Robotics at CERN

Eloise Matheson, Mario Di Castro, Alessandro Masi

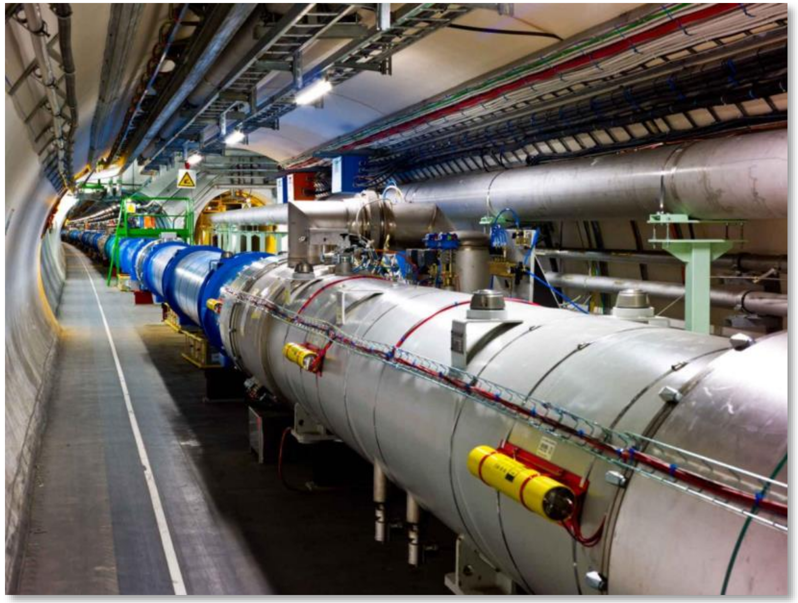
BE-CEM

Contents

Contents

Main Needs for Robotics at CERN

- Inspection, operation and maintenance of radioactive particle accelerators devices towards maintainability and availability increase
  - ✓ Experimental areas and objects not built to be remote handled/inspected
    - ✓ Any intervention may lead to “surprises”
    - ✓ Risk of contamination



The LHC tunnel

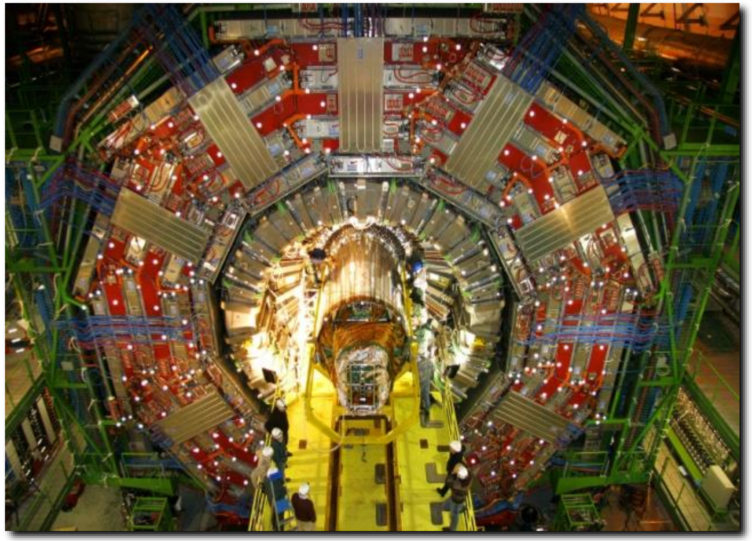
North Area experimental zone

Radioactive sample handled by a robot

Main Challenges for Robotics at CERN

- Maintenance, intervention and inspection in harsh and semi-structured environments
- Radiation, magnetic disturbances, delicate equipment not designed for robots, big distances, communication, time for the intervention, highly skilled technicians required (non robotic operators), etc.

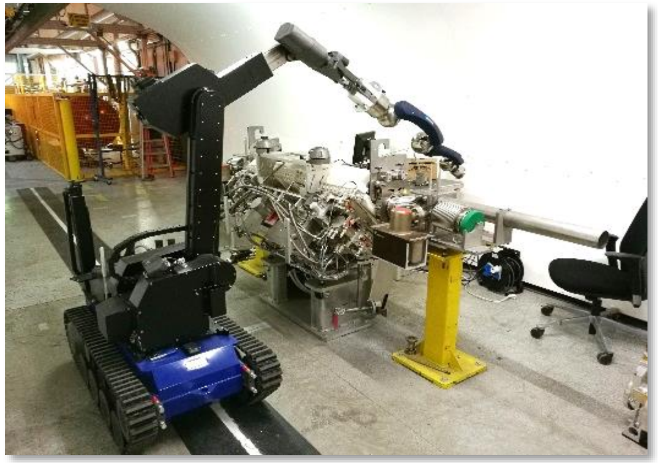


Contents

CERN's Robots

Telemax robot

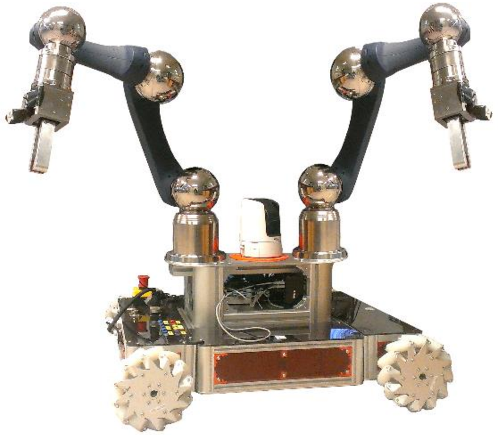


Teodor robot

Train Inspection Monorail (CERN made)

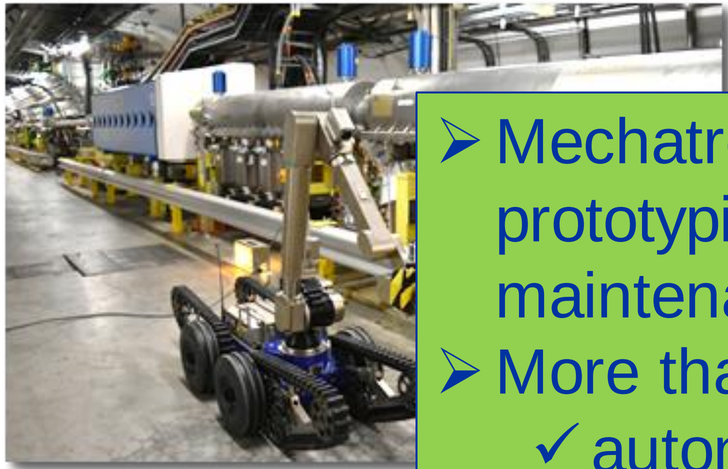
CERNBot (CERN made)

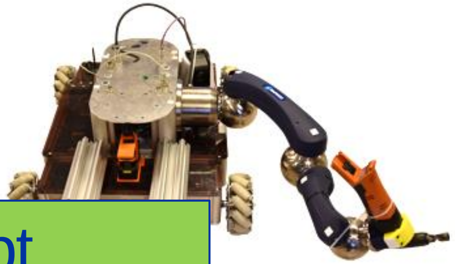
EXTRM Robot (CERN made)



CERNBot in different configurations

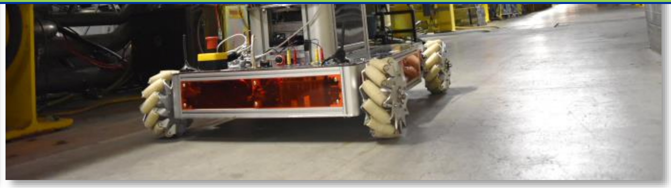
CERN’s Robots

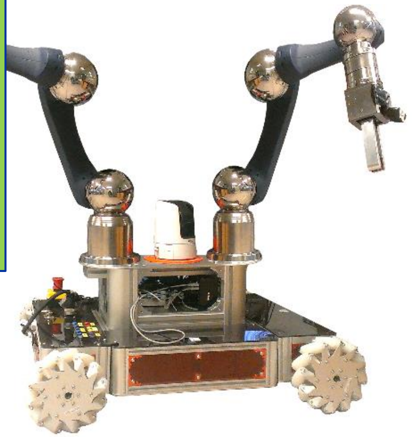




- ➢ Mechatronics conception, design, proof of concept, prototyping, series production, operations, maintenance, tools and procedures
- ➢ More than 20 robots in operation
  - ✓ autonomous inspections
  - ✓ teleoperations
  - ✓ assisted telemanipulation
  - ✓ autonomous remote operation
  - ✓ safety, search and rescue

Telemax rob





Train Inspection Monorail (CERN made)

CERNBot (CERN made)

EXTRM Robot (CERN made)

CERNBot in different configurations

Robots are mainly used at CERN for:

- Human intervention procedures preparation
- Environmental measurements, maintenance and inspection in radioactive areas
- Quality assurance
- Post-mortem analysis/inspection of radioactive devices
- Reconnaissance
- Search and rescue
- Decommissioning/Dismantling

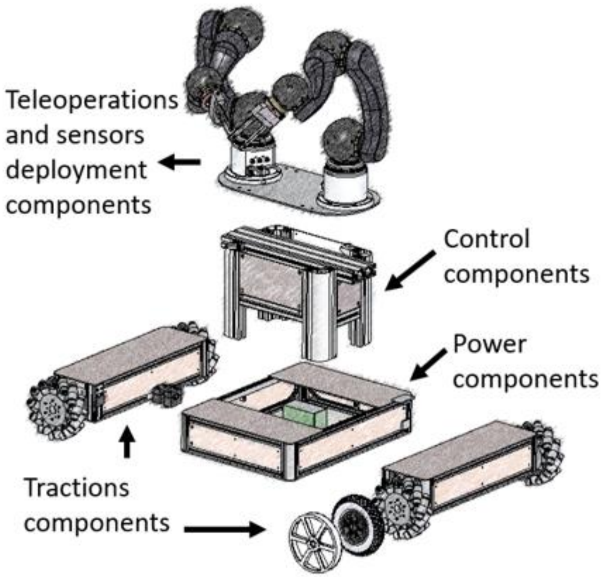
Main Motivations for Custom Robotic Development

- Industrial solutions do not cover all of CERN needs for remote maintenance and quality control

- Strong need to develop **a modular and adaptable robotic framework/system for** unstructured and harsh environments

- Necessity of having the human, the machine and the interface working together adopting **user friendly interfaces**
  - ✓ Increase of proprioception reducing operator’s stress

CERNbot platform design

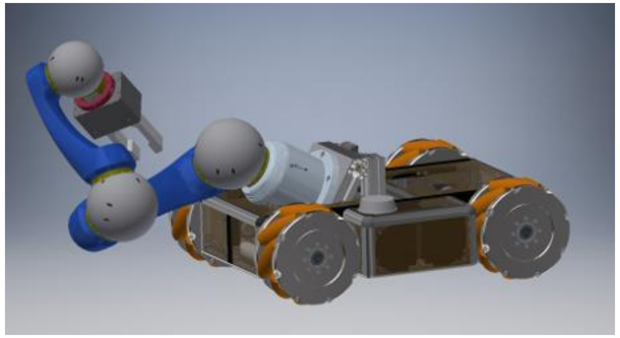
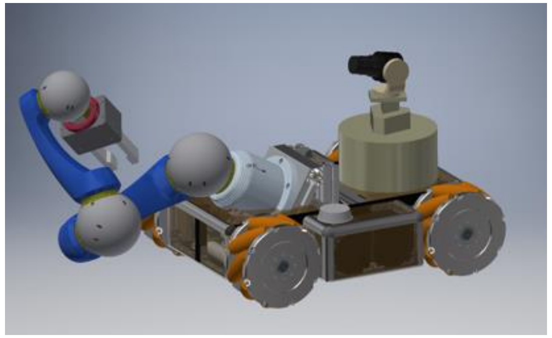
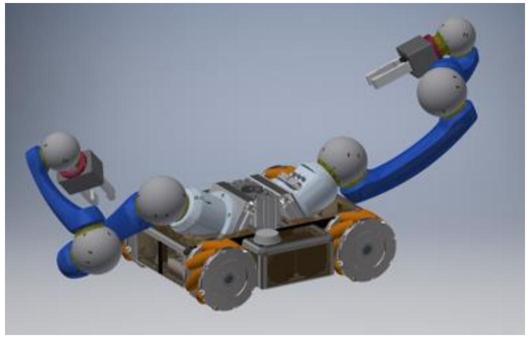


- CERNBot is a custom ground robotic platform normally equipped with two robotic 6DOF arms and grippers for bimanual operation
- Modularity means the same base can be used in different ways to adapt the structure to the task
- The robot has the capability to remove or add modules to add functionality or adapt the shape
- Maxon brushless DC motors for base

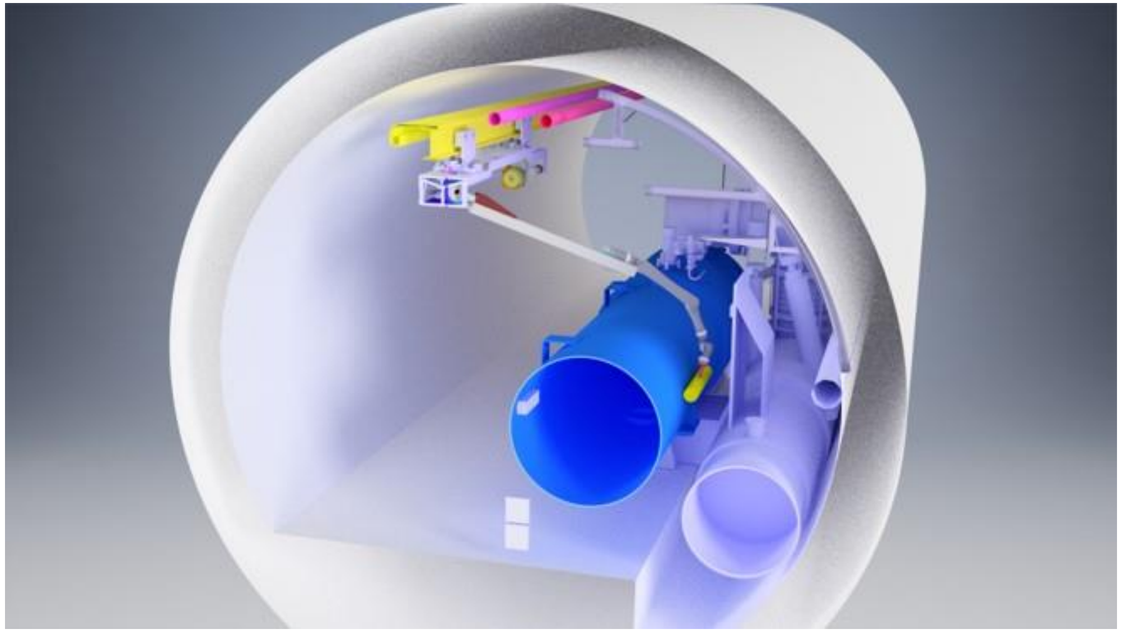
CERNbot compact design

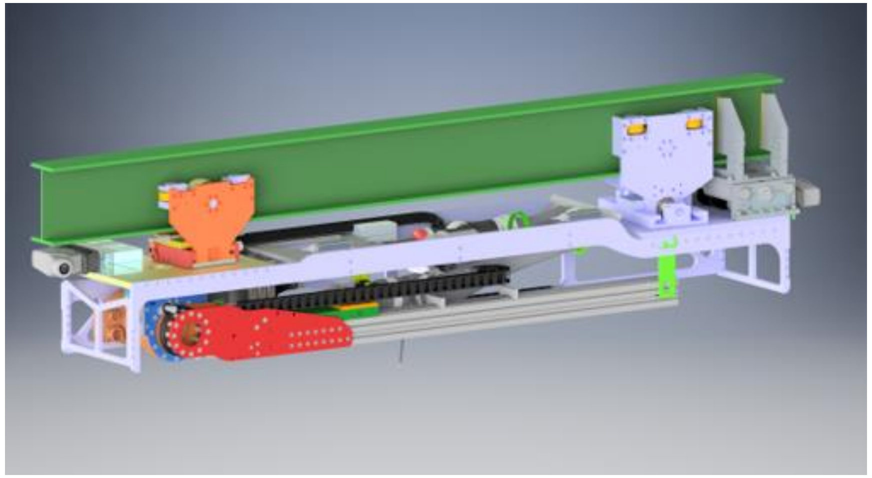
- Starting from the CERNBot, a new family of robotic platforms has been developed to address the needs of compact platforms in constrained spaces/access

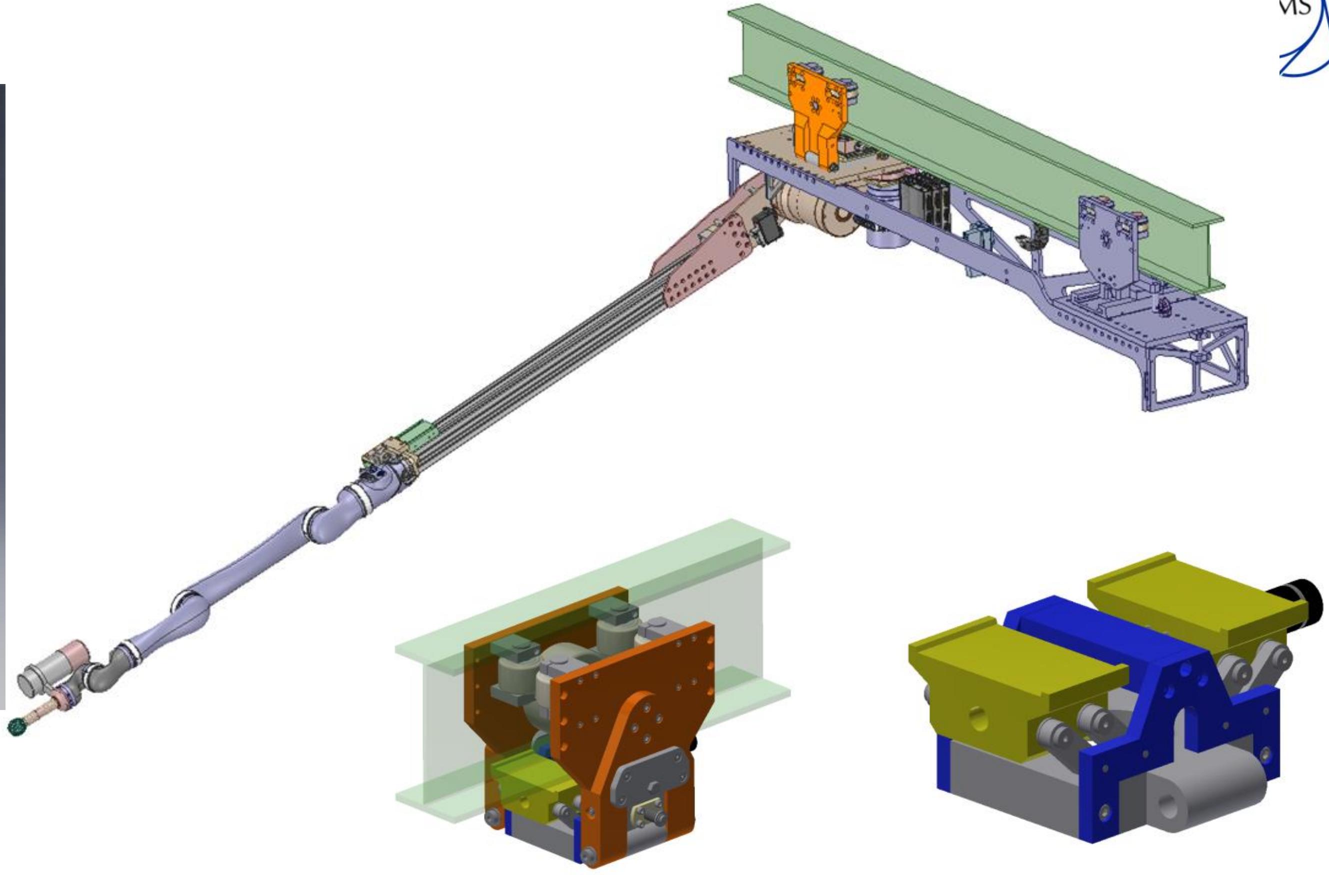
- Modularity saves design time and reduces costs


TIM Platform design







- ➢ Monorail mounted robot with different wagons – motors, batteries, sensors, arms
- ➢ Different wagons for specific missions

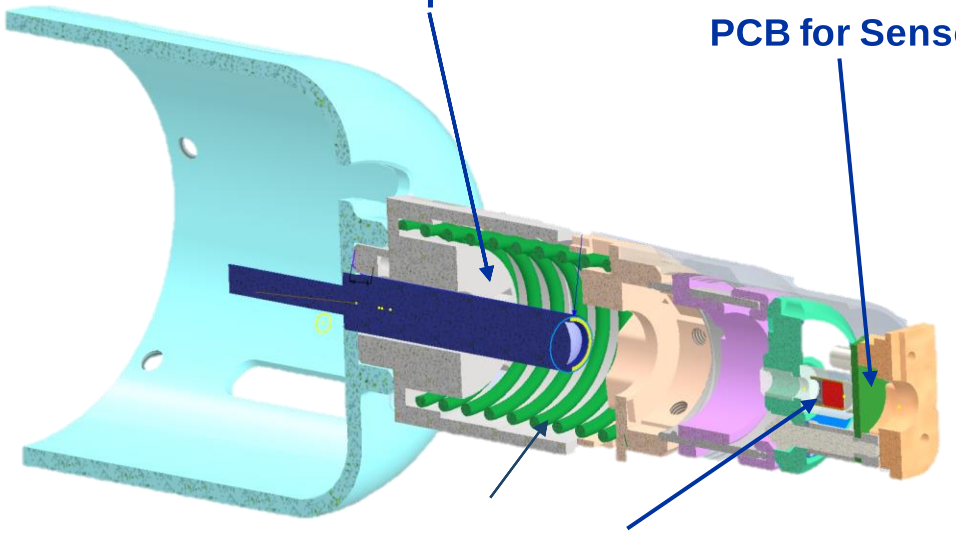
TIM Robot Wagon

Manipulator

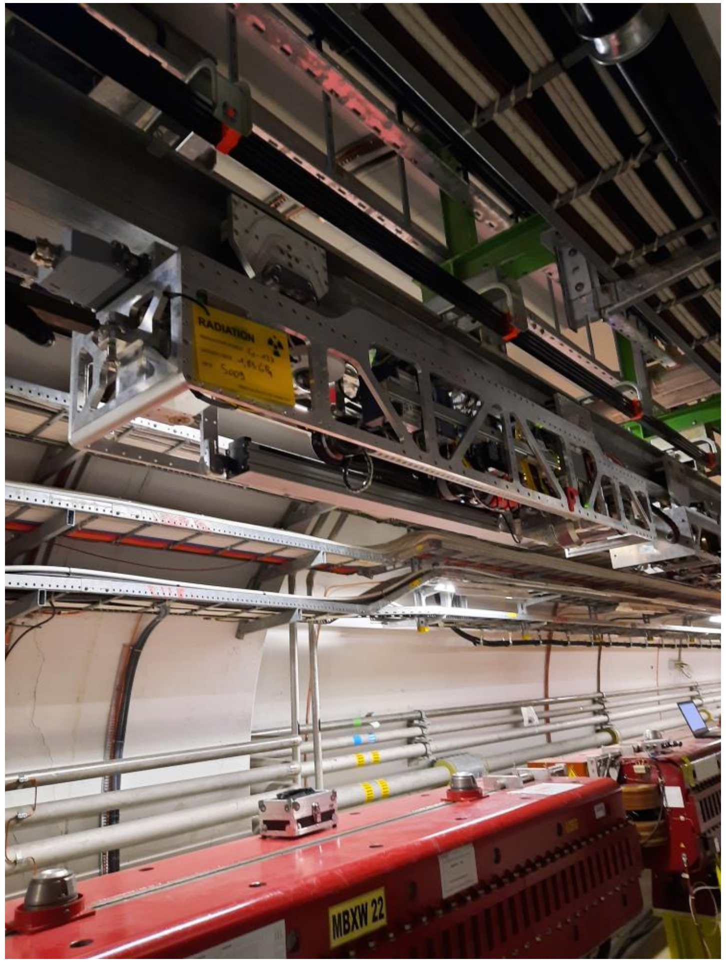
- 6 DoF Kinova Gen2 arm
- 3 DoF custom CERN arm
  - 1DoF (linear axis) for workspace extension
  - 2DoF (rotational axes) for transveral positioning
  - These are based on PMSM with strain wave gears
- Stabilisation axis on the wagon

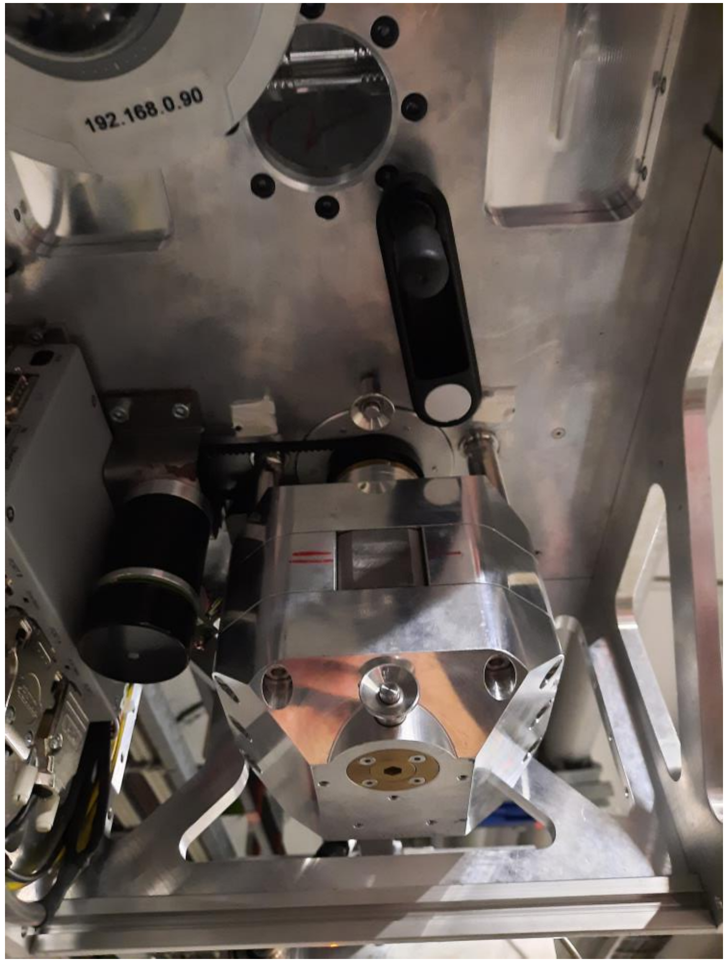
End Effector

- Safe grasping system
- Integrated endoscopic camera
- Compliant flexible tip



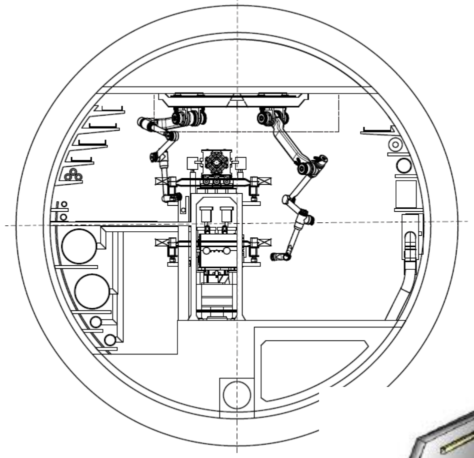
TIM Robot Wagon

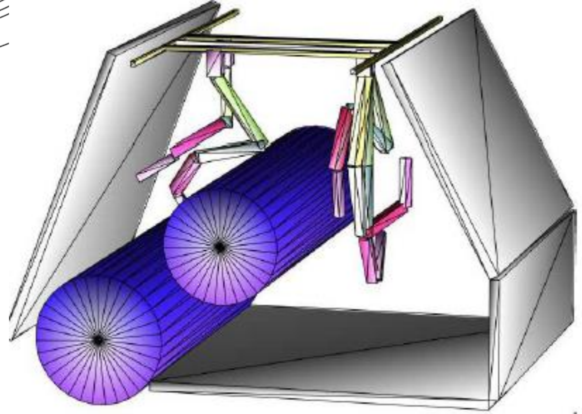


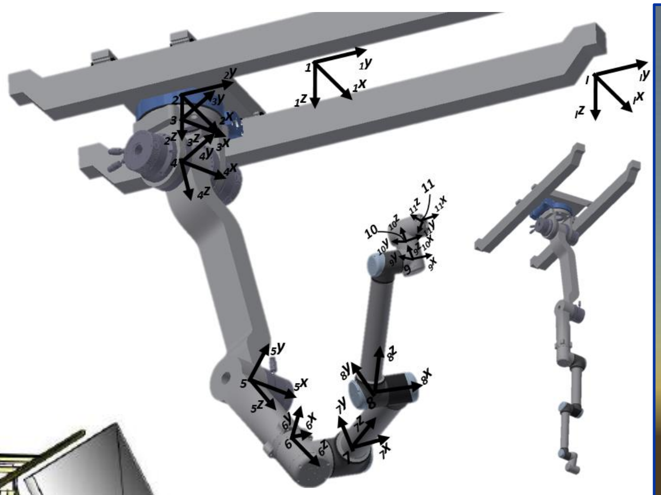


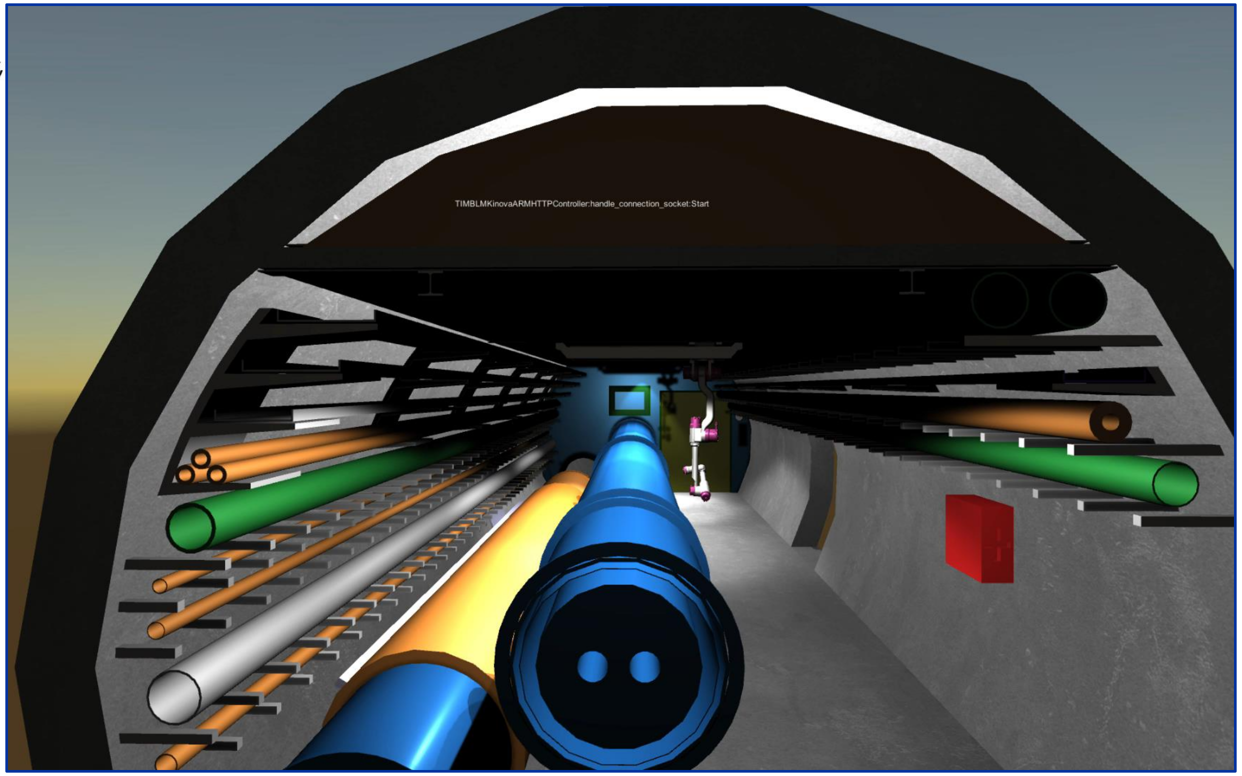
Robotics for the FCC [1]

- Novel robotics platforms and controls for remote maintenance and intervention in case of accident.
- Ability to reach 100km of ring within 10 minutes

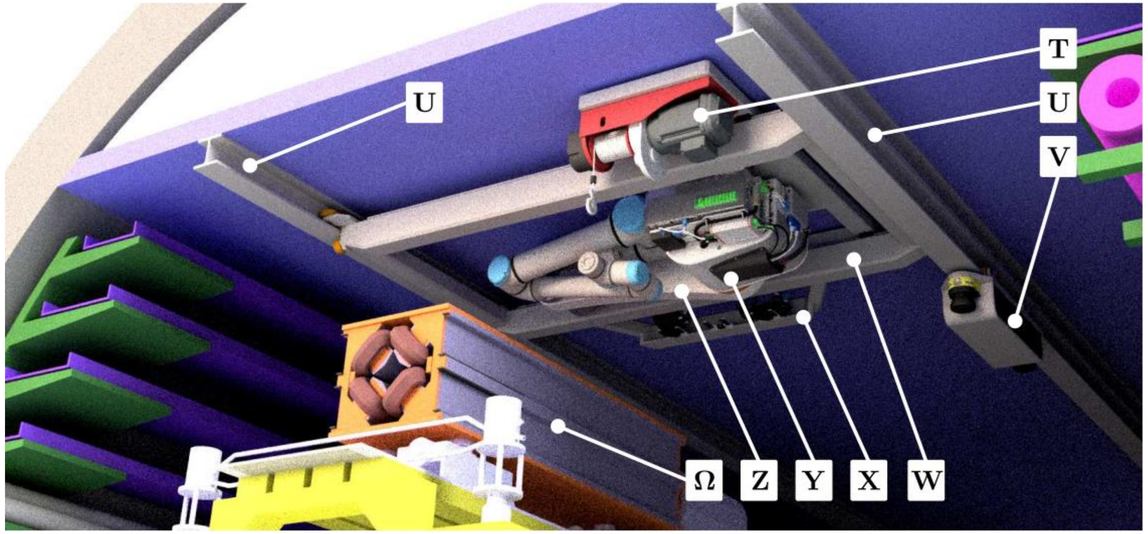




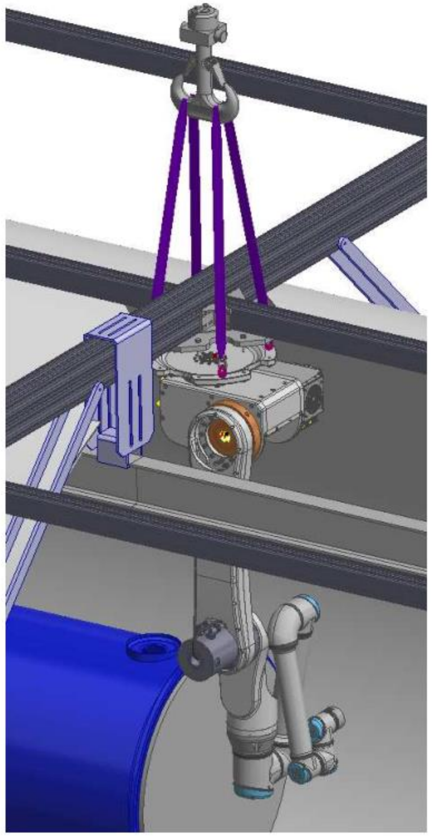




FCC Robot Arm



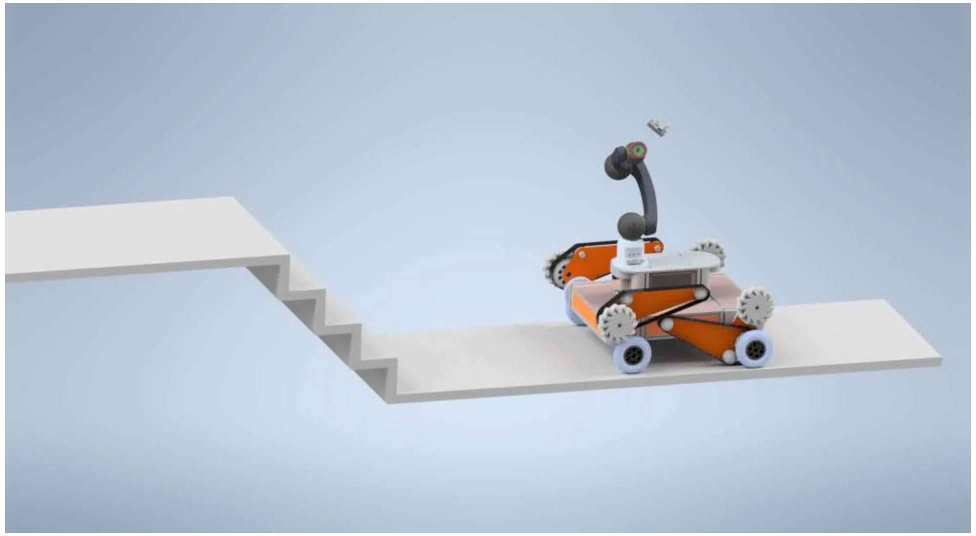
Recommendations for a Robotic System	Main System	Locomotion	Rail Guided; Two rails for stability; (**U**)
		Manipulator	highly redundant manipulator facilitating high dexterity and low footprint; (**Y** and **Z**)
		Power Supply	Continuous supply through rails; (**U**) Emergency supply through battery system; (**Y**)
		Additional Features	Winch for high payloads; (**T**) Tool changing system for various applications; (**X**)
	Emergency System		Small and fast inspection system; Capable of bypassing the main system; Minimum speed of 35 km/h; (**V**)
	Integration		Rails Mounted on Ceiling; Integration of 8 robotic systems; Radiation save parking spots in the 8 access and service caverns; Passing through fire and section doors via automated hatches; High level communication via rails;



- UR10e arm mounted on custom CERN 3DOF arm based on PMSMs with strain wave gears

Modular Robots

- Adaptive traction system for ground robots
- Hyper-redundant (snake) robot for inspection and teleoperation support (third eye) in confined space (including beam pipe inspection)
- Fusing hydraulic and mechanic technologies for a novel robotic arm (more precision and payload) for portable machining/CNC system allowing in-situ interventions on highly radioactive objects
- Improvement of autonomy of robotic operation using machine learning



Commerical Arms that we use

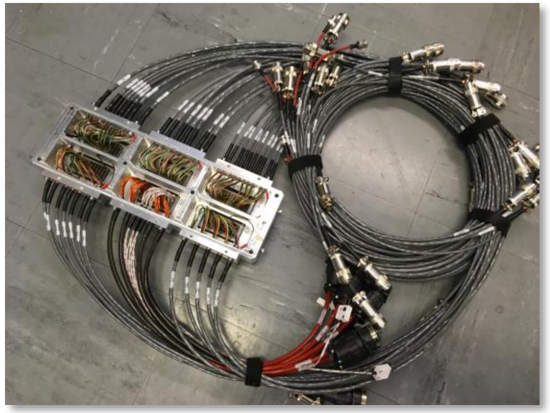
With Mobile Bases

- Schunk LWA (discontinued)
  - Issues with Hall Encoders
- Pilz PRBT (soon to be discontinued)
  - Based on Schunk IP
- Kinova Gen2 and Gen3
  - Limited precision but nice size, some API issues
- Universal Robot 10e
  - Controller box (small) to be integrated, ok for big bases

With Stationary Bases

- Kuka Iiwa
- Kuka KUKA KR120 - R2700 extra HA

Beam Intercepting Devices (BIDS)



- BE-CEM-MRO section is responsible for the design, installation, control, operation and maintenance of the mechatronics control systems for Beam Intercepting Devices (BIDs i.e. collimators, beam stoppers and dumps, slits, scrapers etc.)
- ~250 devices, ~1200 actuators, ~5000 sensors
- Development and maintenance of BIDs and monitoring devices FESA classes, monitoring tools and expert interfaces for piquet intervention.
- Development and support of industrial automation solutions based on PLCs, mechatronic actuators/sensors and mechatronics R&D.
- Inhouse development of motor drivers with long cables
- BIDs operation support and coordination of the piquet service of the group

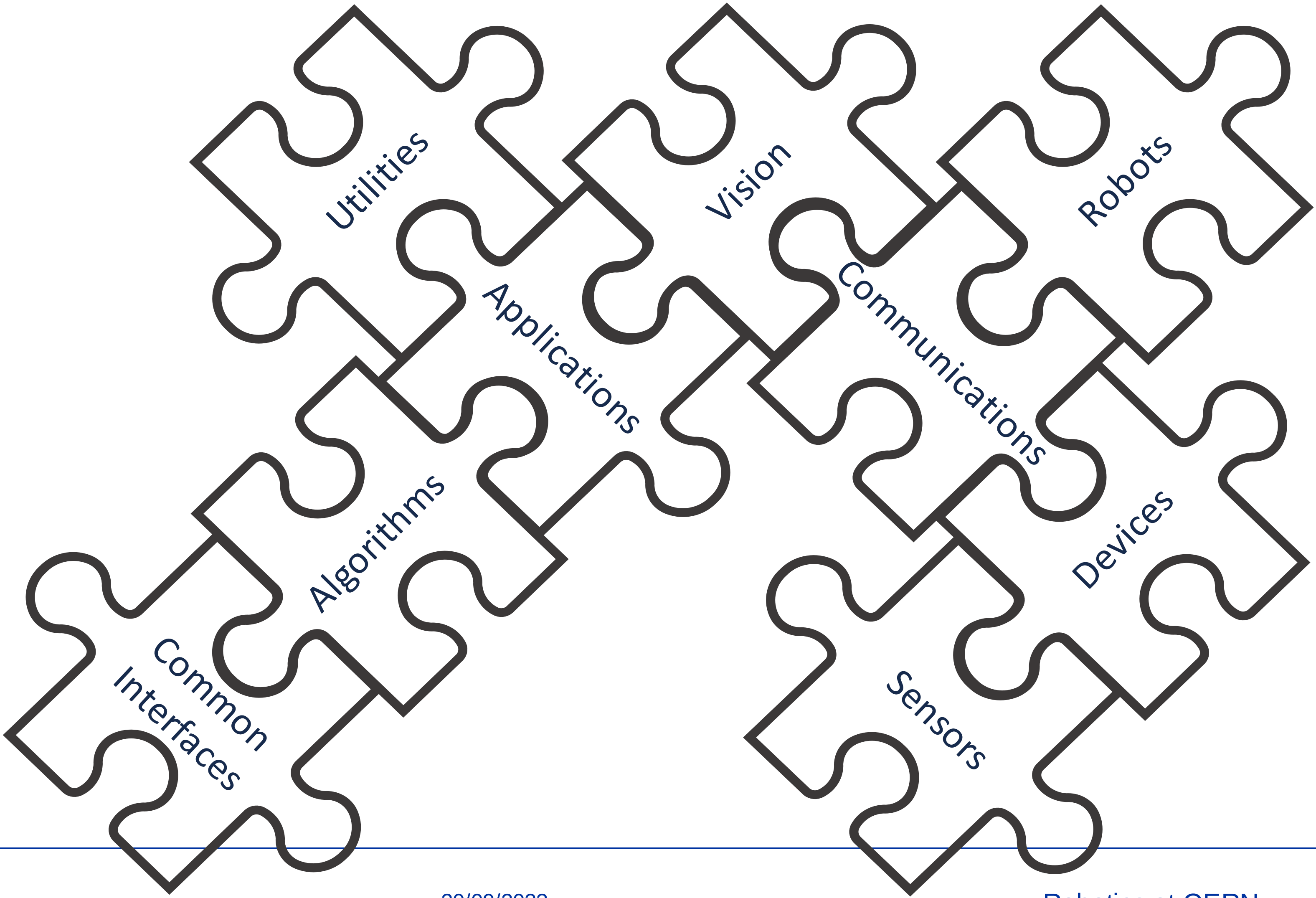
LHC Collimator

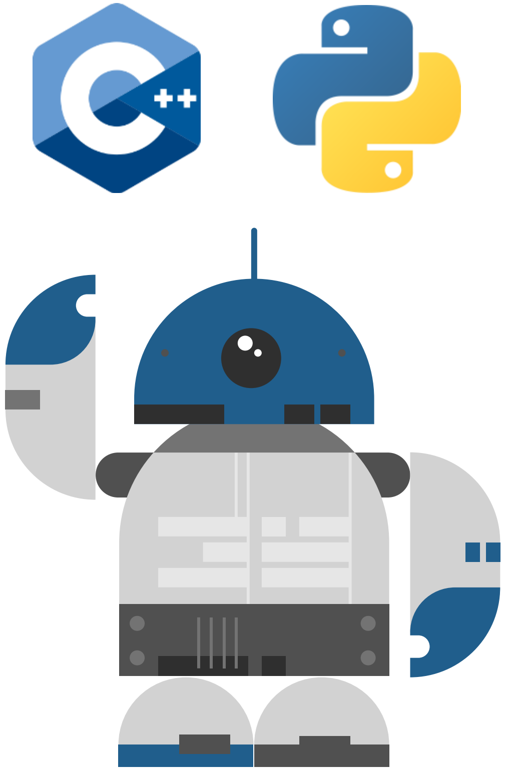
LHC Goniometer

Contents

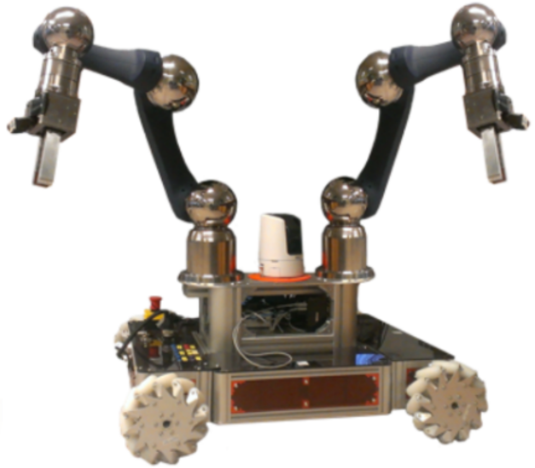
CERN Software: CERNTAURO framework

- Modular Architecture containing onboard software for robotic operations





CERN Software: Control Framework



ROBOT WITH INSTALLED EQUIPMENT AND ITS ON-BOARD COMPUTER

CERN ROBOTIC FRAMEWORK (C++ framework)

- Communication with devices
- Processing the information from sensors
- Real-time control
- Communication points

Communication over mobile 4G network, WiFi or CERN internal network

2D GUI (Windows Presentation Foundation, C#)

3D (Mixed Reality) GUI (Unity, C#)

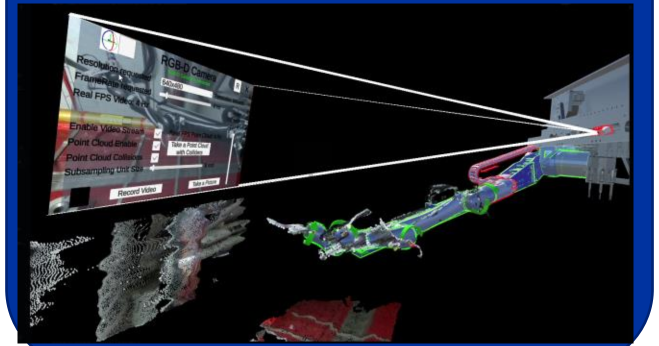
TELEOPERATOR CONTROLLING THE ROBOT VIA A PC OR USING HEAD-MOUNTED DEVICES

Current GUI in MRO

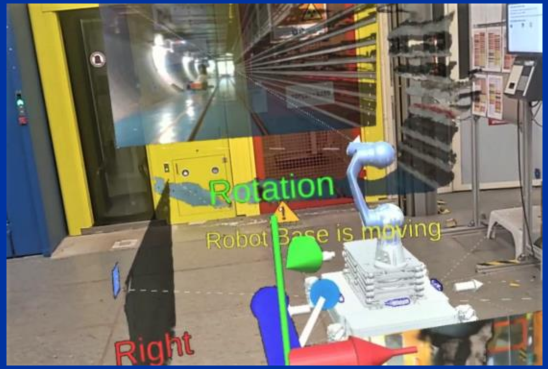
Unity

2D HRI

3D HRI

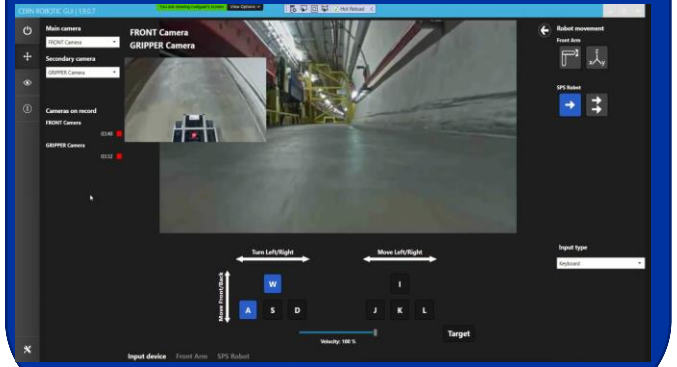


XR HRI



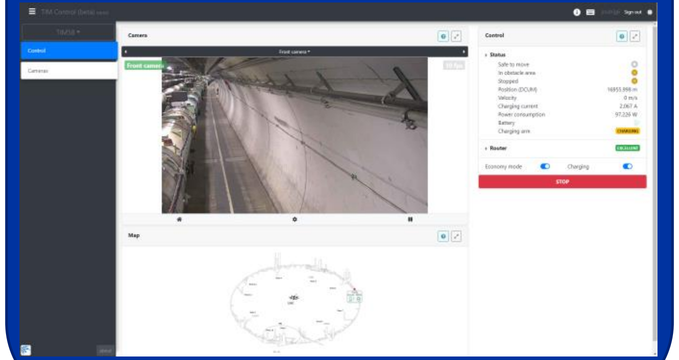
WPF

2D HRI

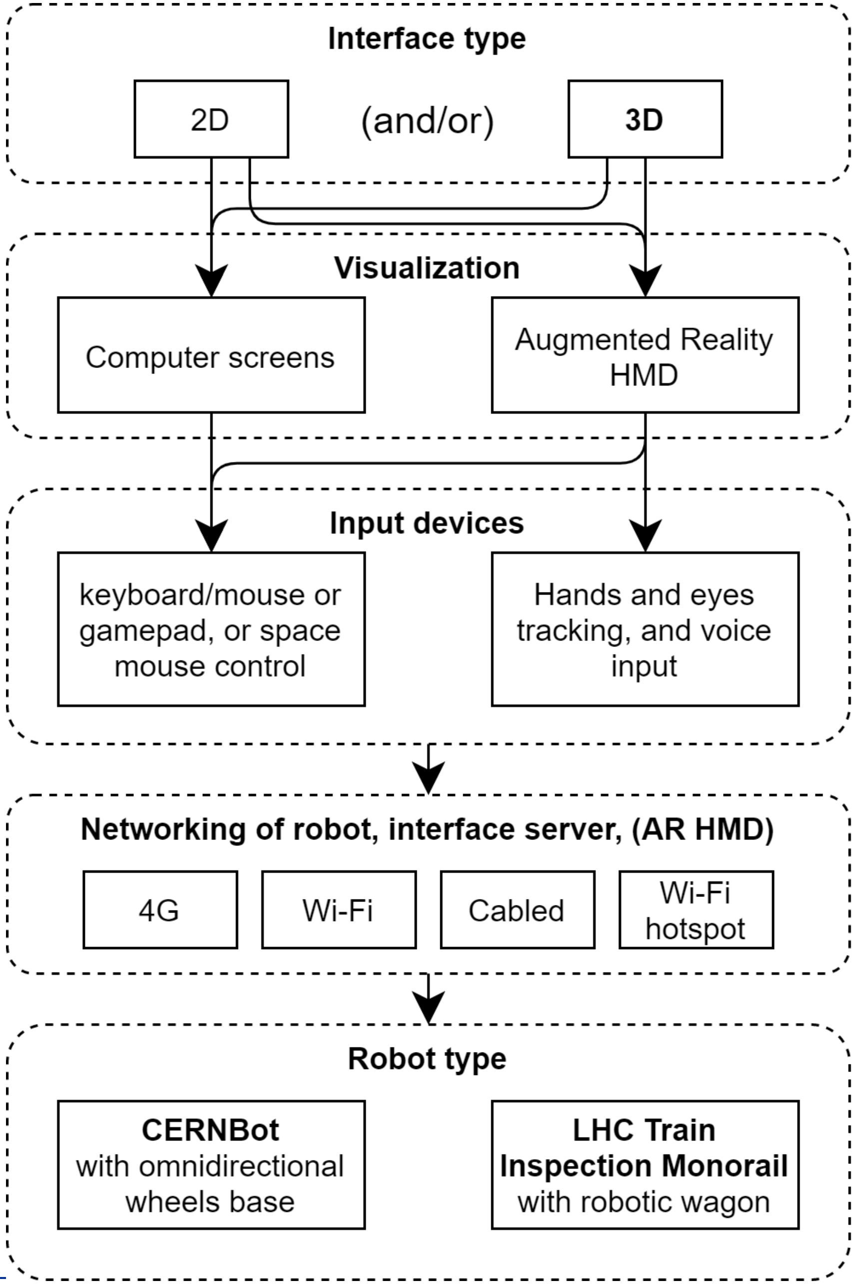


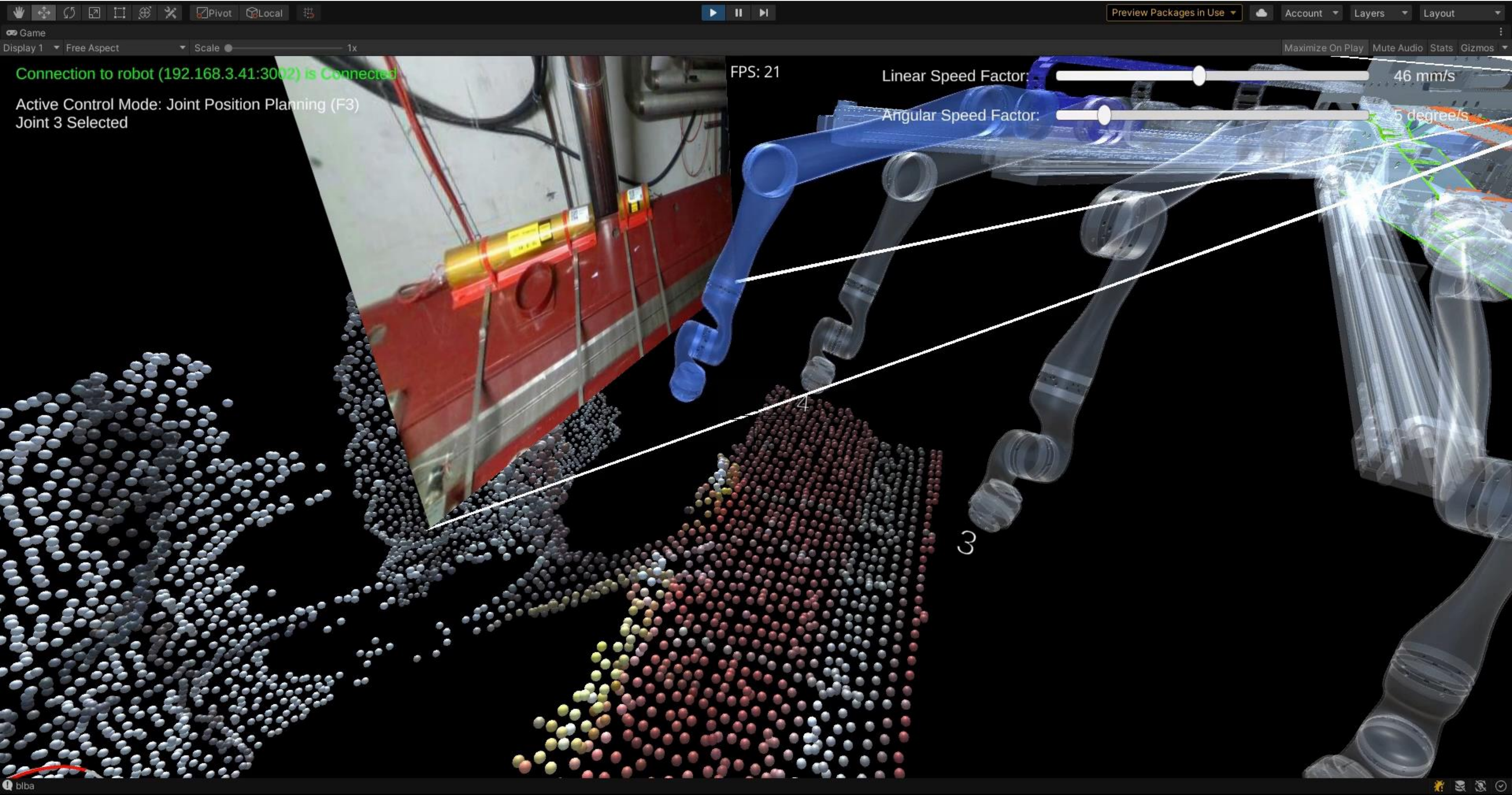
Web Tech

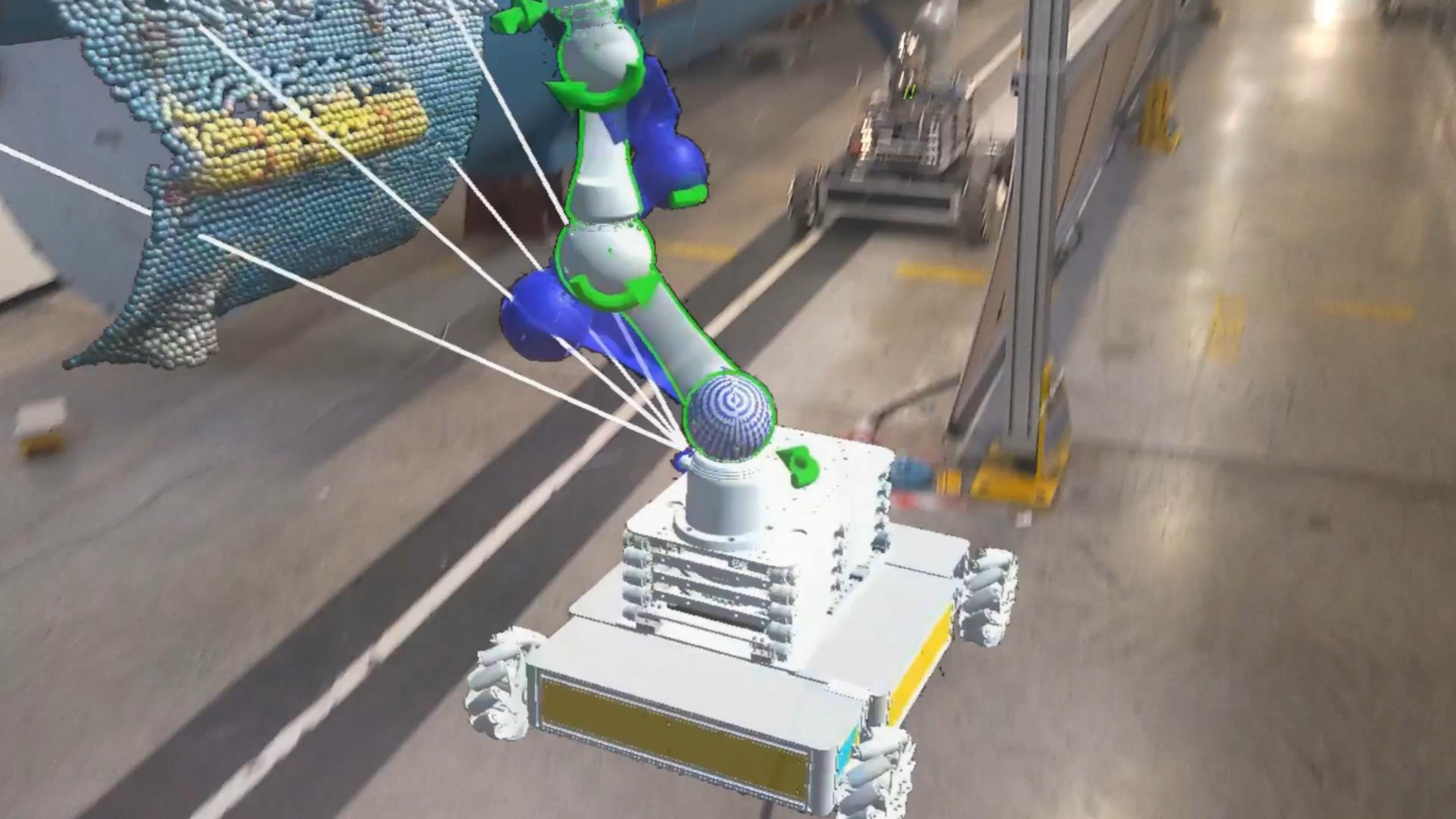
2D HRI



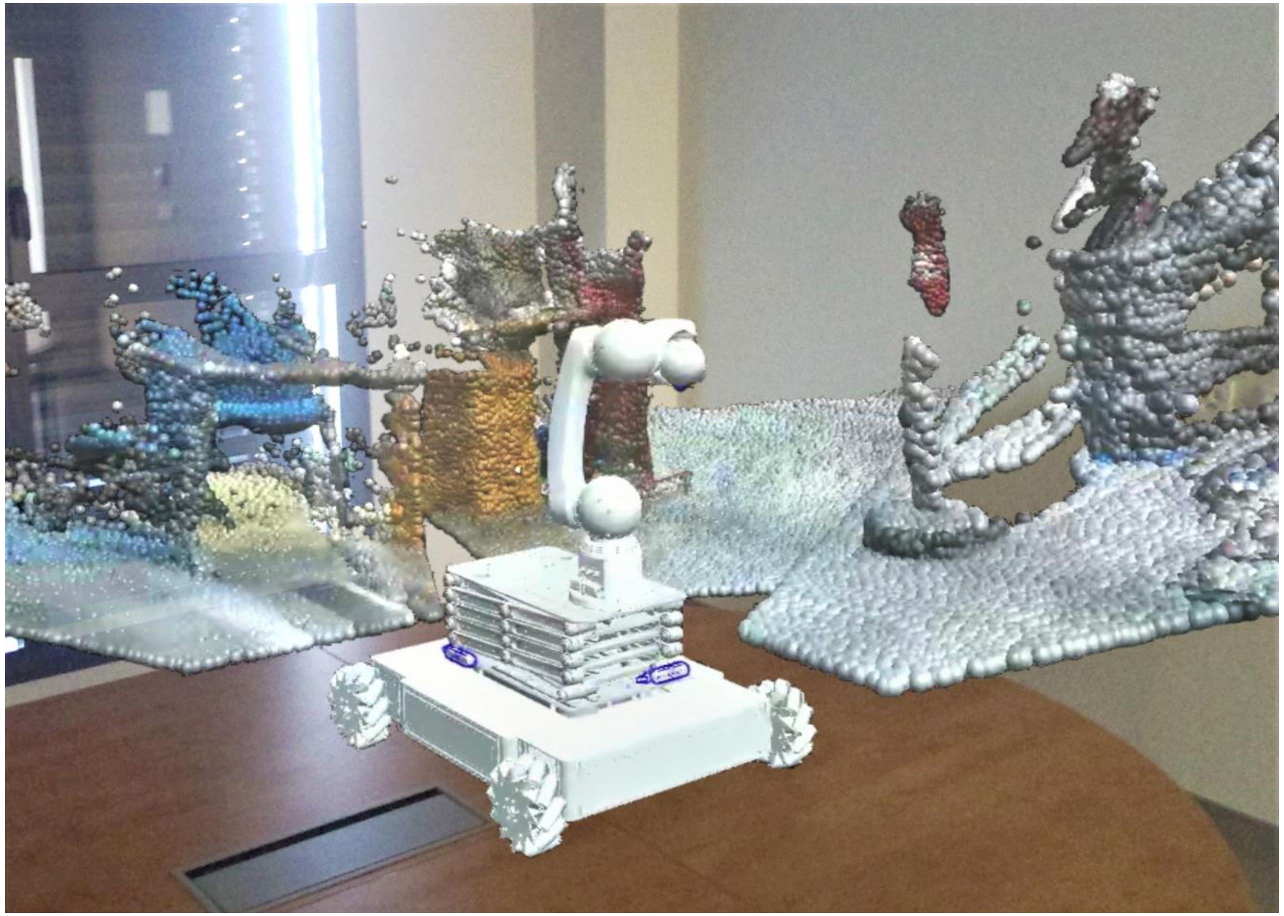
2D, 3D, VR, AR, MR synergies



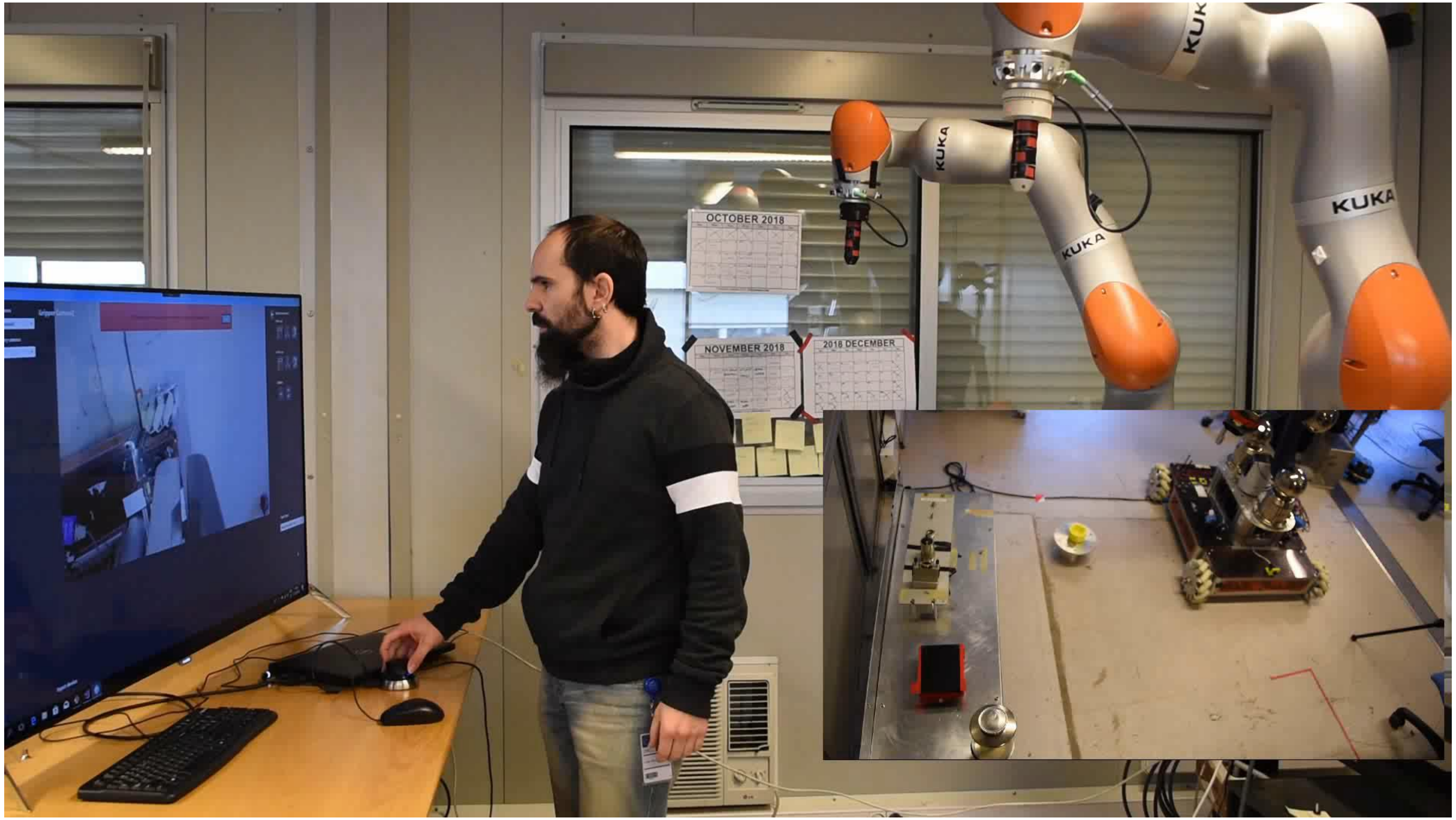

Pivot
Local
Preview Packages in Use
Account
Layers
Layout
Game
Display 1
Free Aspect
Scale
1x
Maximize On Play
Mute Audio
Stats
Gizmos
Connection to robot (192.168.3.41:3002) is Connected
Active Control Mode: Joint Position Planning (F3)
Joint 3 Selected
FPS: 21
Linear Speed Factor:
46 mm/s
Angular Speed Factor:
5 degree/s
3
4
blba



Full view of environment and robot: videos and point clouds

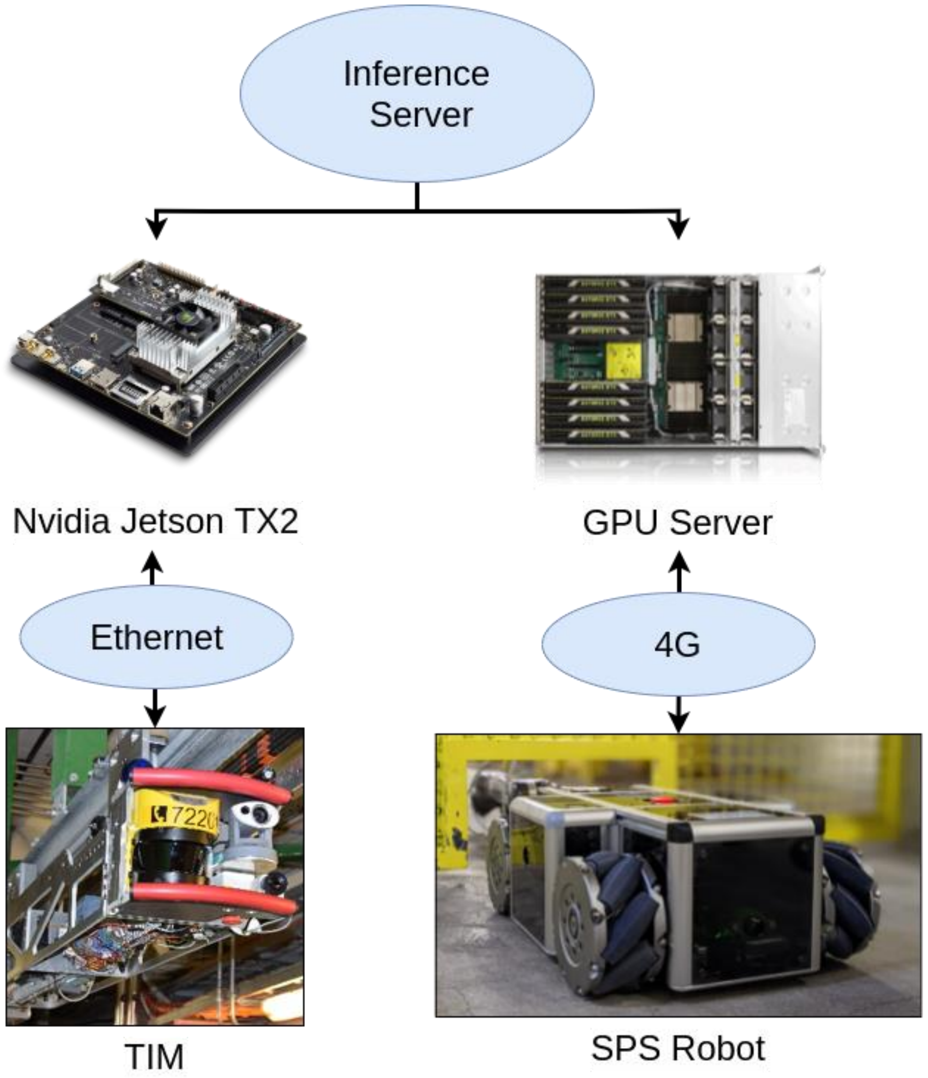


Multi-Arm Teleoperation with Haptic Feedback



- Integrating Virtuose Haption also for teleoperations with haptic feedback

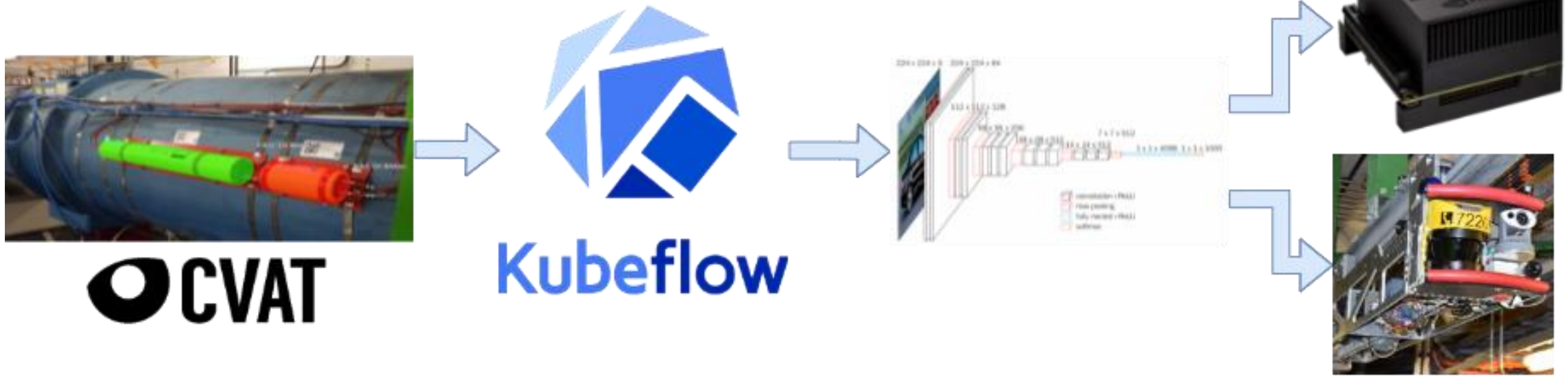
Framework for Deep Learning Inference



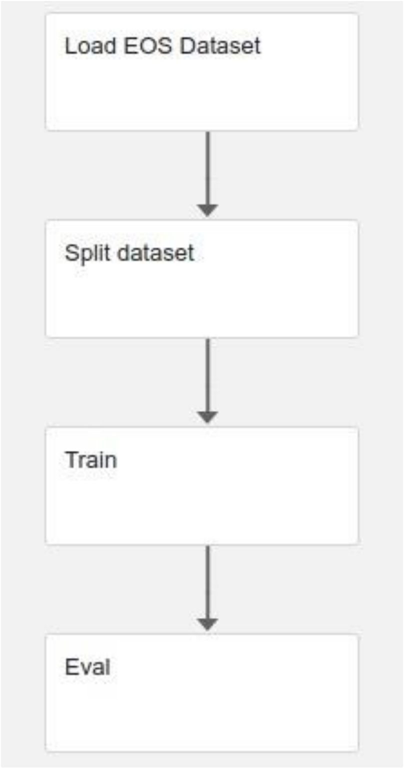
- Easy to use, low latency Inference
- C++, Python, C# clients
- Support TensorFlow, Pytorch and TensorRT frameworks as back-end
- Support model formats: Keras SavedModel, TensorFlow SavedModel, TorchScript, ONNNX
- Optimised for reduced bandwidth networks

Machine Learning lifecycle

- Image annotation done with Computer Vision Annotation Tool (CVAT) by Intel with added tool of SAM from Meta (under test)
- Datasets stored in CERN storage EOS.
- Model are trained using CERNs KubeFlow server.
- It also includes tools for hyperparameter optimization (Katib).



Robotics Machine Learning lifecycle



KubeFlow Training pipeline

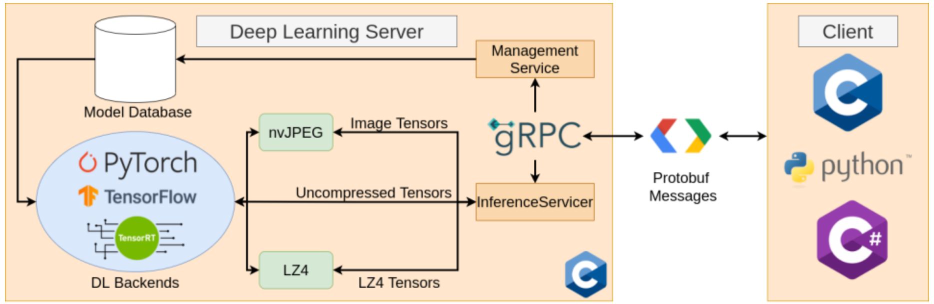
Machine Learning model deployment

- Models are developed in TensorFlow and PyTorch.
- We can run local inference using Torch and TensorFlow C++ API’s.
- Future support for TensorRT for inference speed increase.

TensorFlow

PyTorch

TensorRT



Custom Inference Server

Machine Learning model deployment

- Models are developed in TensorFlow and PyTorch.
- We can run local inference using Torch and TensorFlow C++ API's.
- Future support for TensorRT for inference speed increase.
- Nvidia Triton for remote client/server inference (can run multiple frameworks).

TensorFlow

PyTorch

TensorRT

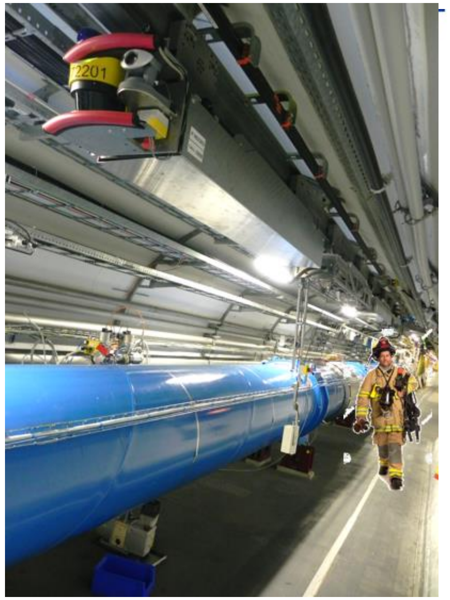
NVIDIA

TRITON INFERENCE SERVER

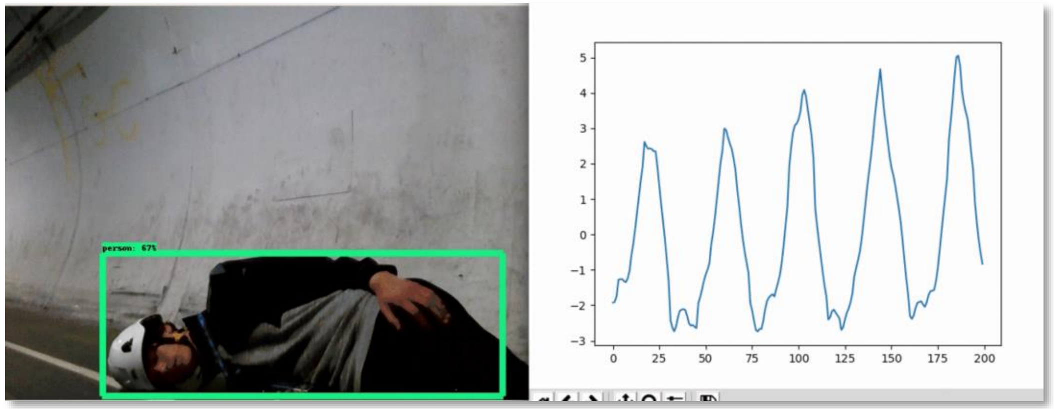
Search and Rescue Robot

- Follow and “drone” accessing firefighting team
- Precise staff localization in harsh environment
- Environmental measurements into augmented reality showed on tablet or glasses for example

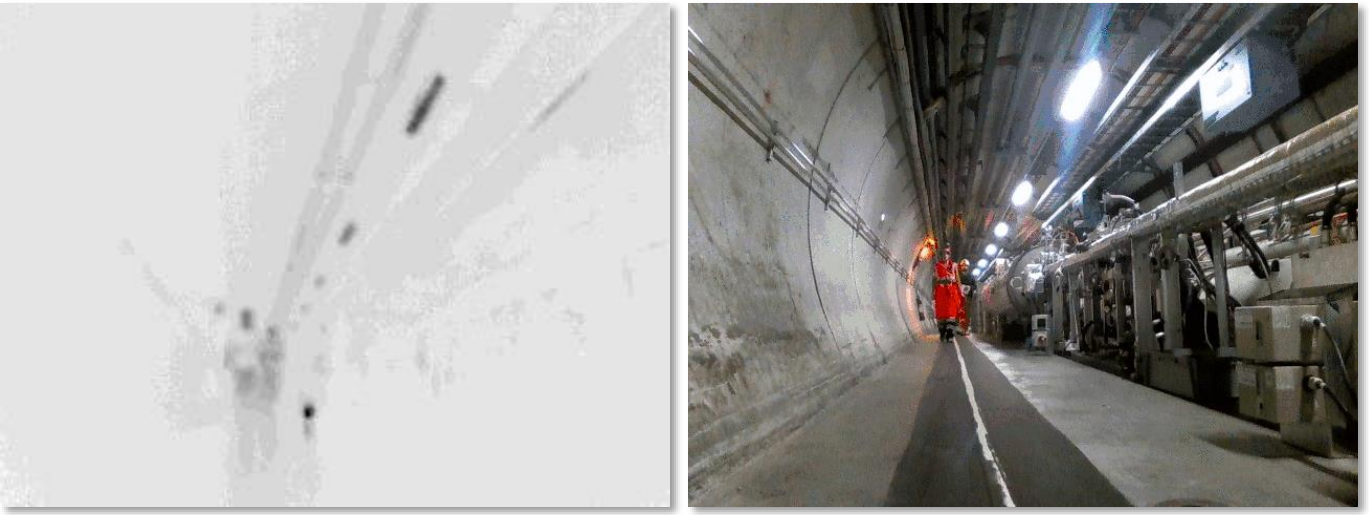
Example of Augmented reality glasses



TIM escorting fire brigade personnel



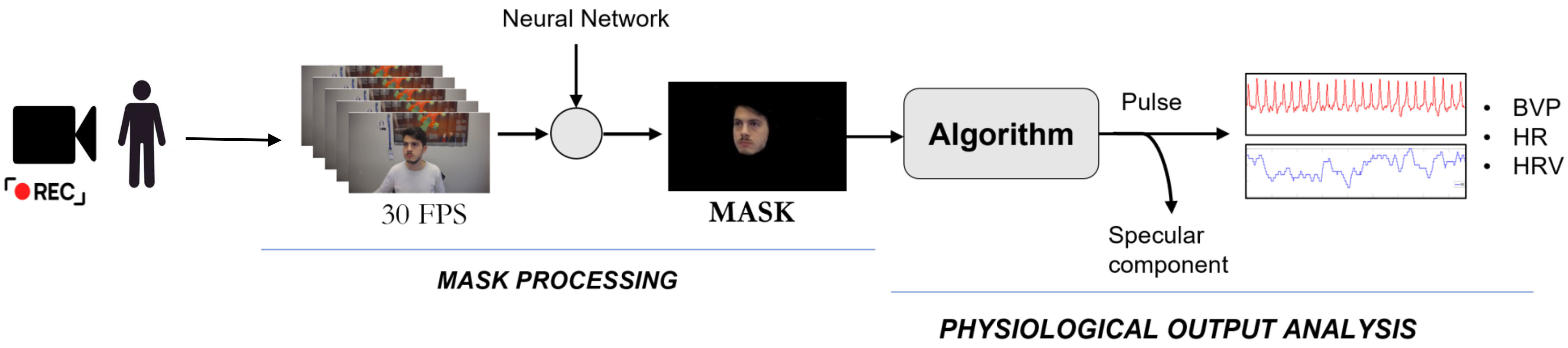
Online respiration monitoring



Online people recognition and tracking

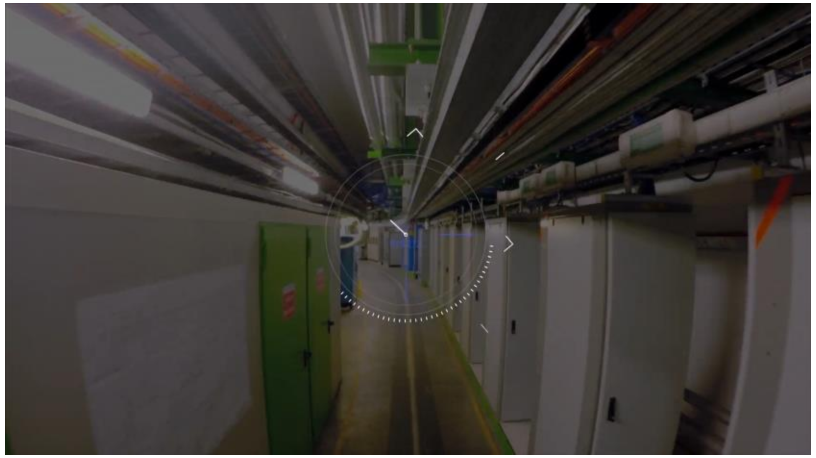
Robots for Health Monitoring

Machine Learning based Human Recognition and Health Monitoring System (MARCHESE)

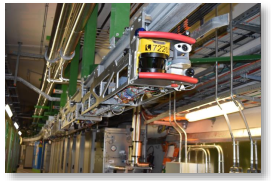


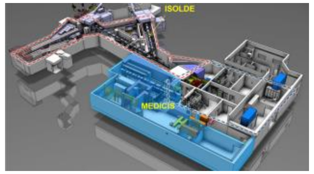
Contents

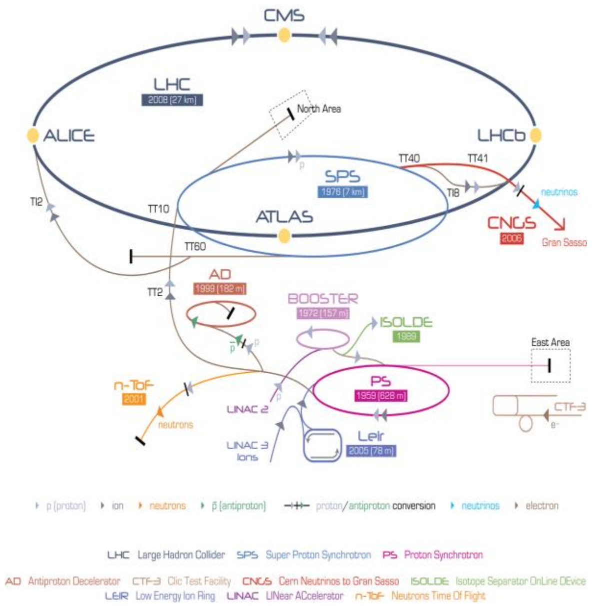
Integration in the Accelerator Complex

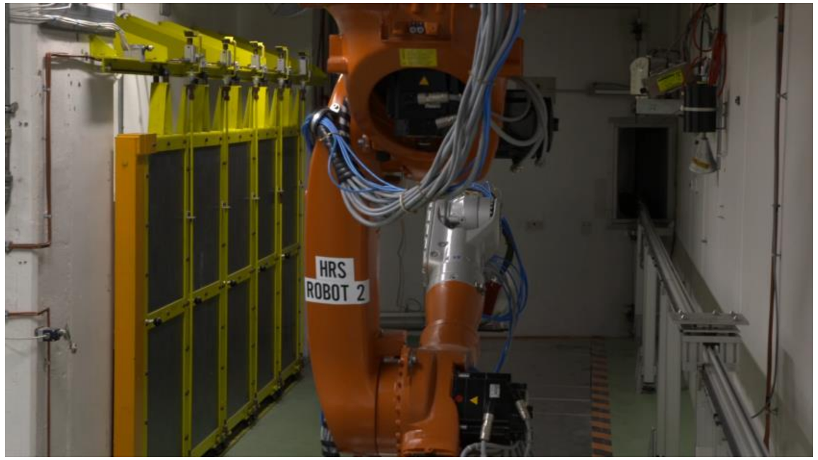


TIM Robot



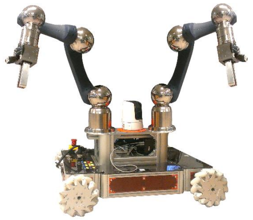






ISOLDE MEDICIS

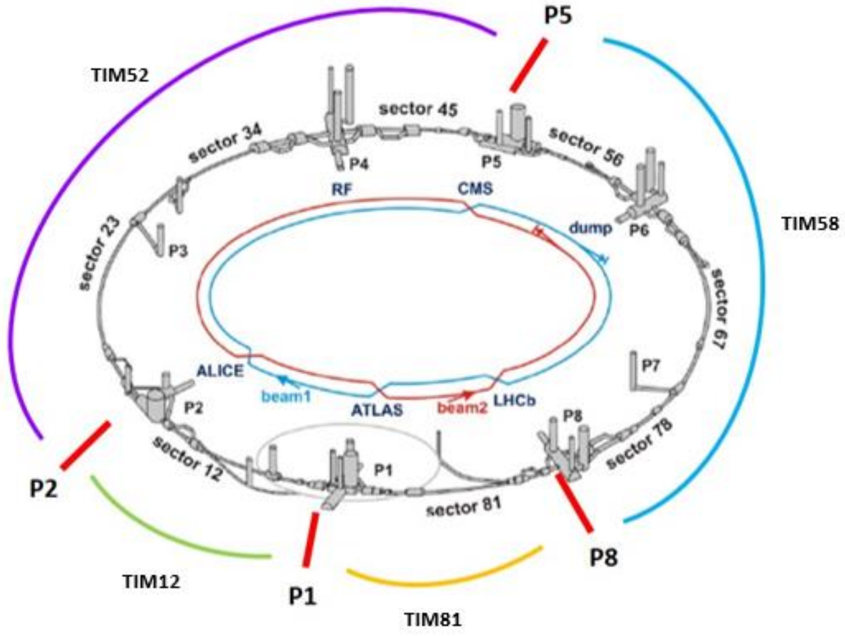
CERNBot

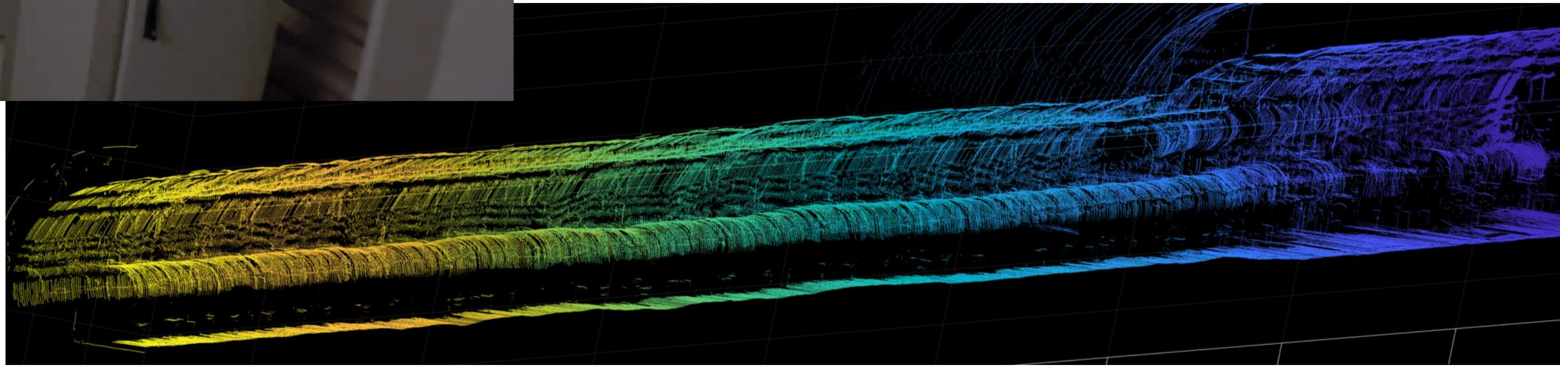


CHARMBot

Interventions: 2020

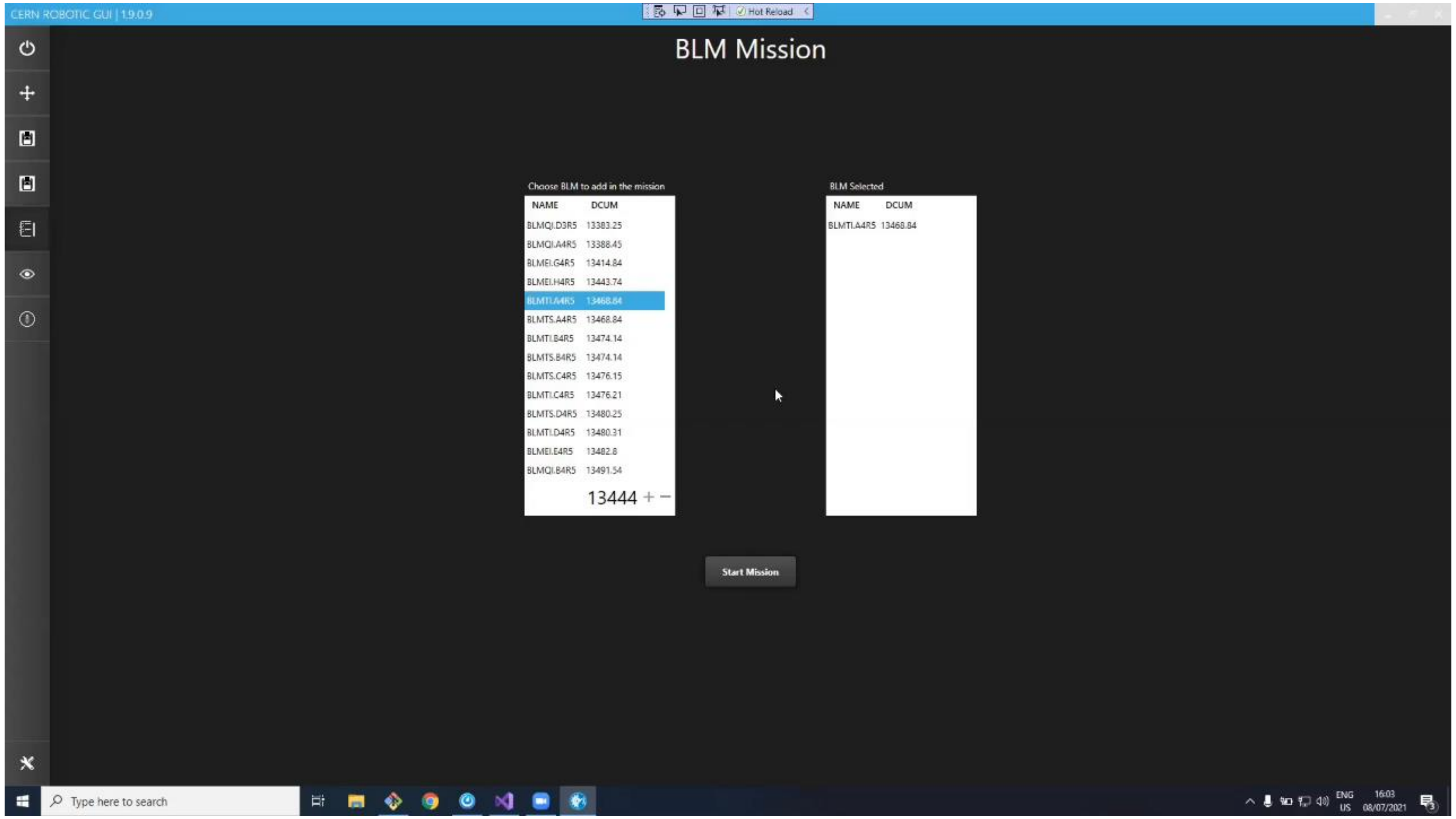
LHC TIM Robot for RP surveys

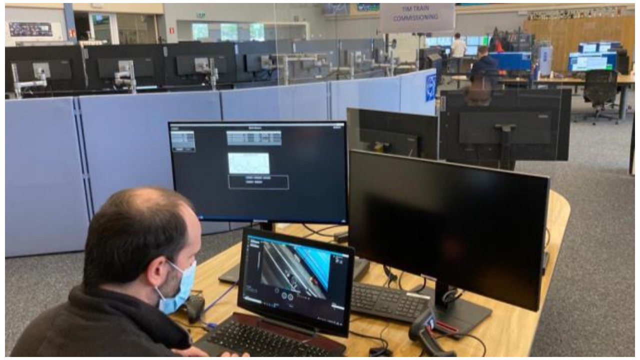




LHC TIM Robot for BLM Validation

- BLM Validation campaign in 2021

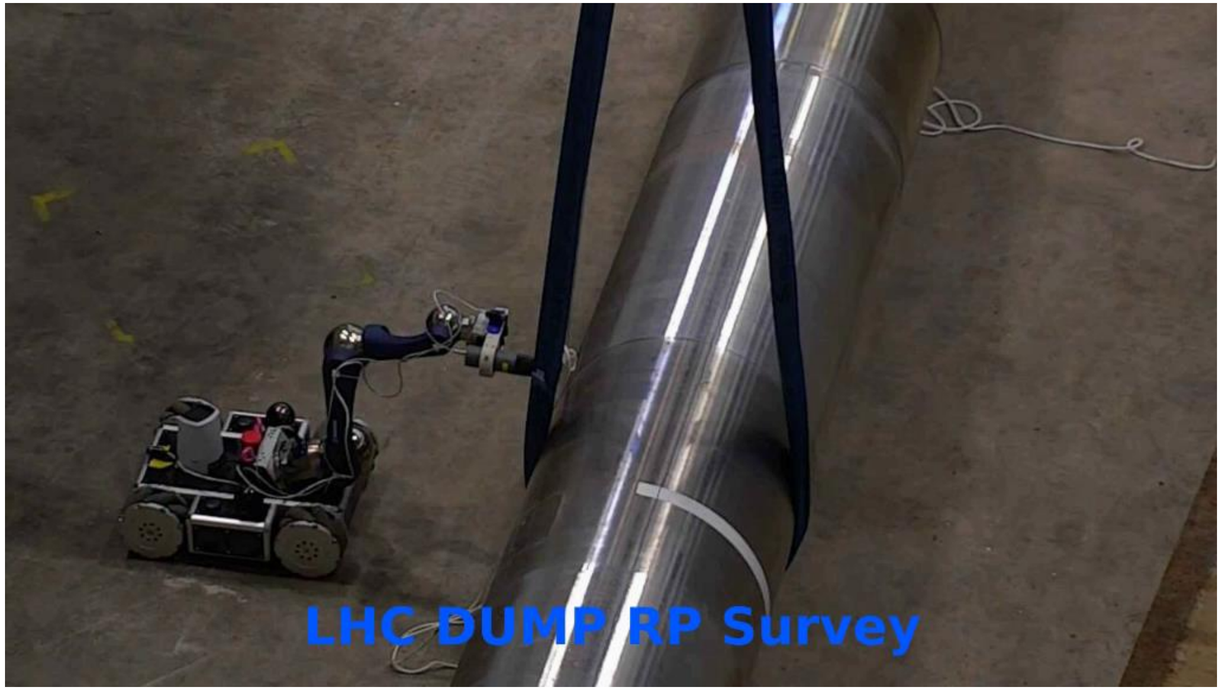




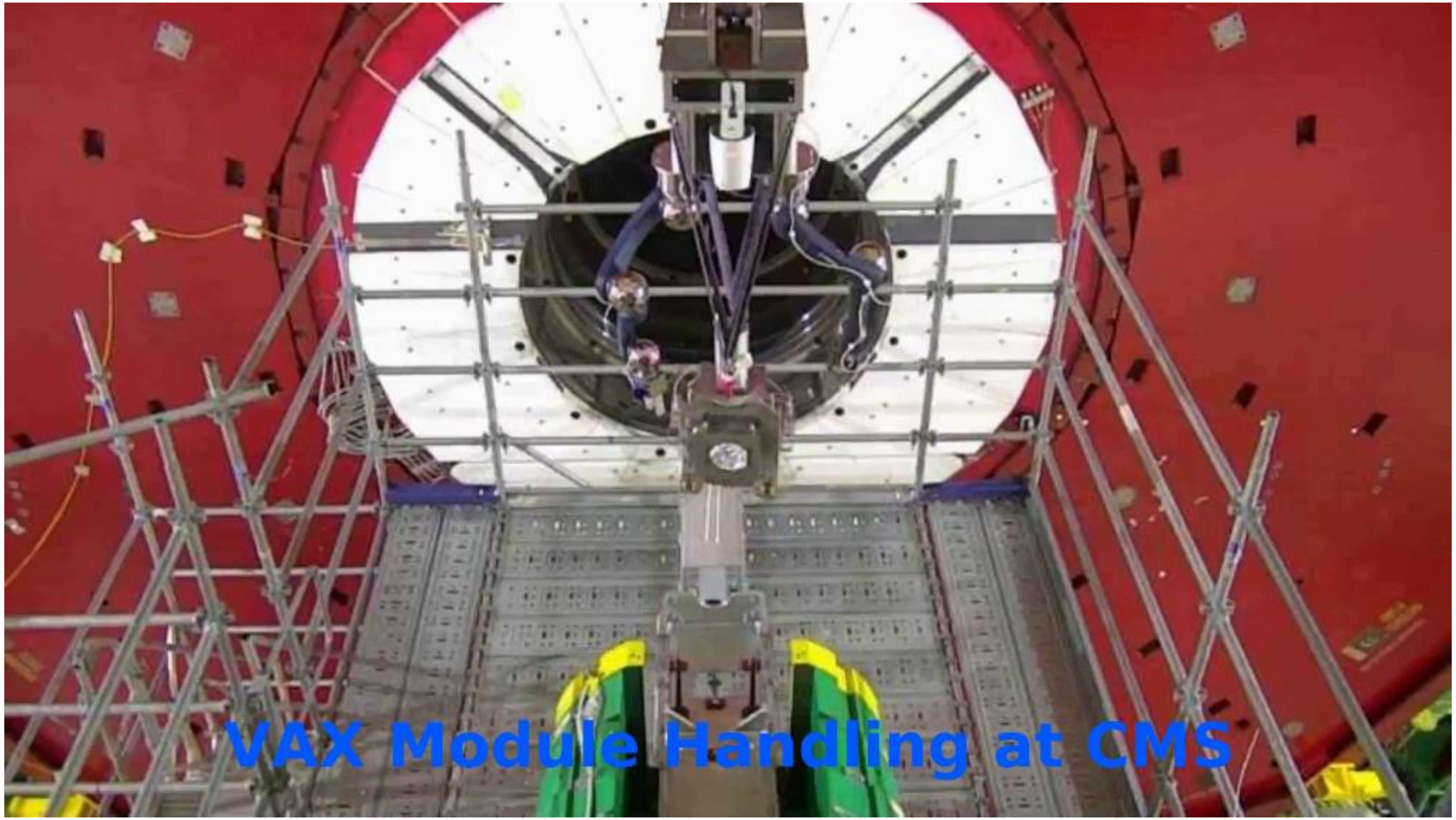
SPS Robot

- Permanently installed robot with charging system in 2021
- Main function to perform RP surveys and other inspection tasks
- Equipped with 6DOF arm
- Autonomous sector door detection, recognition and passage – heavily relies on vision

CERNBot compact use cases

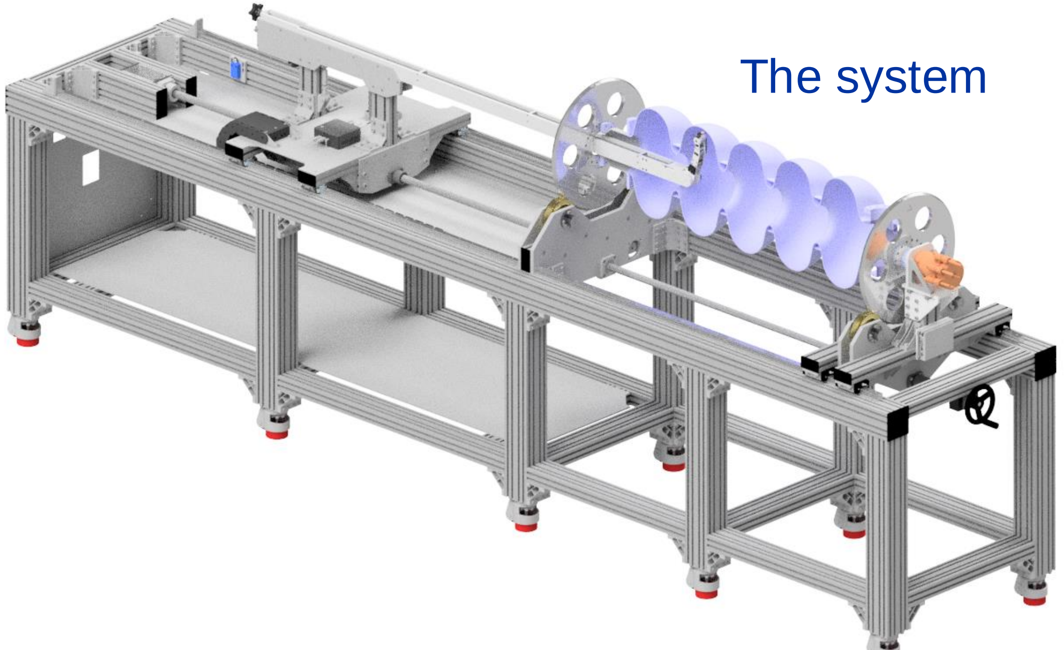


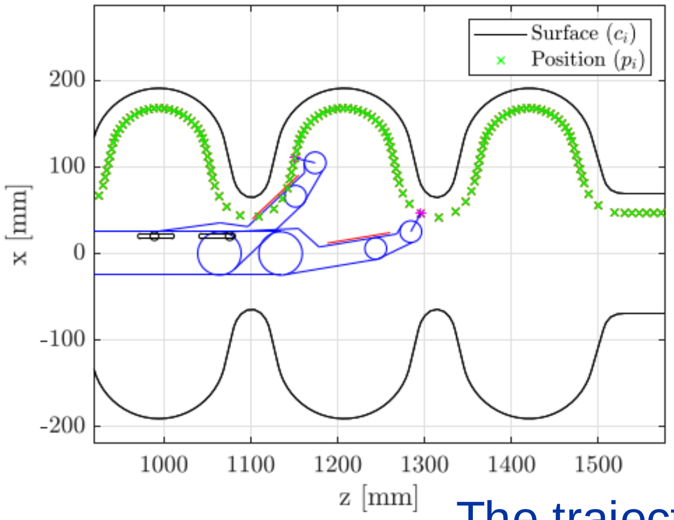
CRANEBot



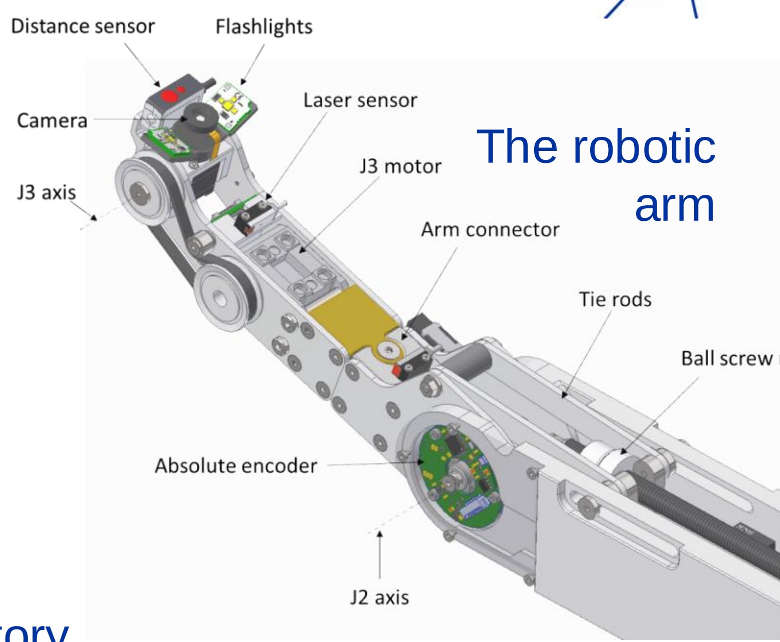
Automated Robotic Inspection System for RF Cavities - ARIS

The system





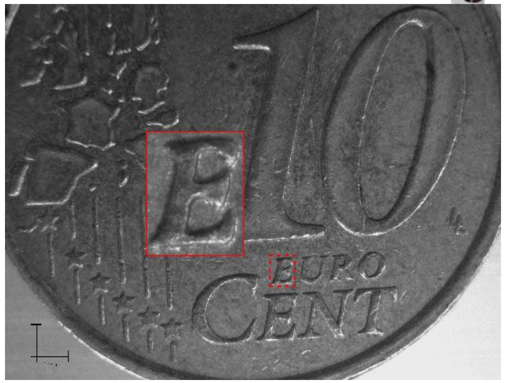
The trajectory

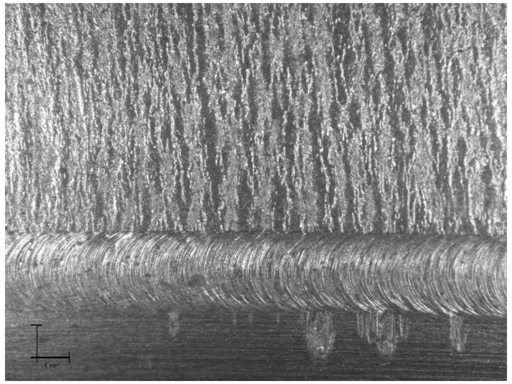


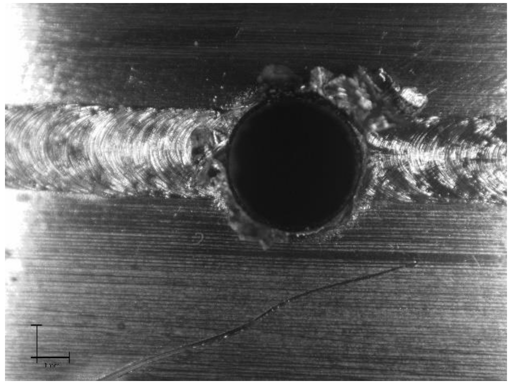
The robotic arm

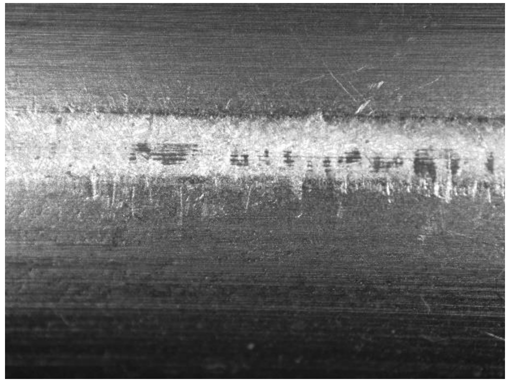
Results:

- 1 picture ≅ 50MB
- Full scan ≅ 20'000 pics
- Full scan ≅ 1 TB
- Full scan time = 12 hours



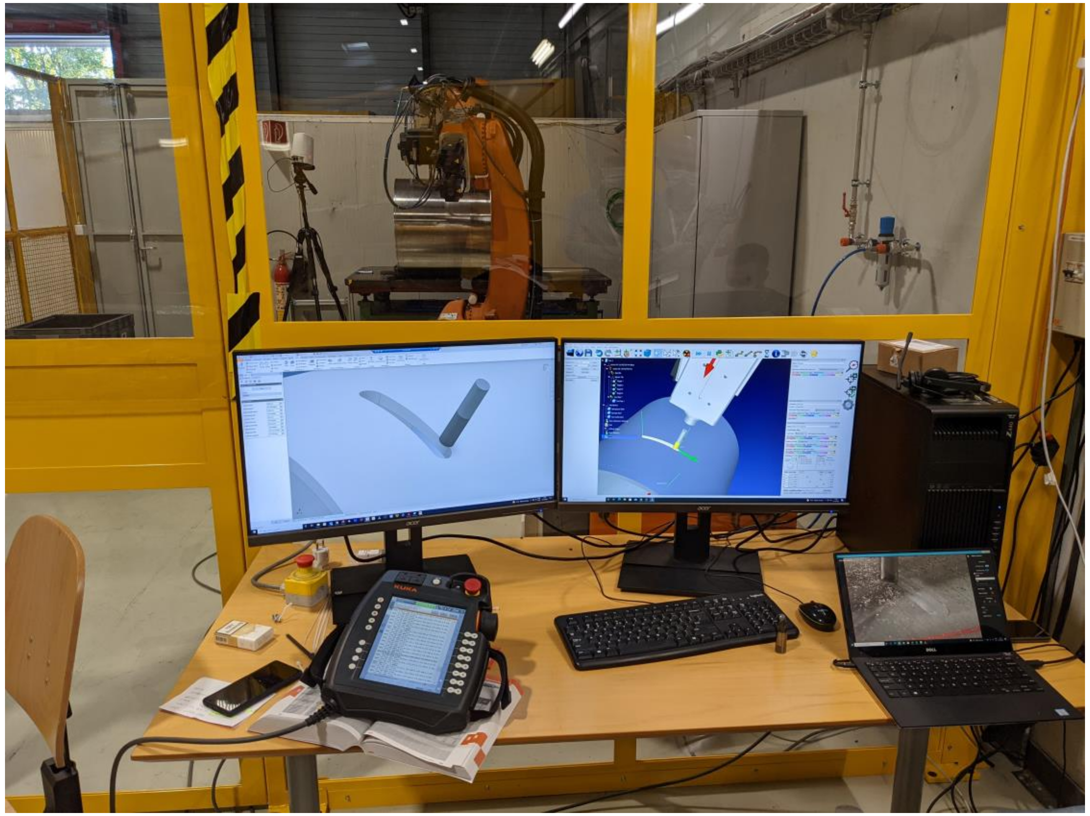






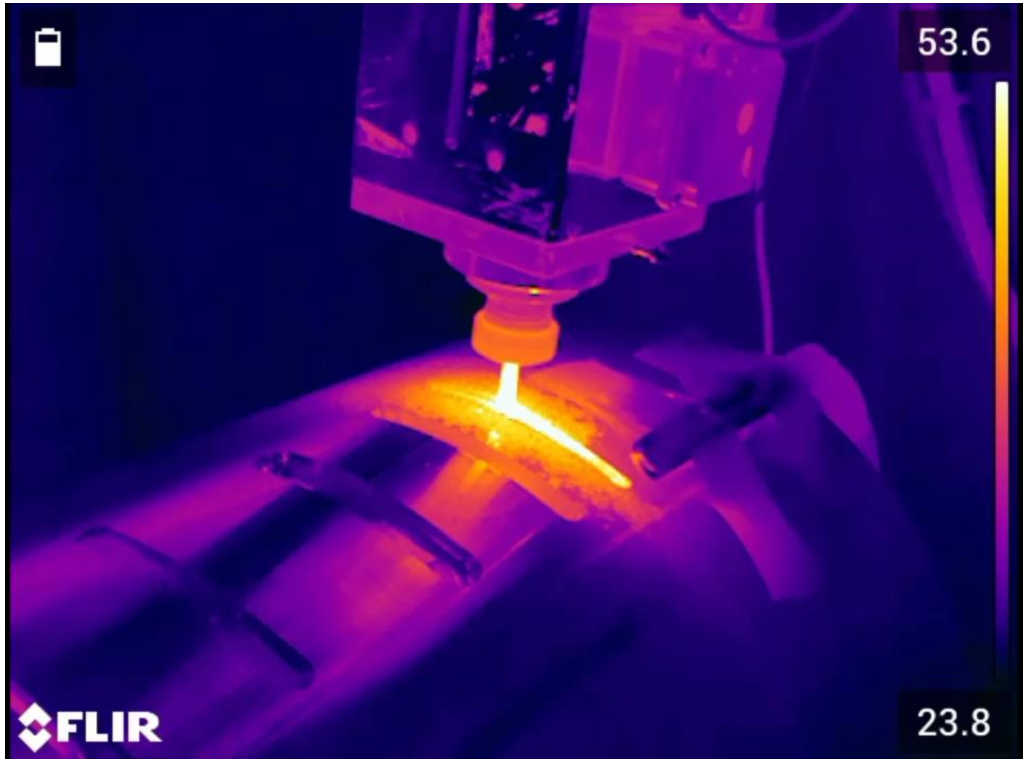
Robots for Milling: LHC TDE

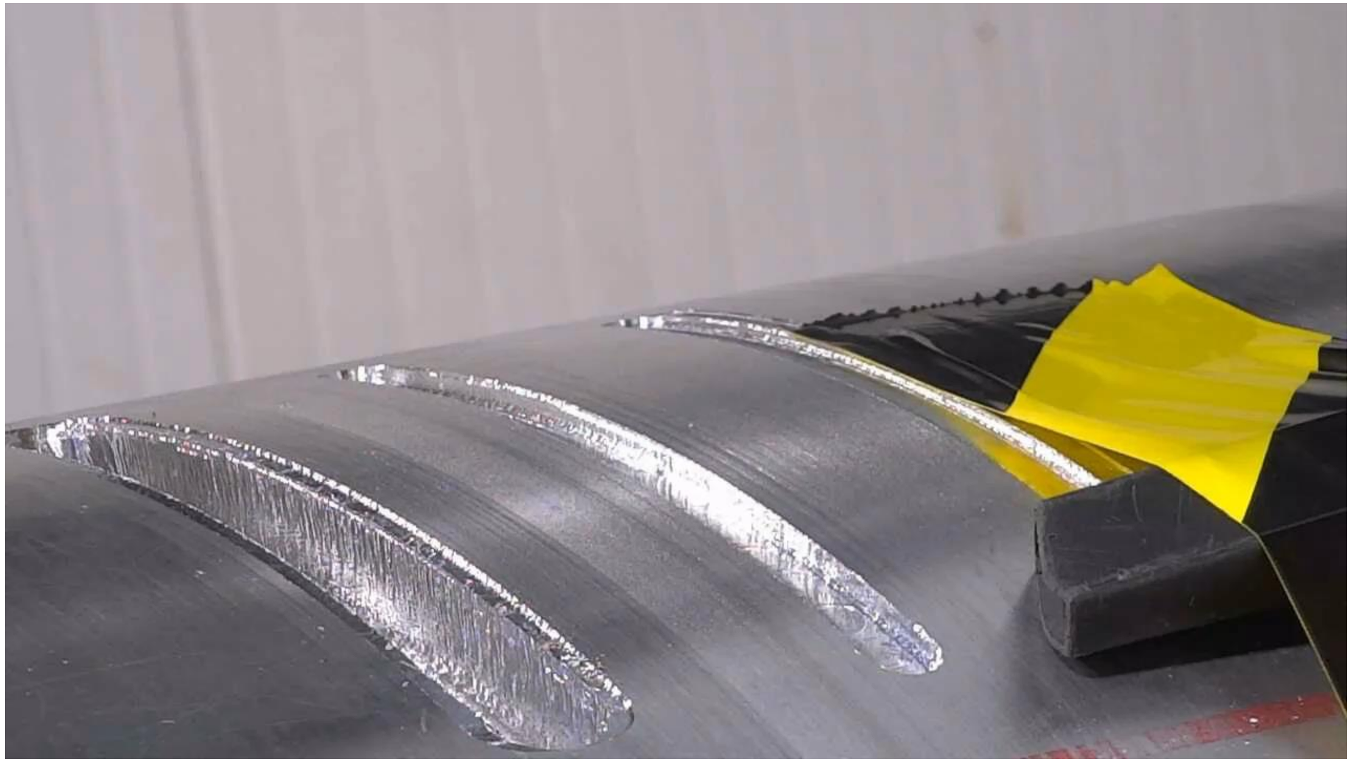
- ➢Milling of 318 LN high strength stainless steel vessel
- ➢Dry and low temperature cutting
- ➢No production of volatile particles or contaminated fluids



Robots for Milling: LHC TDE

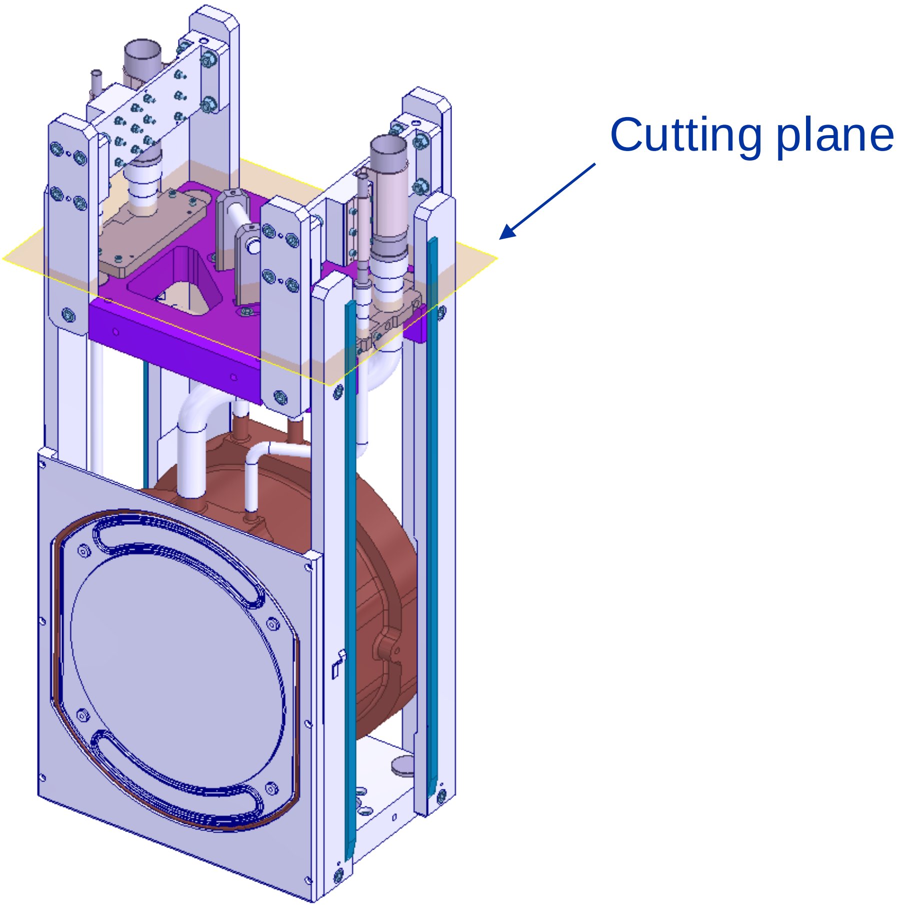
- ➢The cutting parameters created chips (length ~ 5 mm) confined to the working area
- ➢A vacuum cleaning system was mounted on the spindle

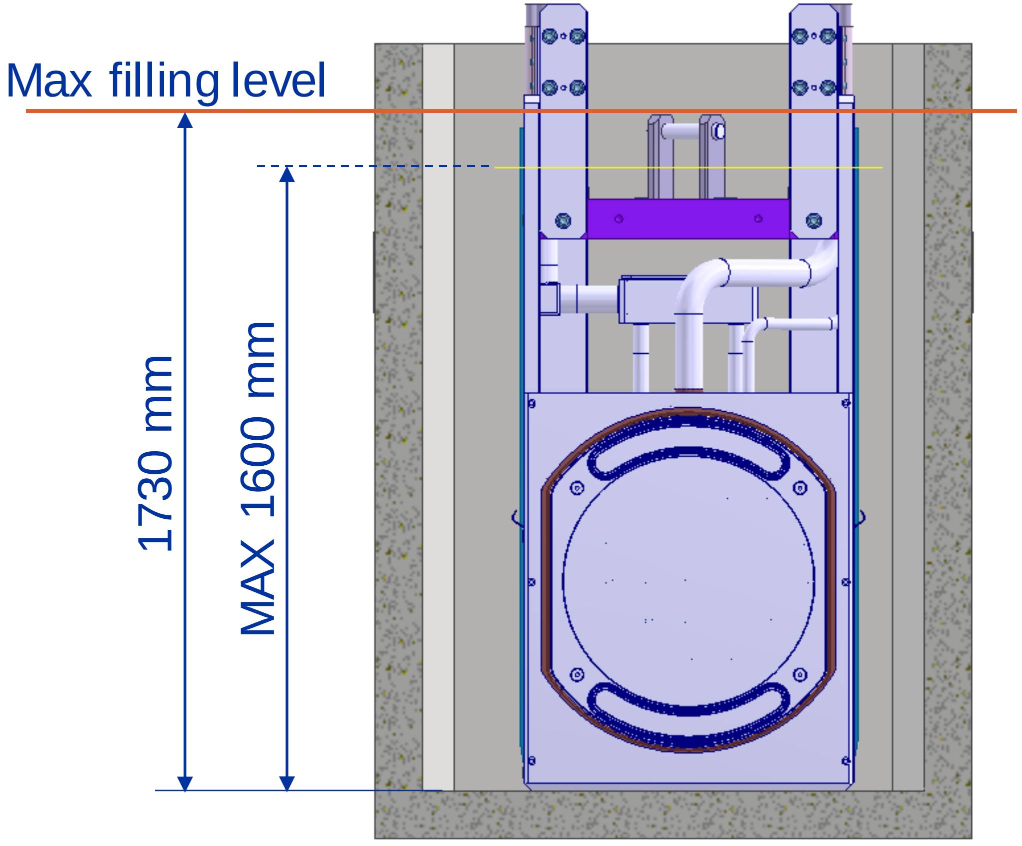




n-TOF Target Autopsy: Planned Intervention

- To cut the frame and prepare the target for radioactive waste long term storage



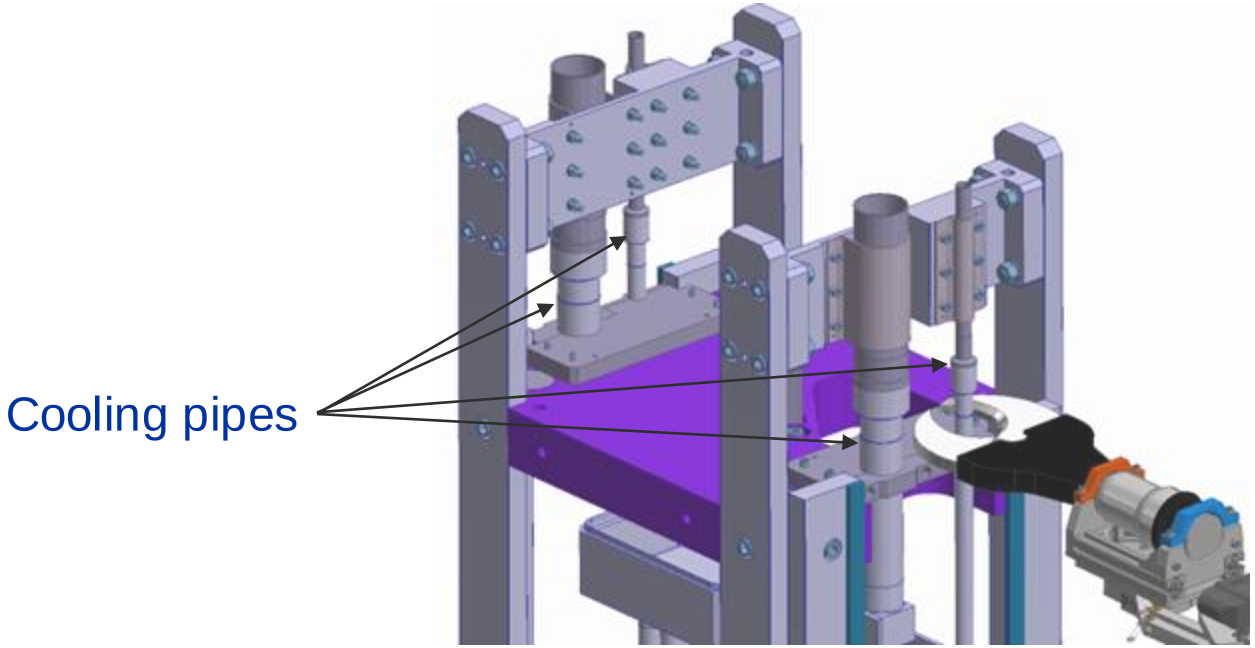


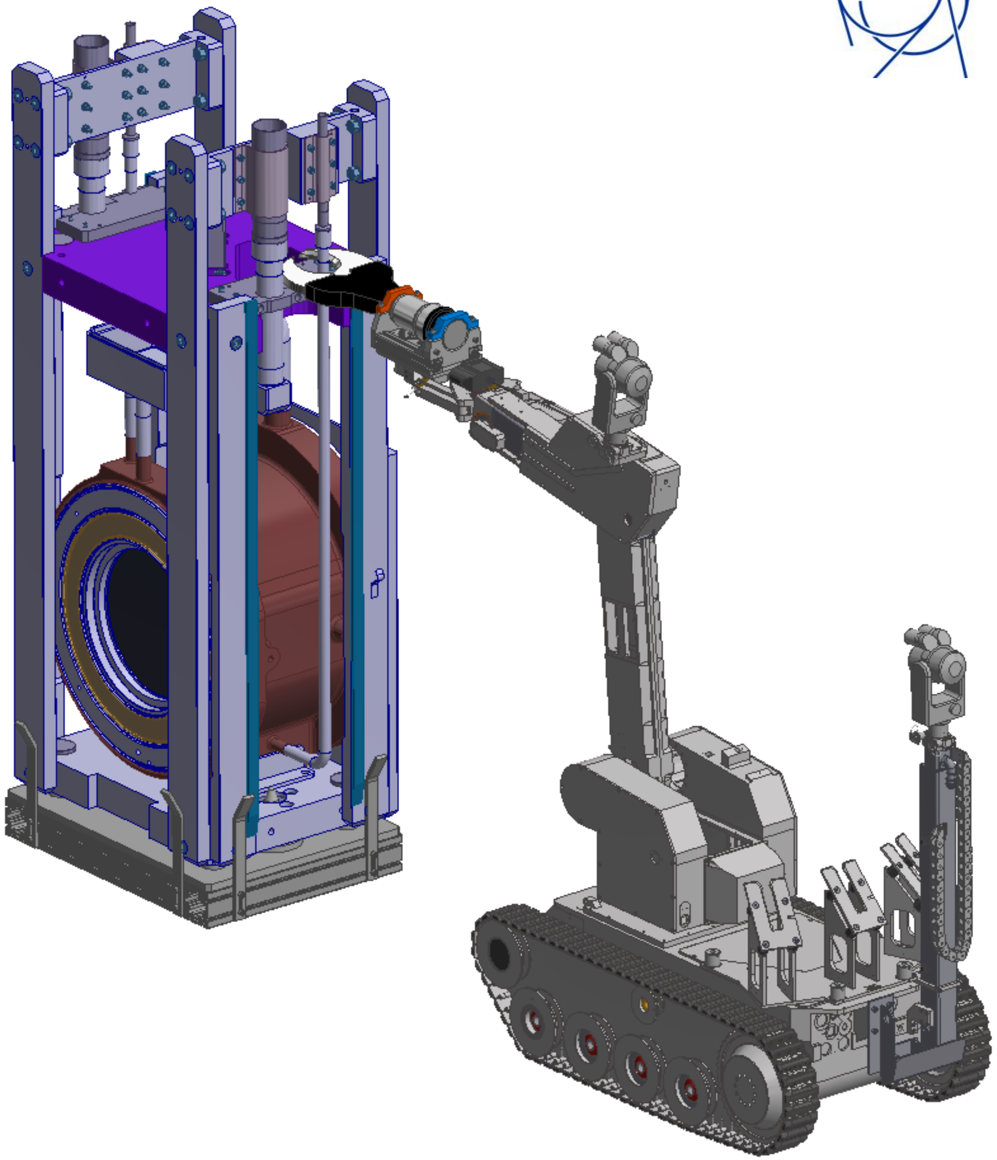
PSI – Betoncontainer Typ KC-T12

Robotic Procedure

- **Cooling pipes cutting**

Once the side profiles have been cut, the 4 cooling pipes are sheared using the hydraulic cutter installed on Teodor

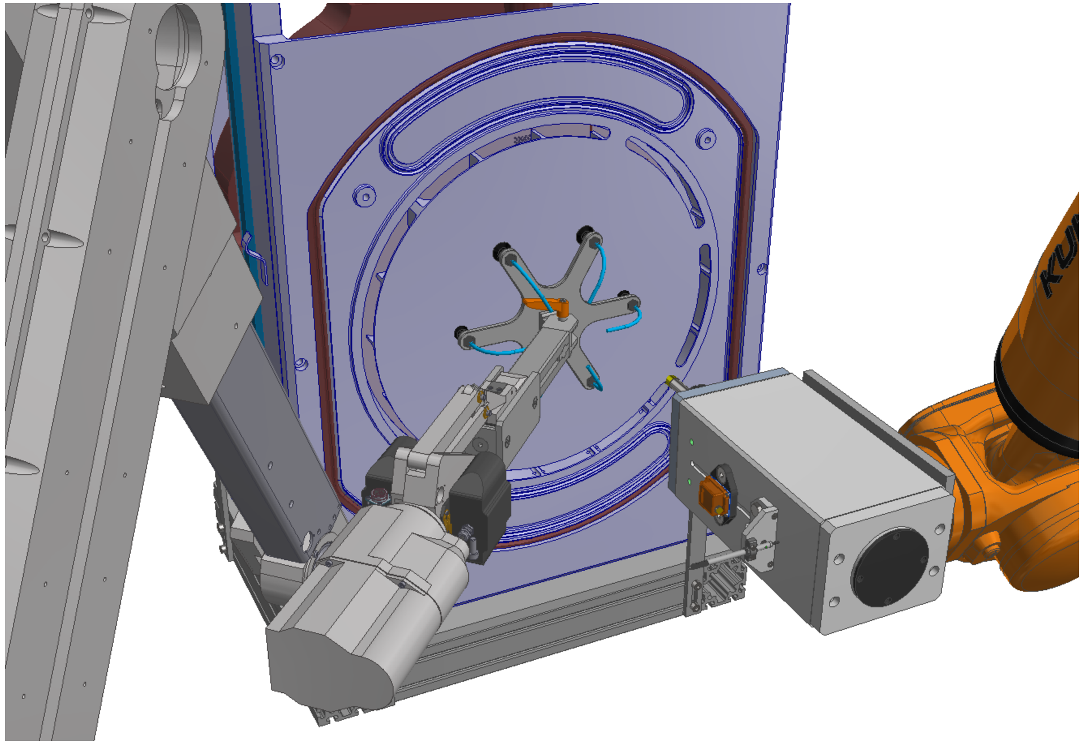


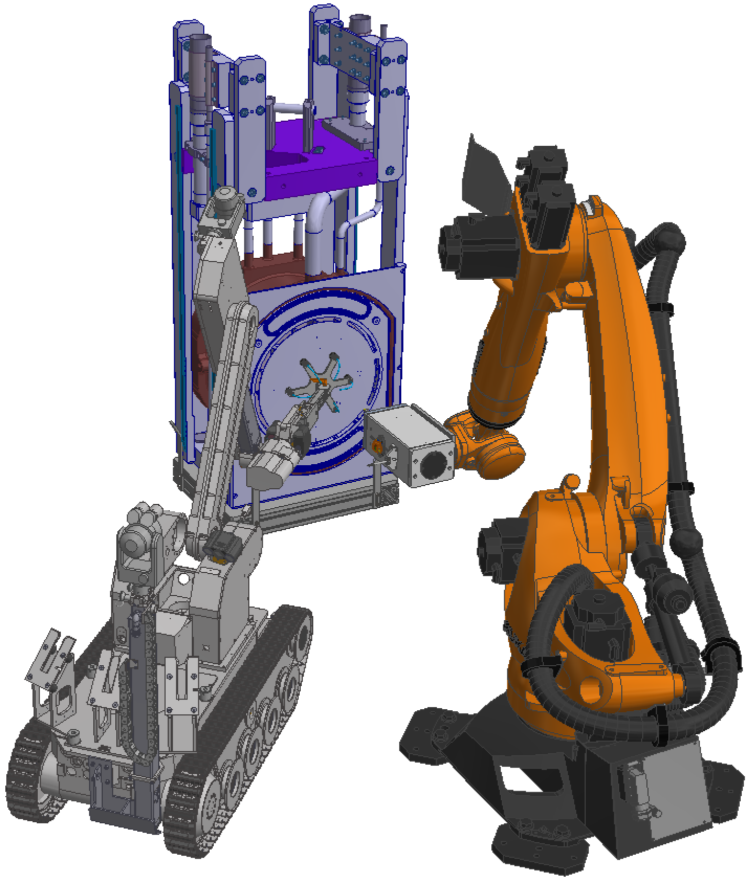


Robotic Procedure

- **Windows layer grasping and attaching points milling**

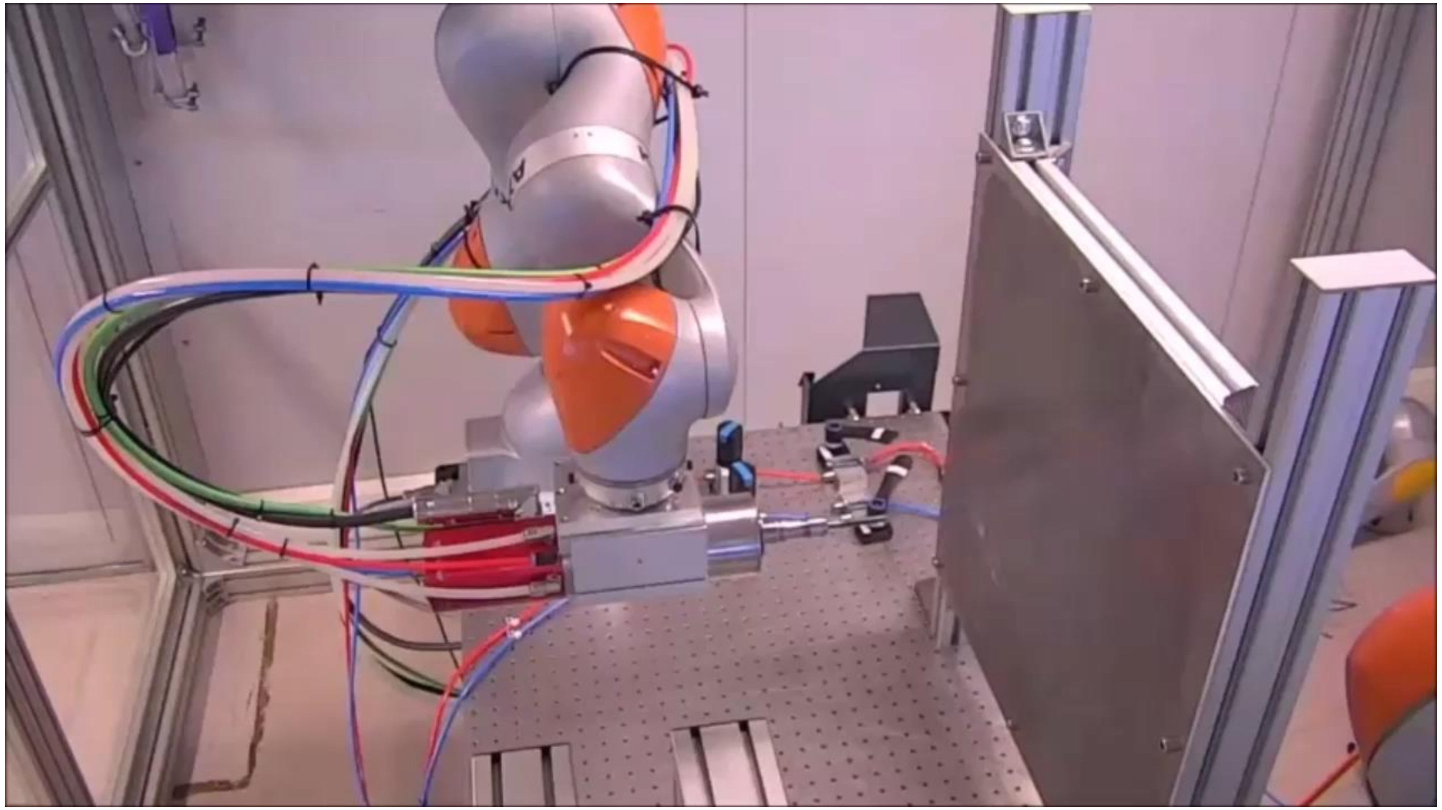
While Teodor holds the window with the vacuum gripper, the three attachment points are milled in sequence (from the first to the third)

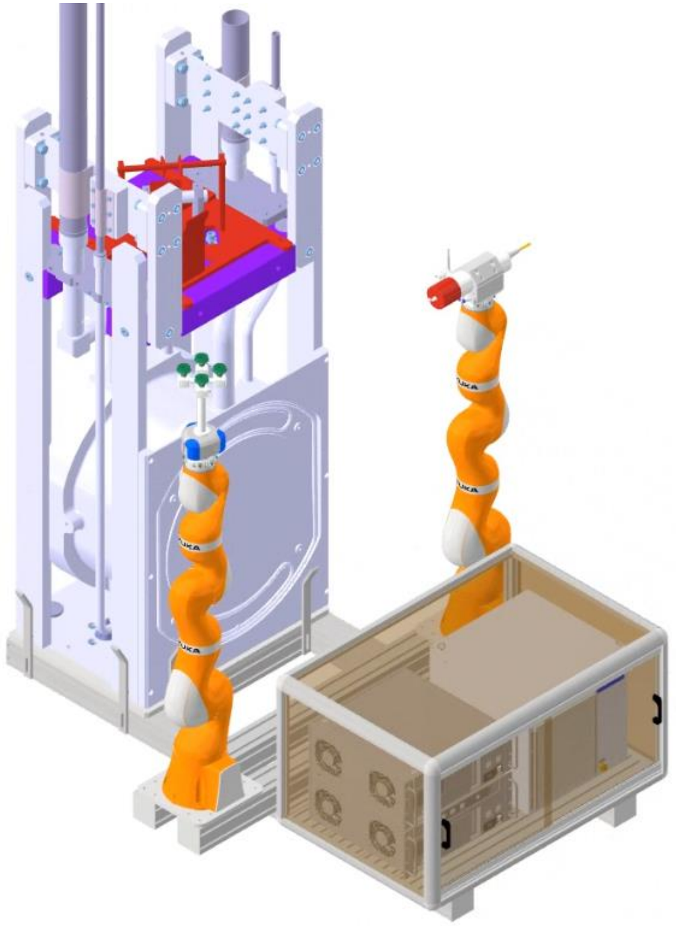




Robotic Procedure

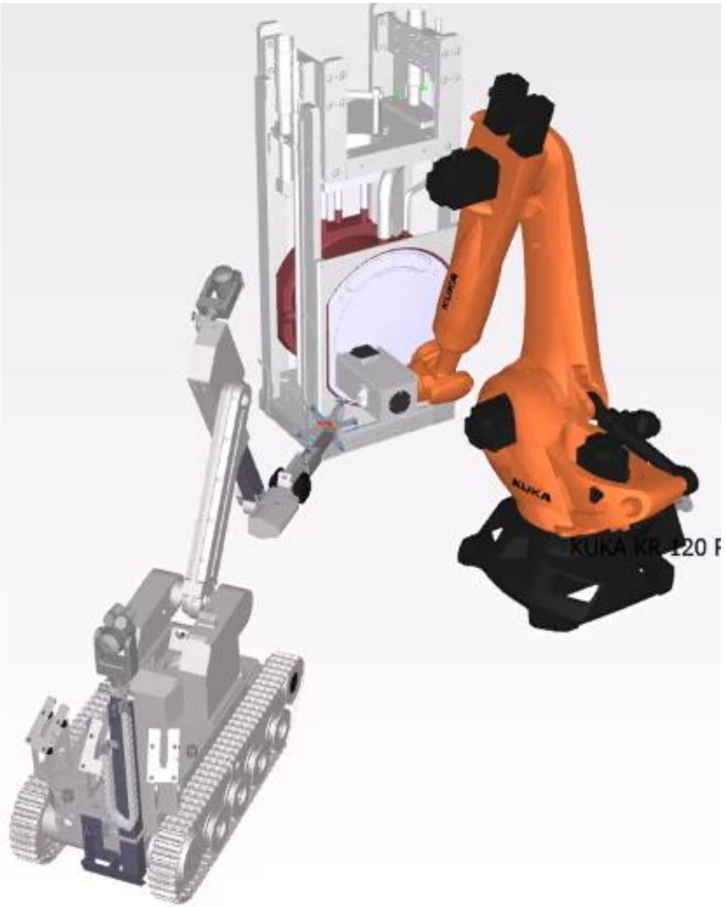
- ➢nTof core inspection and sampling study
- ➢Opening the target by robotic milling solution
- ➢Core inspection and sample extraction

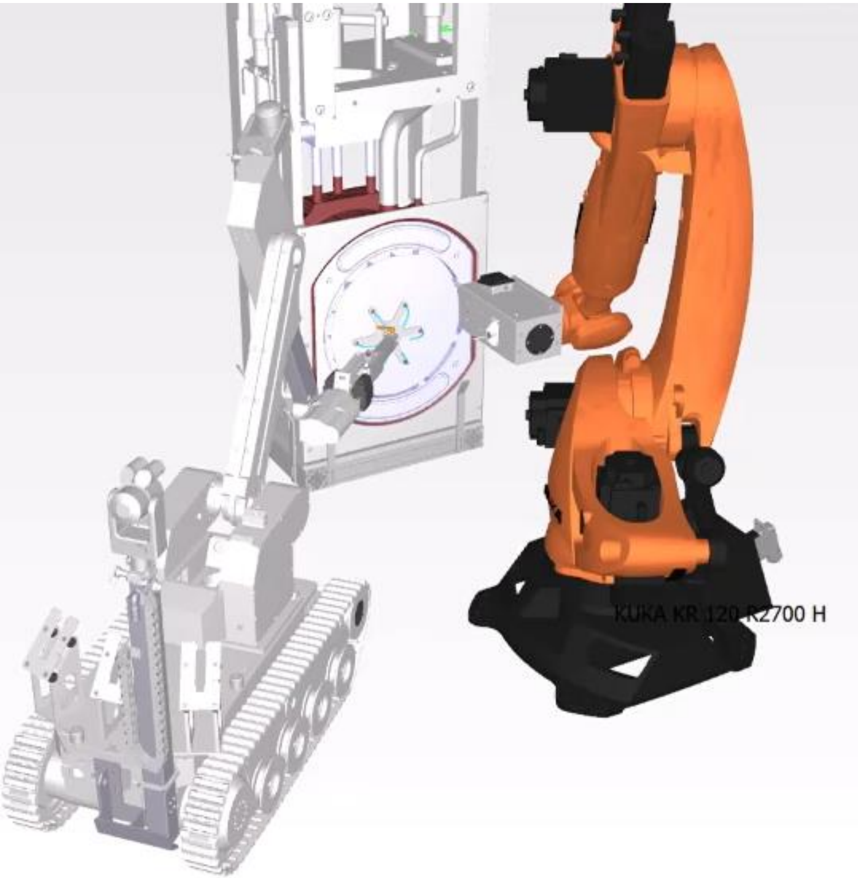


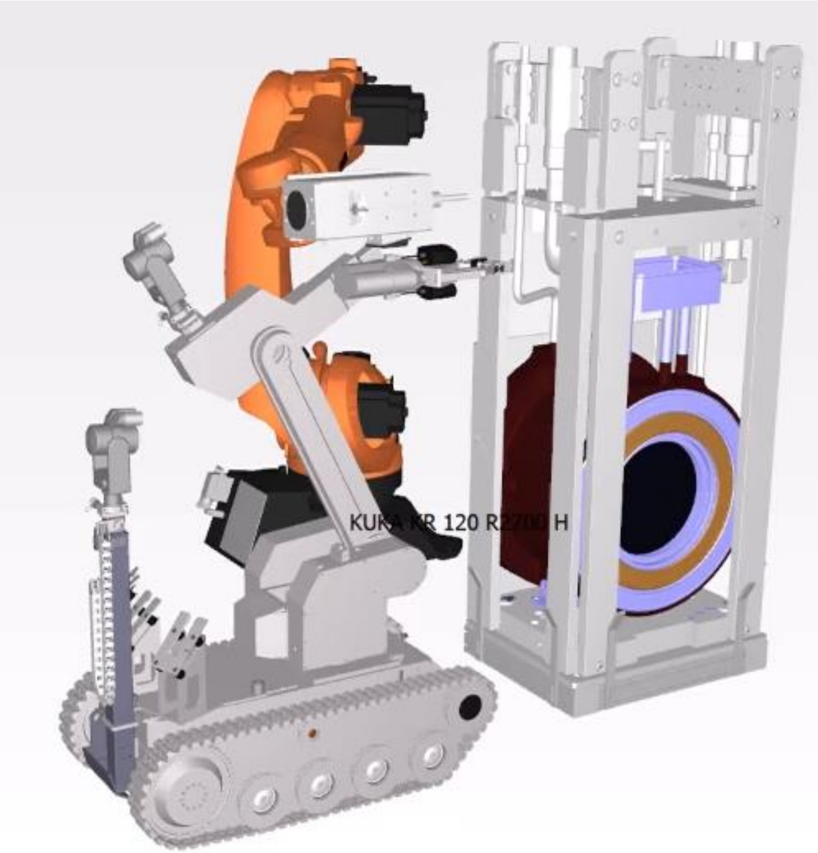


Studies and tests carried out

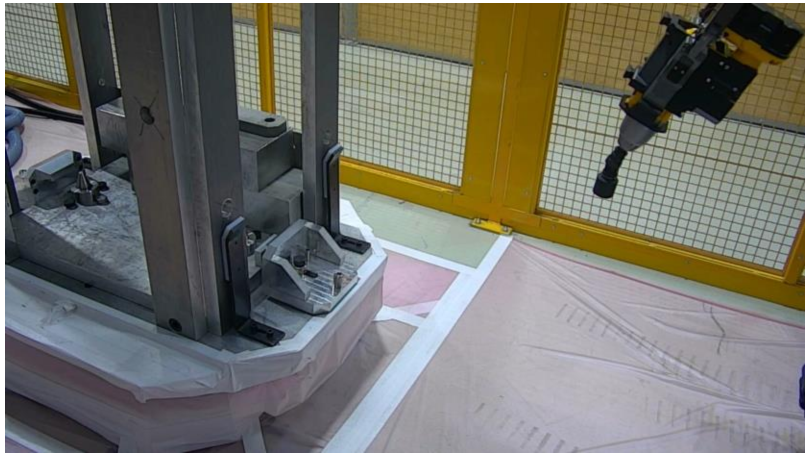
- **Virtual tests of reachability and collision avoidance for all the intervention steps**



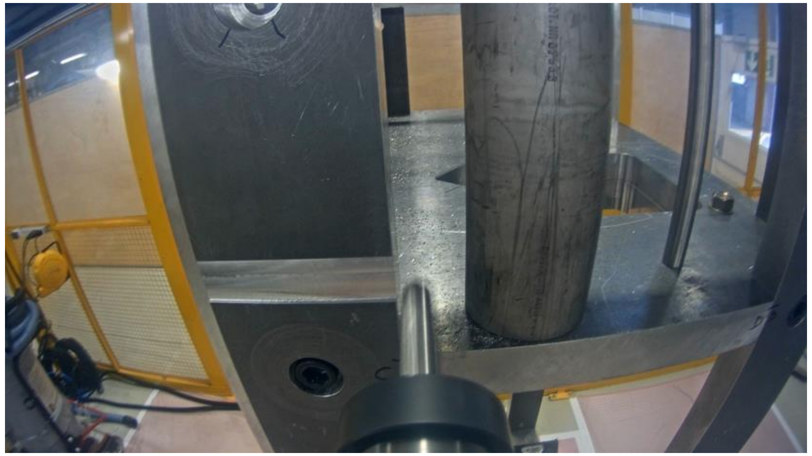




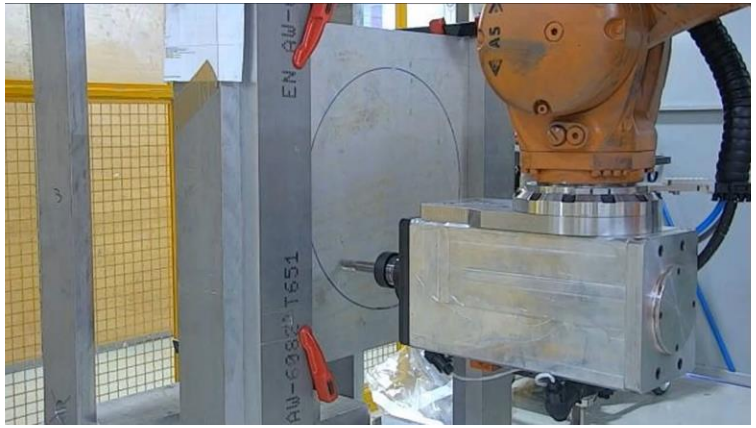
Studies and tests carried out



Clamping System



Frame Milling

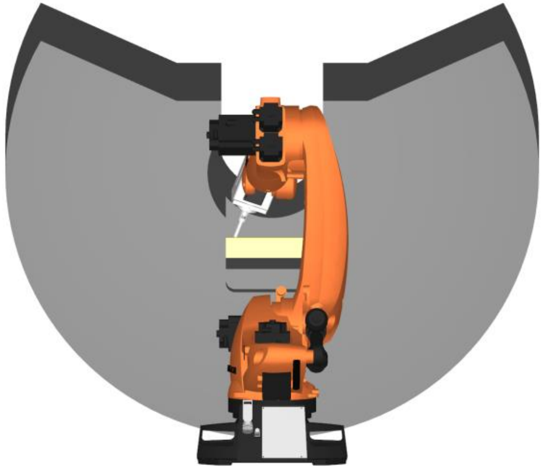


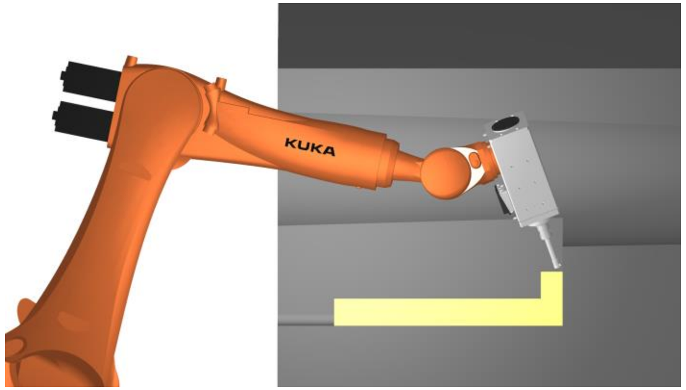
Window Milling

Lifting Test

Robots for Milling: ATLAS

- ATLAS Shielding JFC3 modification by robotic machining



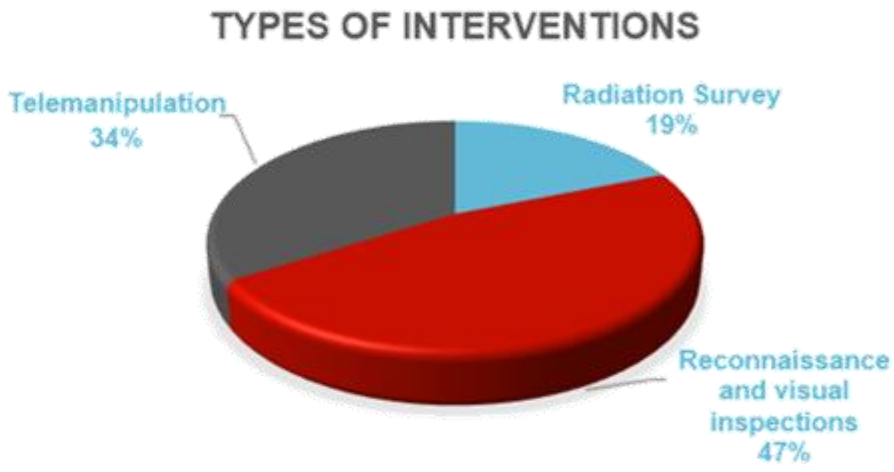


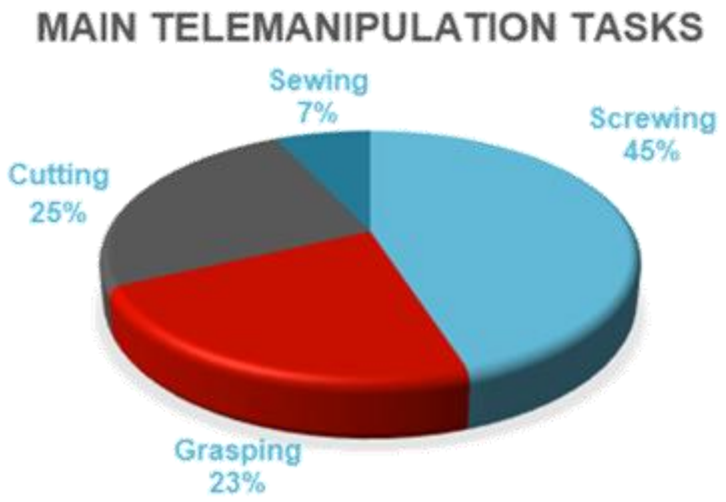
AD Robot & Target Exchange

Contents

Robotics Interventions

- ➢ **More than 1000 robotic operations over the last 8 years**
- ➢ **More than 1500 hours of in-situ robotic operations**
- ➢ **Strong machine availability boost for planned and unplanned/emergency tasks**
- ✓ ISOLDE target exchange, takes 2 hours, for human intervention min 3 days of “target cooldown” would be required
- ✓ Postmortem analysis anticipate knowledge on cause of failure and mitigation effects on new design → Improvement in reliability
- ✓ Remote maintenance interventions usually don’t need machines cool-down period

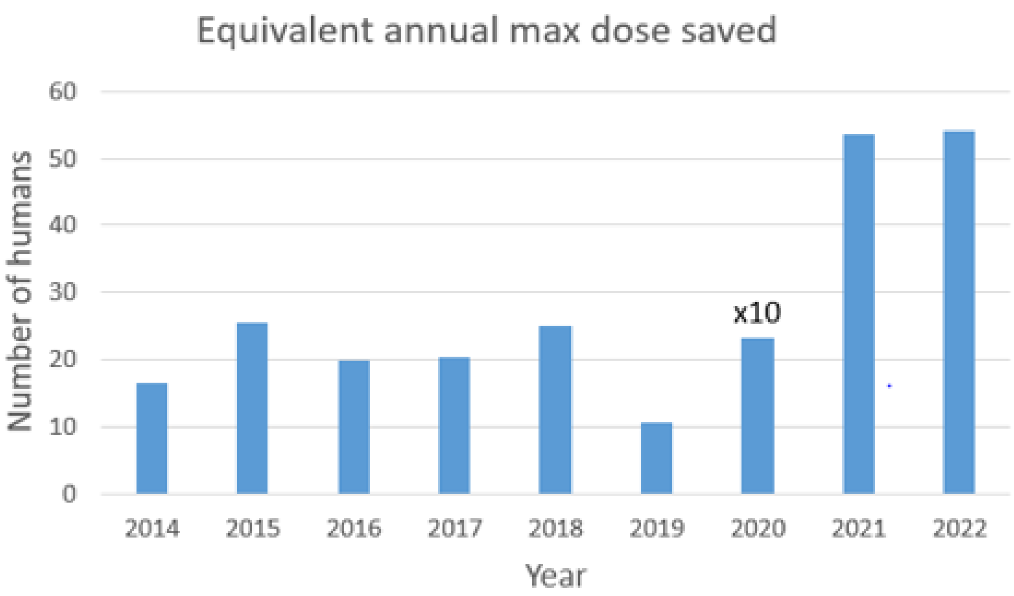


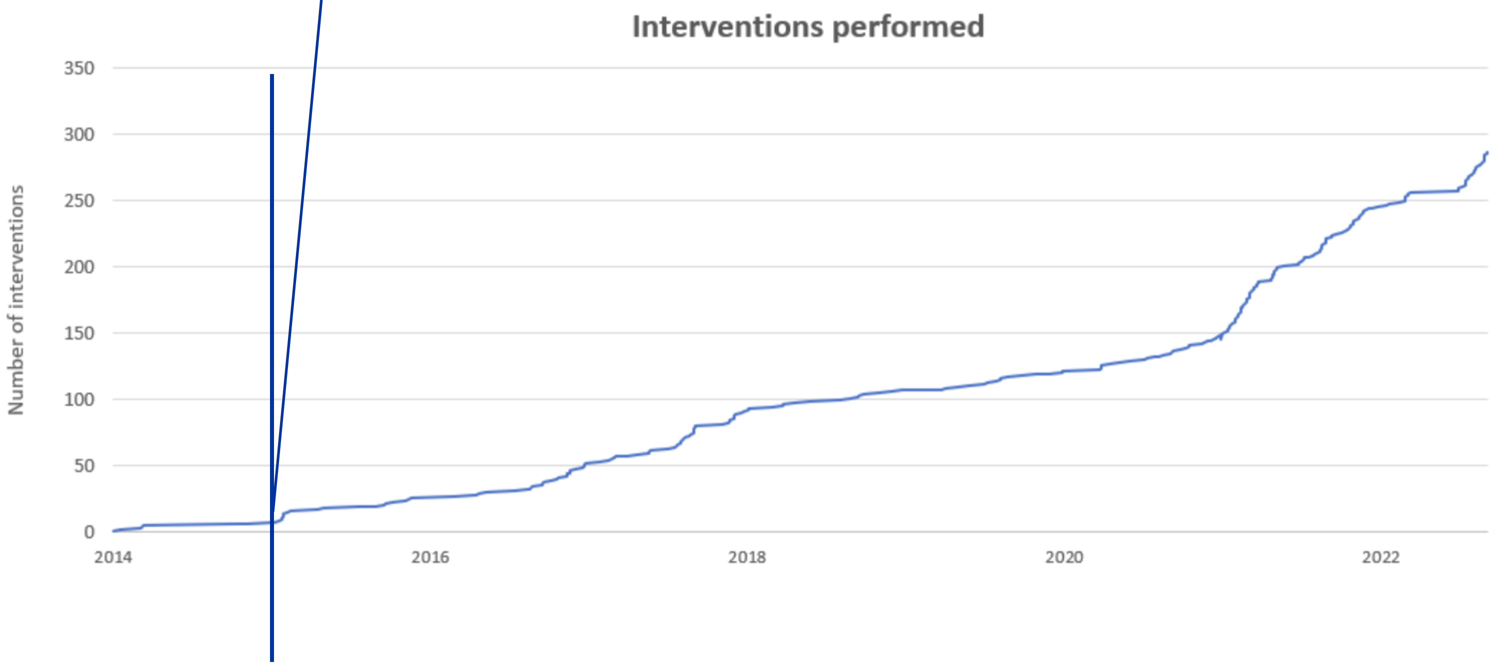


Continuing developing best practice for equipment design and robotic intervention procedures and tools including recovery scenarios

Robotic Support at CERN

Started to apply CERN custom made robotic solutions.
Remote maintenance capabilities and modularity strongly increased!





Our Impact

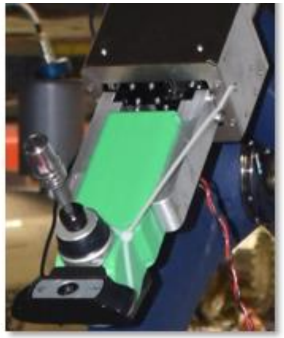
- More than 15 modular robots developed
- Novel tools and intervention procedures based on feedback from operators (towards development of ‘best practices’)
- Novel simulation tools for training and dose estimations
- Novel control software and HRI
- Several Master and PhD Thesis supervised (>30)
- Several publications to conferences and high impact factor journals (>50)
- Over 6 ongoing research collaborations
- Chair of the EURobotics Teleoperation Working Group

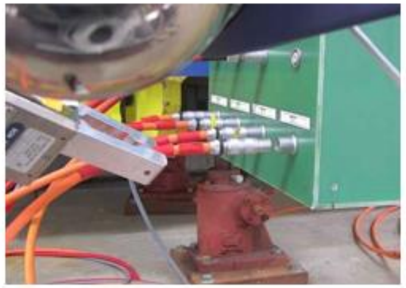
Procedures and Tools

- Several time consuming and costly tools, procedures and mockups prepared for intervention on non-robotic friendly interfaces
- Intervention procedures, recovery scenarios, tools and mock-ups are as important as the robot
- Standardization of interfaces and procedures → reduces costs and intervention time



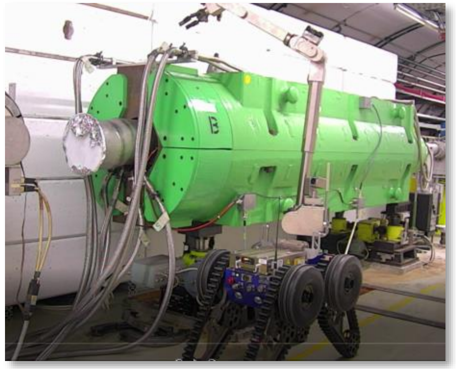
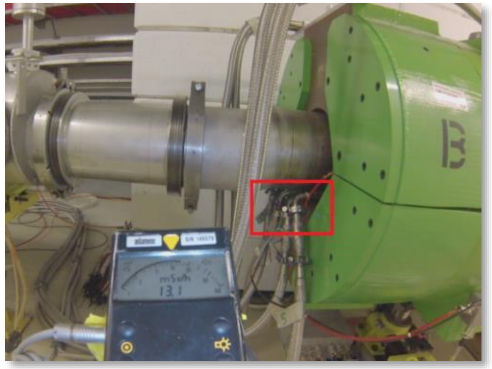




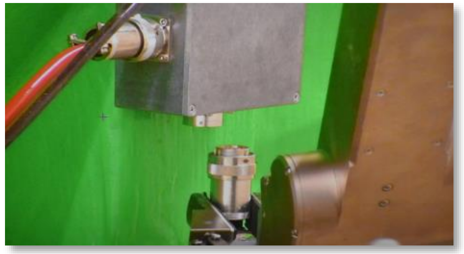



Importance of the Design Phase

- Designing machines that can be maintained by robots using appropriate and easily accessible interfaces will increase maintainability and decrease human exposure to hazards







Easier remote or hands-on manipulation than chain-type connection

Guidelines for Robot Code of Practice

Modularity	Maintenance Time Labelling & guides Spare Parts
Accessibility	Space Access Visual
Simplicity	Components Procedures Natural Laws Aid
Standardization	COTS Sizes Cost reduction
Radiation & Decontamination	Surfaces Coverings Lifetimes & Shielding

EDMS: #2263542

Guidelines for Robot Code of Practice

Connectors

- Push/Pull
- 90º vs straight

Fasteners

- Bolt Heads & Lead-in
- Threaded vs Nuts
- Captive Bolts

Fluid Coupling

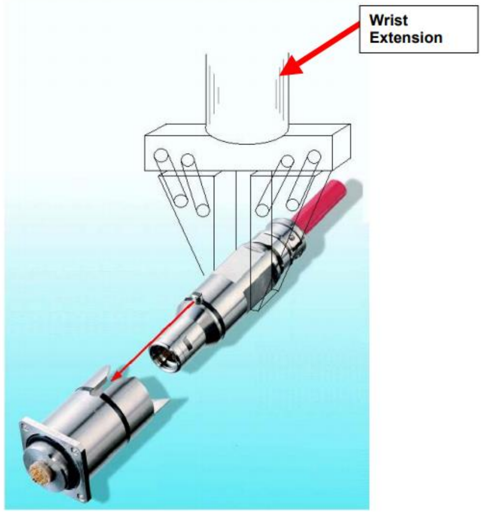
- Quick release
- Flexible hose
- Force for handling

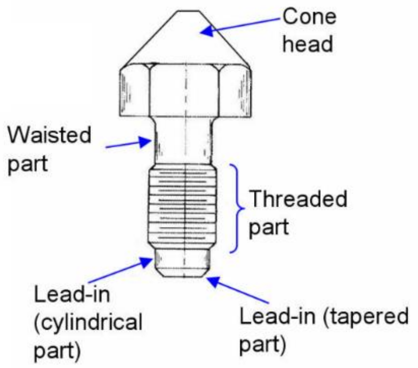
Pipes & flanges

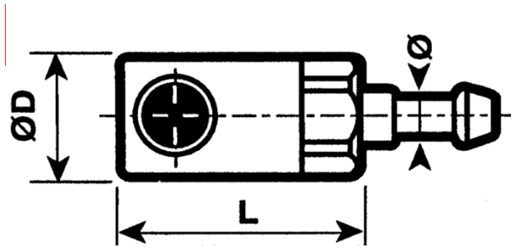
- Quick Disconnect System
- Consider seals
- Pipe dimensions

Patch Panels

- Element space
- Custom design
- Non-blocking position







Interesting collaborations with ORANO?

- RadHard development of cobot-esque arm (for mobile base) e.g. Pilz/Schunk
- RadHard development of the KUKA for stationary applications
- Collaboration around back-engineering tools for end-effectors
- As well as many other collaboration possibilities regarding user interfaces/other software

References

1. “A Robotic System for Remote Interventions in the FCC Complex”, Hannes Gamper, FCC Week 2021, https://indico.cern.ch/event/995850/contributions/4405716/
2. CERN Academic Lecture Series: Robotics activities at CERN - Robotic Solutions for remote maintenance, 2022, https://indico.cern.ch/event/1055745/
3. “i-TIM: A Robotic System for Safety, Measurements, Inspection and Maintenance in Harsh Environments”, Mario di Castro et al, 2018, https://inspirehep.net/literature/1702507
4. “A Dual Arm Robotic Platform Control for Navigation”, Mario di Castro et al, 2017, https://inspirehep.net/files/645de51cb422766dc3e58c9a402a9704
5. “CERNTAURO: A Modular Architecture for Robotic Inspection and Telemanipulation in Harsh and Semi-Structured Environments”, Mario di Castro et al, 2018, https://ieeexplore.ieee.org/document/8391705
6. “An Advanced, Adaptive and Multimodal Graphical User Interface for Human-robot Teleoperation in Radioactive Scenarios”, Giacomo Lunghi et al, 2016, https://dl.acm.org/doi/10.5220/0005971402240231
7. “Vision-based change detection for inspection of tunnel liners”, Leanne Attard et al, 2018, https://www.sciencedirect.com/science/article/pii/S0926580517305769