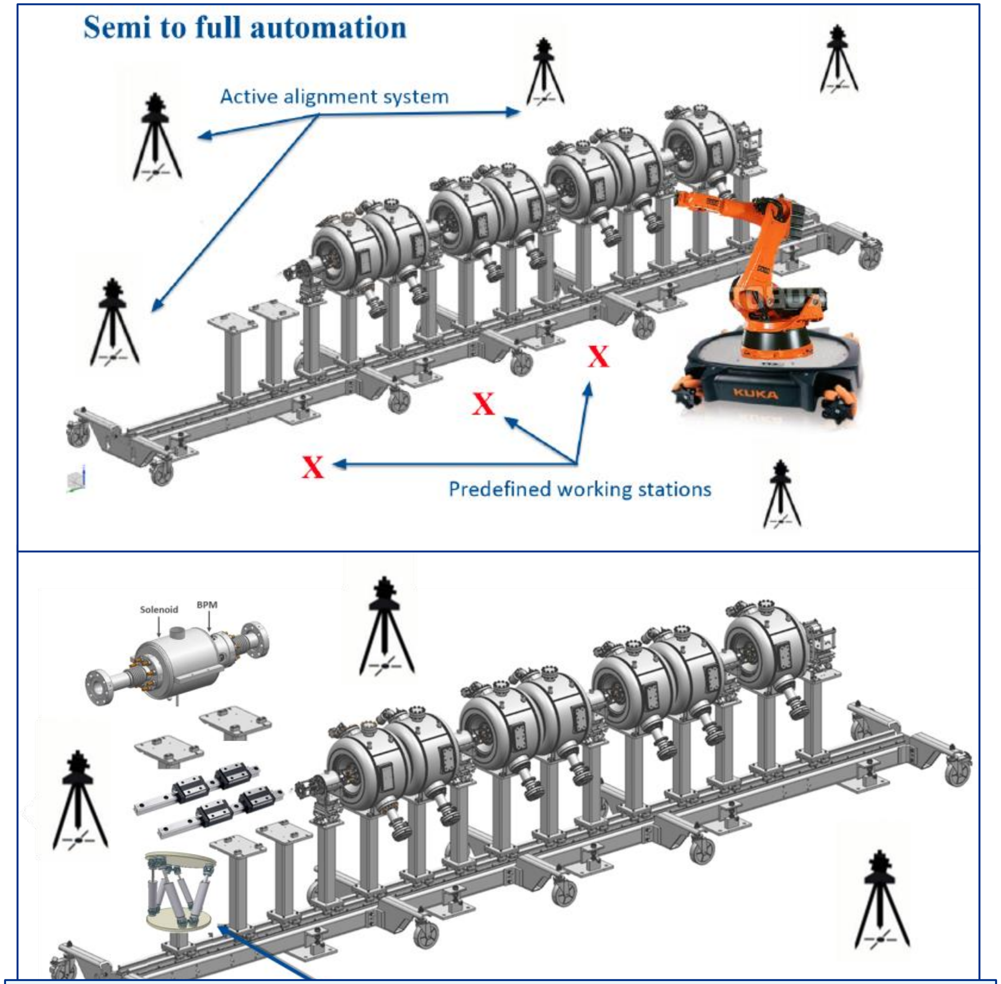
Support and collaboration with the BE group at CERN
Thanks to J.C. Gayde
G. Kautzmann

Conclusion

- Survey of the available technologies and compatibility with cleanroom
- **Implemented a preliminary pose reconstruction** solution to be applied to alignment purposes in cleanroom environment
- **HBCAM used for alignment and also to monitor critical phases** of the first PIP-II prototype cryomodule

Next steps

- Multi-camera setup
- Study of the achievable precision and accuracy
- Close the loop between pose recognition and active alignment



Move forward cryomodule robotically assisted assembly