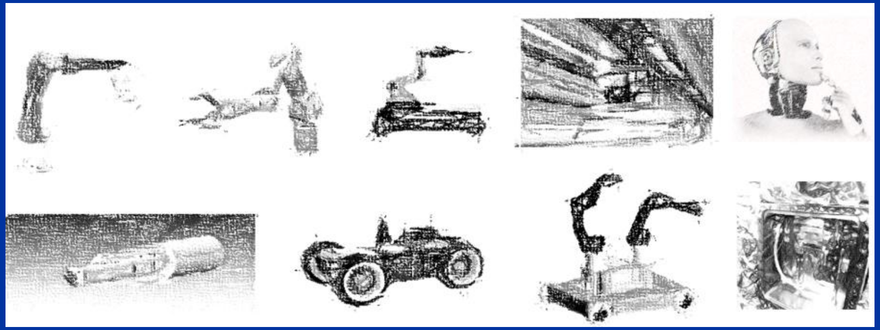
Controls Electronics & Mechatronics

Robotic Solutions for Remote Maintenance and Quality Assurance

BE-CEM-MRO



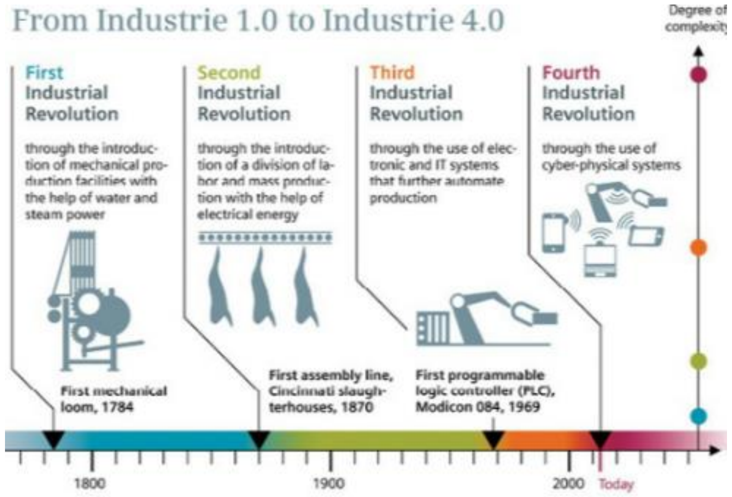
BE-CEM Technical Meeting, 16.11.2021

Content

- Introduction and state of the art
- Needs and challenges for robotics at CERN
- The robotic service in BE-CEM
- Future objectives
- Conclusions

Robotics

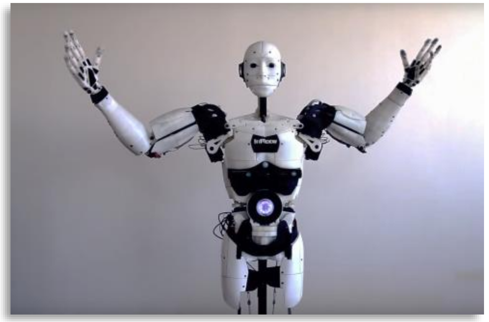
- **Industry 4.0**
  - ✓ Robots
  - ✓ Artificial intelligence
  - ✓ Internet of things
  - ✓ Diffuse signals
  - ✓ Sensor fusion
  - ✓ Simplification in the use of robots



- **Human-robot cooperation**
  - ✓ ISO 2011
  - ✓ Robots can assist humans
  - ✓ Robot learning by demonstration

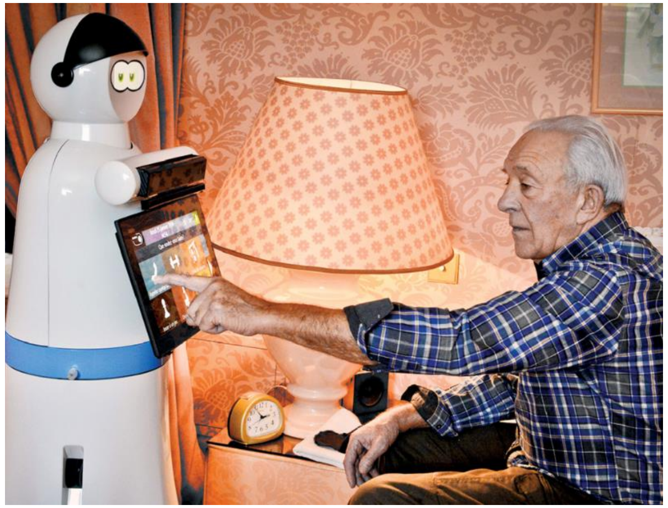
Robotics: type of robots (based on application)

- ✓ Hobbies, competition and entertainment
  - ❑ Suitable for high school teaching
- ✓ Industrial
  - ❑ Repetitive tasks
- ✓ Medical
  - ❑ Surgery/Rehabilitation
- ✓ Domestic or household
- ✓ Military
- ✓ Service and space robot
  - ❑ Research
  - ❑ Intelligent



Where R&D in Robotics Worldwide is Mainly Going?

- **Focus/resources on:**
- ✓ Social robotics
- ✓ Autonomous driving vehicles
- ✓ Surgical robotics
  - ❖ Powered by AI



Machine learning in Robotics #3

- Robotics community is investing strongly in machine learning adapted to social robotics

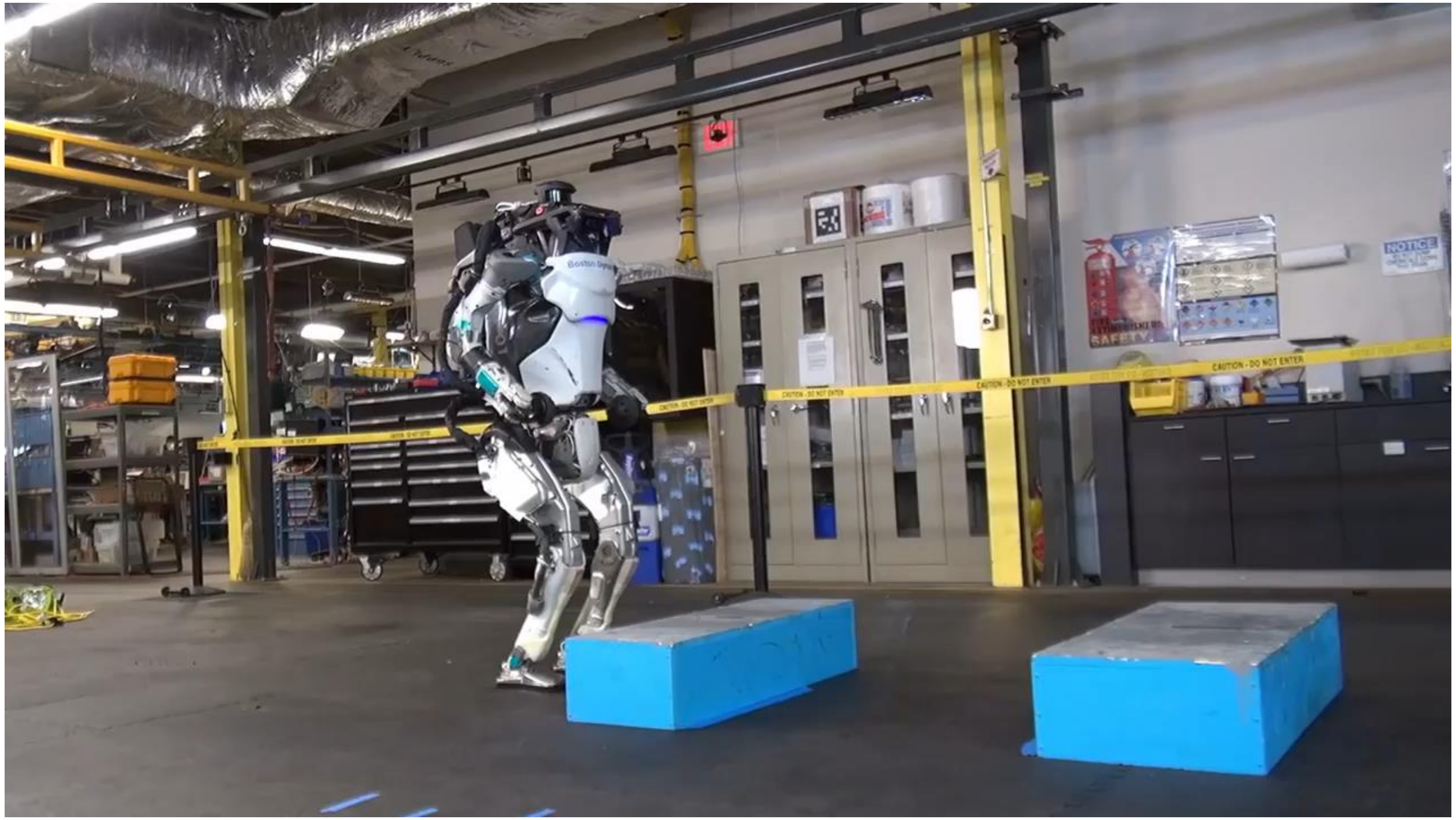
Jia Jia

Our dream: Robots made in Hollywood

iRobot, Chicago 2035

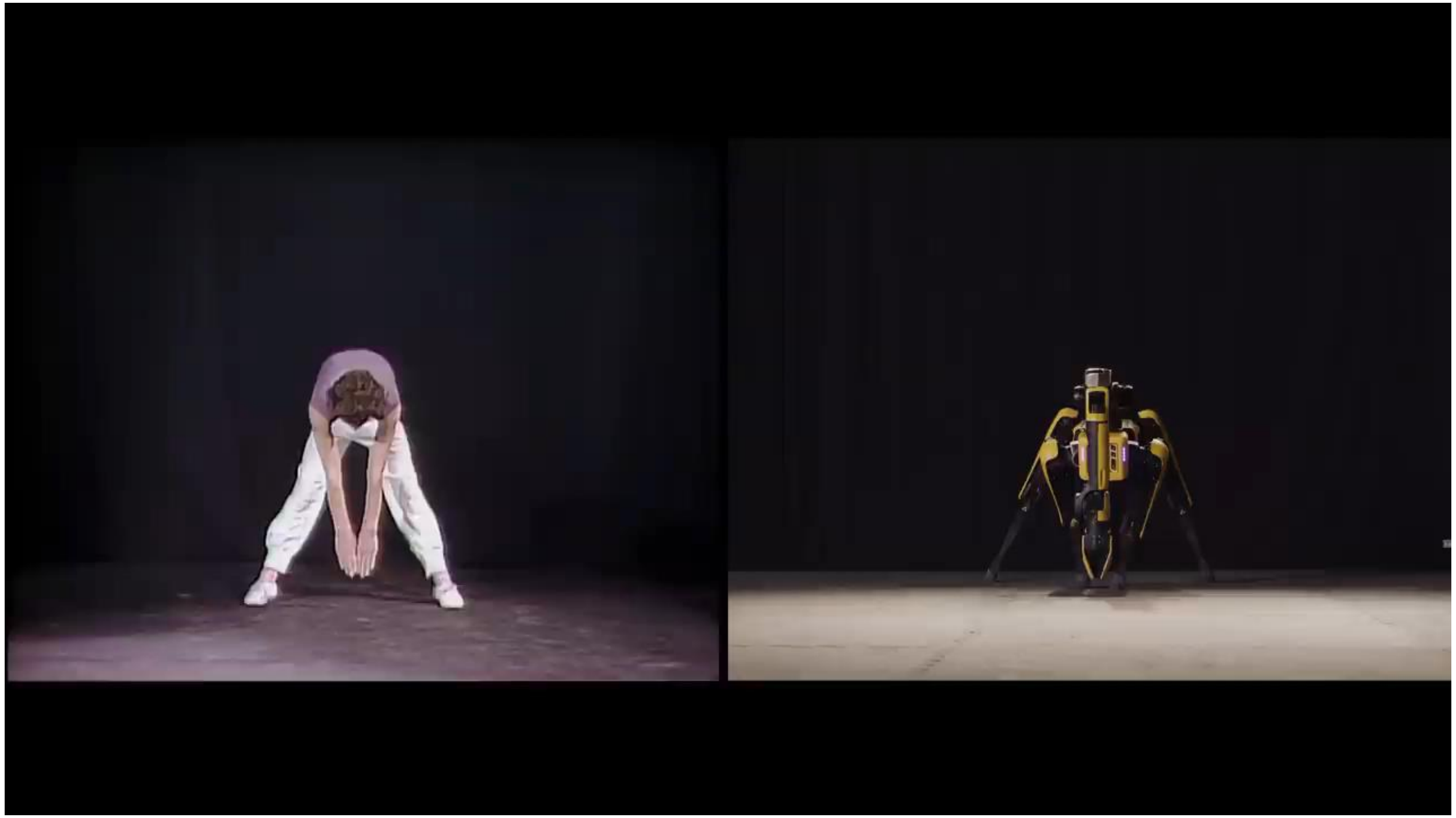
Robots made by *Boston Dynamics*

ATLAS: A mystery for the robotic community

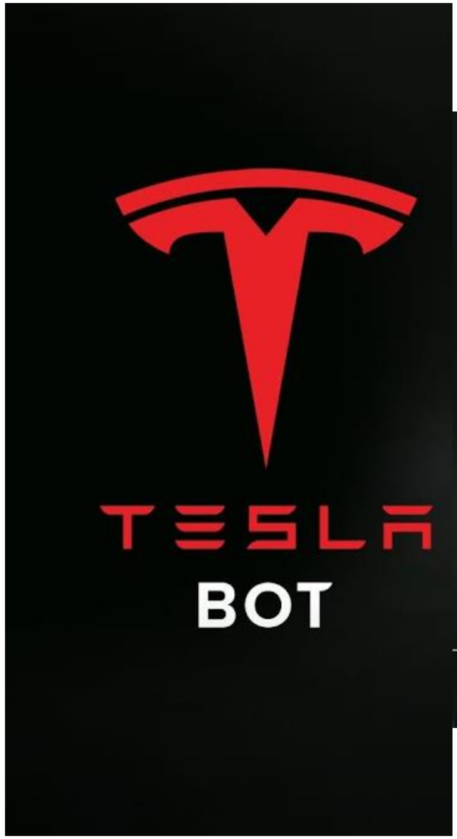


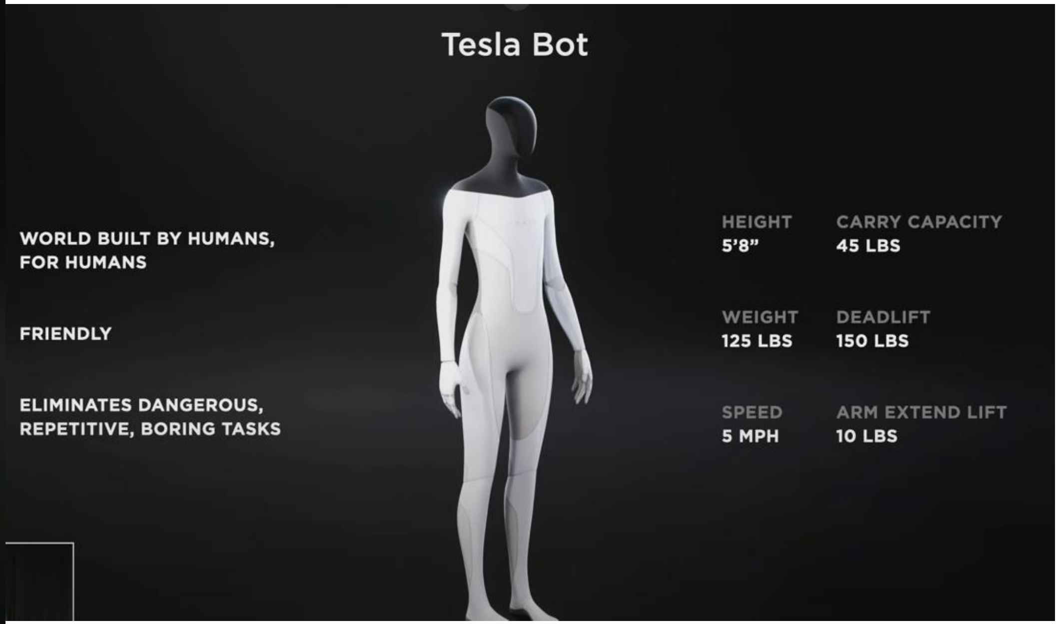
Robots made by *Boston Dynamics*

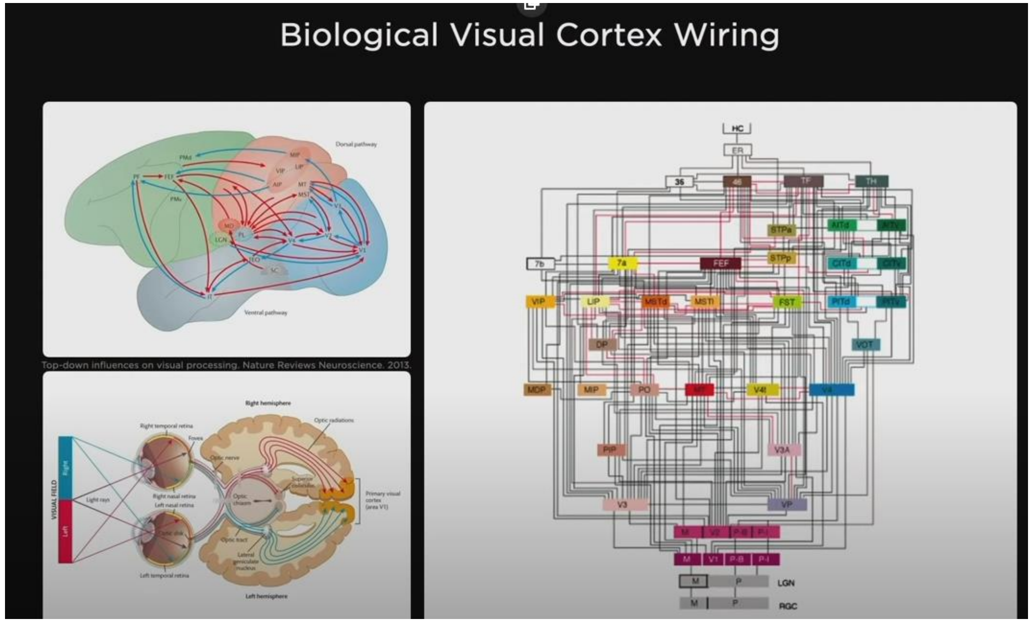
Spot: A mystery for the robotic community



Recently announced a new robot: TESLA bot

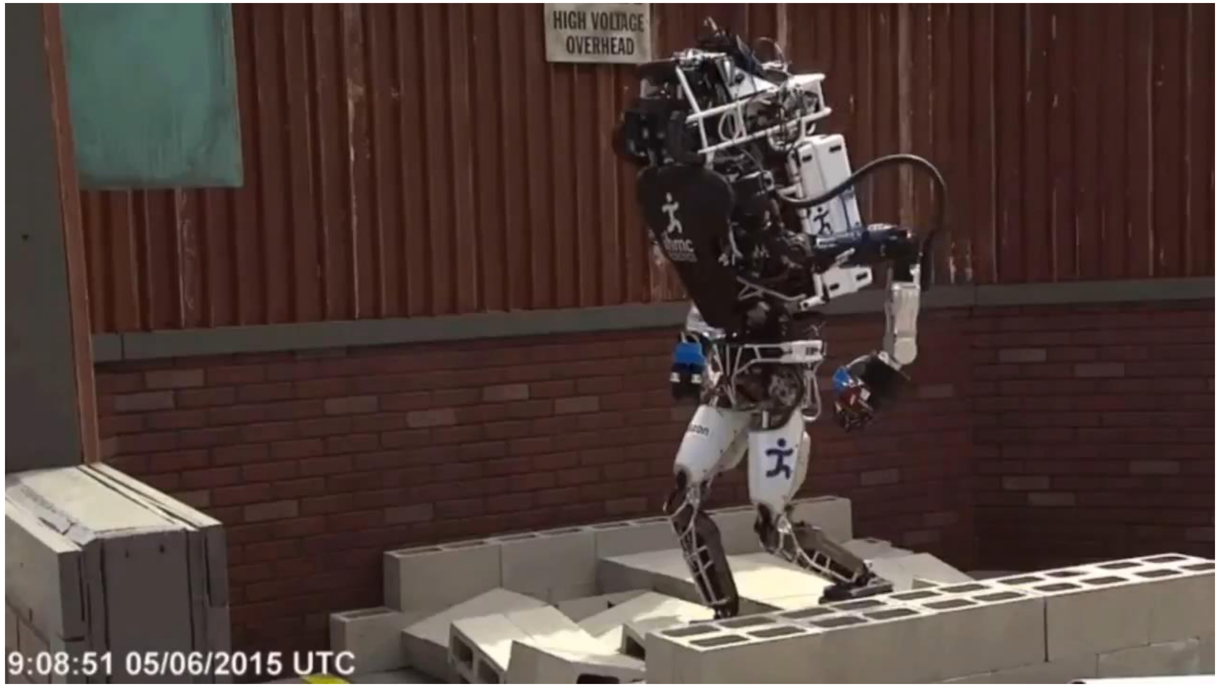






Robots trying to solve “real” tasks

DARPA Robotics Challenge [5]

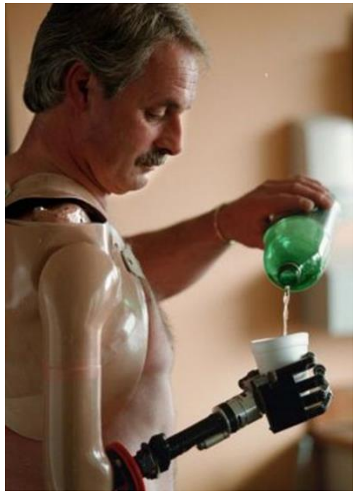


Robotics

- **Ethical aspects** [3] [4]
  - ✓ Will robots replace humans?
  - ✓ Will robots take our jobs?
  - ✓ Will robots make humans unnecessary?
  - ✓ Is humanity just a phase in a robotic evolution?

Robotics

- **There is a lot of potential in this technology to be beneficial for people**
- **Ultimately, everything depends on how we decide to use the technology**

Robots must improve the quality of work by taking over dangerous, tedious and dirty jobs that are not possible or safe for humans to perform.
ALARA principle followed for each intervention

Opportunity for Robotics

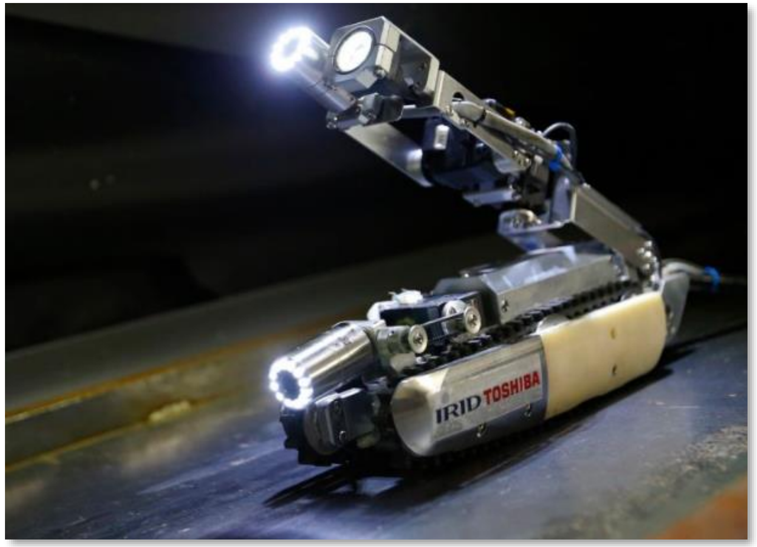
Robotics technology will play a very important role for us to overcome the negative effects of Megatrends

Aging population
Climate change
Urbanization
Etc.

Manufacturing
Food production
Construction
Goods fulfillment
Mobility as a service

Robots in reality (field robotics)

- The only reliable robotic solutions exist in industry for repetitive tasks
- Plenty of ideas and prototypes coming from university, but none of them work reliably for harsh and unstructured environments
  - ✓ At Fukushima, no robot has been capable of safely inspecting the zone and returning to the base



Teleoperation in Universities and Research Centers

- Many recent developments towards maintenance and robotic exploration in space applications
  - ✓ Developments towards human behavior reproduction
  - ✓ Need for well-defined interfaces and tools, as well as hyper-trained operators
- Specific developments for medical applications with constraints not always present in big science facility scenarios (limited supervisory control, no autonomy, large scaling of motion etc.)

Intuitive Surgical: https://www.youtube.com/watch?v=TGjnb86HndU

DLR SUPVIS-JUSTIN: https://www.youtube.com/watch?v=FYvt1UMtyp8

- Mainly test and prototypes devices
- Not necessary designed to be robust
- Industrialization of concepts in most of the cases not possible

Teleoperation in Structured Big Science Facilities

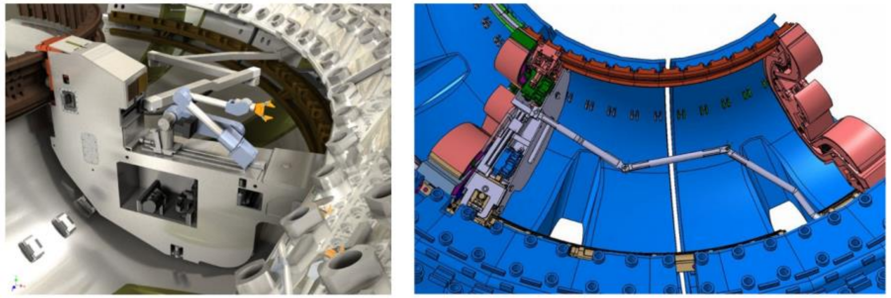
- Joint European Torus (JET)

JET Torus (left) and remote handling approach using the MASCOT system

- Spallation Neutrino Source (SNS)

Remote handling control room and the Telerob EMSM 2B tele-manipulator system in use at SNS

- International Thermonuclear Experimental Reactor (ITER)

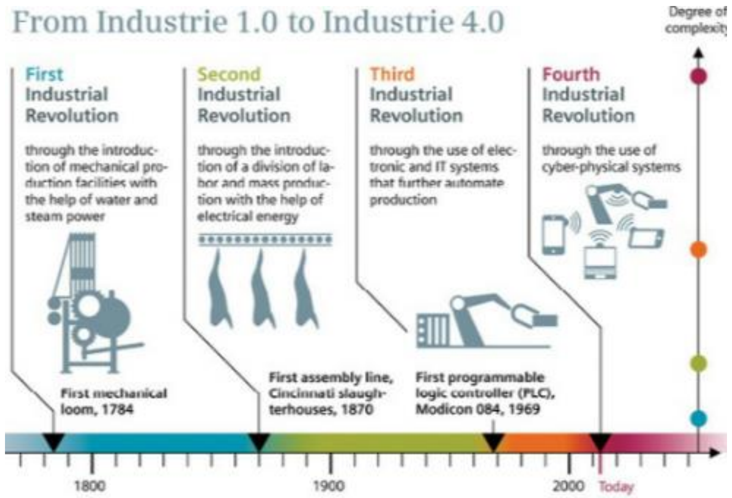


3D image of the remote handling system for the ITER divertor right

- Mainly master-slave tele-manipulators
  - ✓ Bulky installation in structured environment
  - ✓ Tasks well defined
  - ✓ Extremely well trained operators
    - ❖ High maintenance costs
- Unavailability in big science facilities has the most impact on costs
- Maintenance intervention time is extremely critical

Robotics in Industry

- ➢ "No room" for teleoperation applications, need of quick repetitive tasks
- ➢ Long history of industrial robots applied to industrial scenarios mainly for manufacturing
- ➢ Recently human-robot collaborations have been started for highly repetitive scenarios



- ➢ Mainly robots performing repetitive tasks in well structured environment
- ➢ Changing environment/type-of-place where the robots are deployed often implies a refactoring of mechatronic components
    - ✓ Bulky installation in structured environment
    - ✓ Tasks well defined

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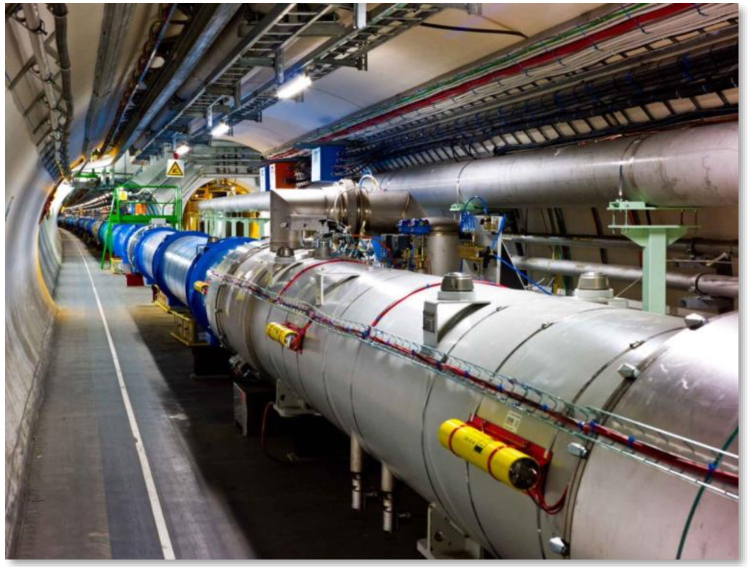
Main needs for robotics at CERN

- **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**



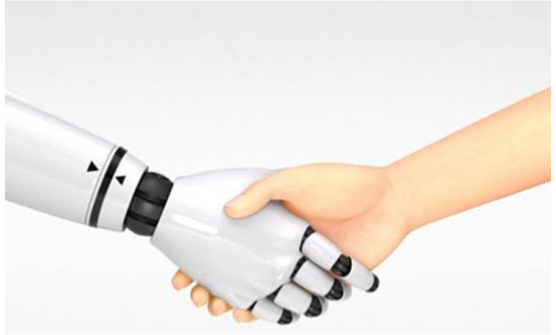
The LHC tunnel

North Area experimental zone

Radioactive sample handled by a robot

Availability

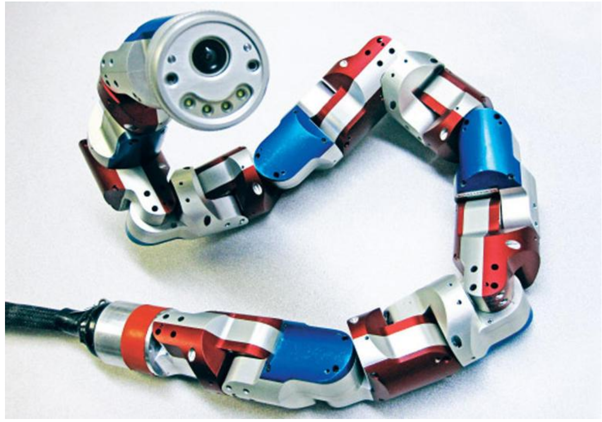
Reliability		Maintainability		Availability
	Constant		Decreases	Decreases
	Constant		Increases	Increases



But before deploying robots, their reliability must be verified to be really high and recovery scenarios must be foreseen

Robotics needed in Big Science Facilities

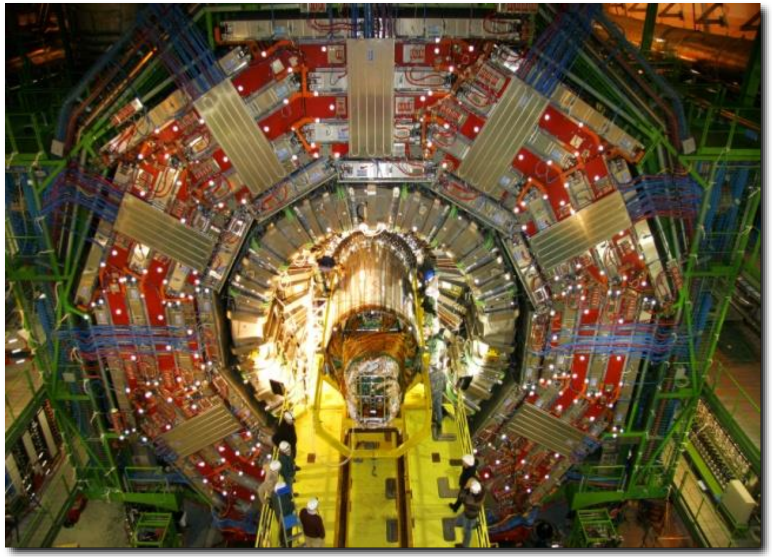
- No single existing robotic solutions can fulfill the needs
- Mobility and manipulation capabilities are required
  - ✓ A “fusion” of several type of robot would be needed
  - ✓ **A modular robot could fulfill several needs**



Main difficulties for robotics at CERN

- Need for 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.



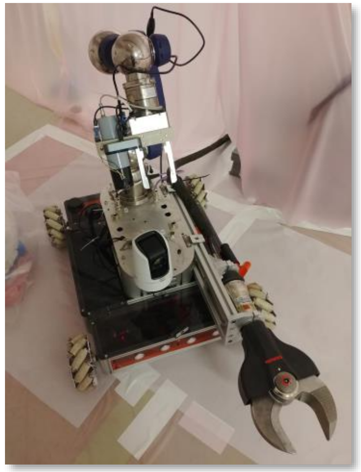



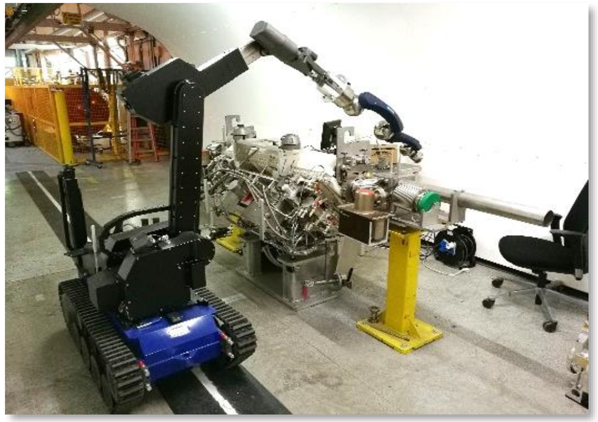
Content

Robotic Support for CERN: Type of Robots Overview

Telemax robot

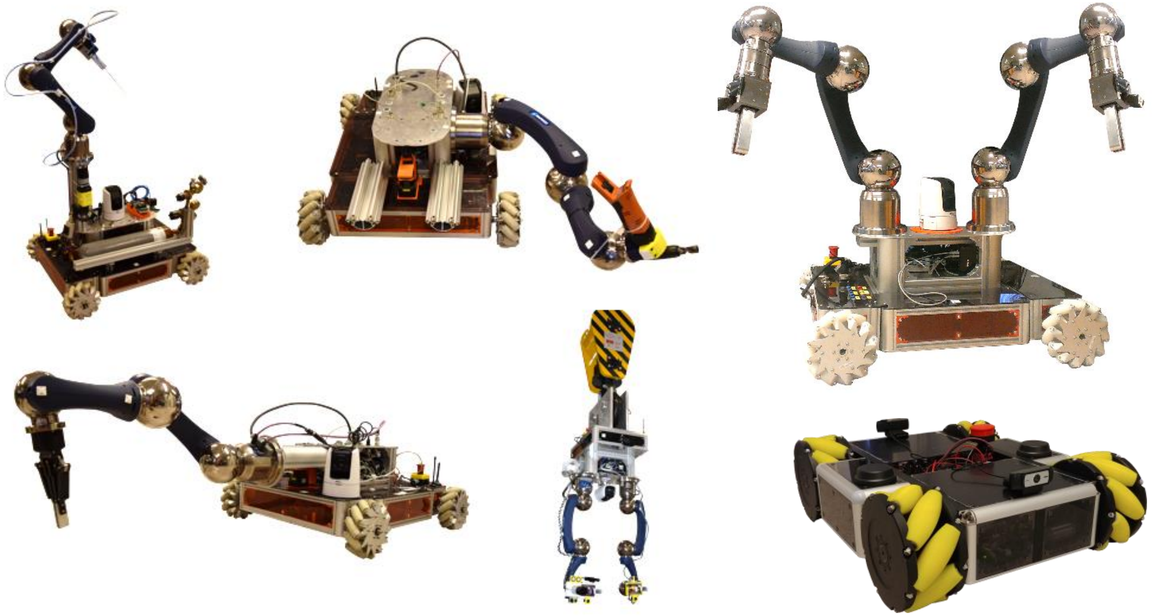
Train Inspection Monorail [10] (CERN made)





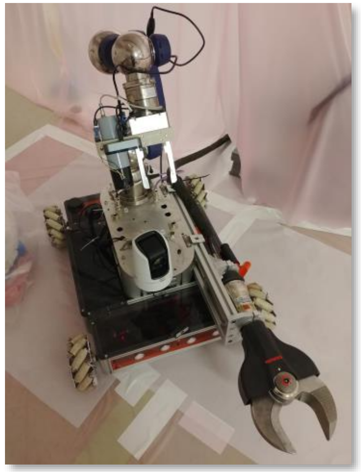
Teodor robot

EXTRM robot (CERN made)



CERNBot [11-17] in different configurations (CERN made)

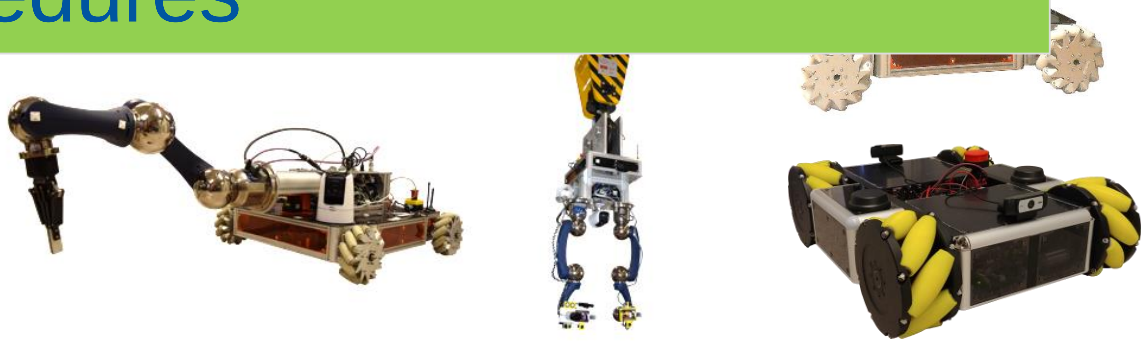
Robotic Support for CERN: Type of Robots Overview



- Mechatronics conceptions, designs, proof of concepts, prototyping, series productions, <u>operations</u>, maintenance, tools and procedures

Teodor robot

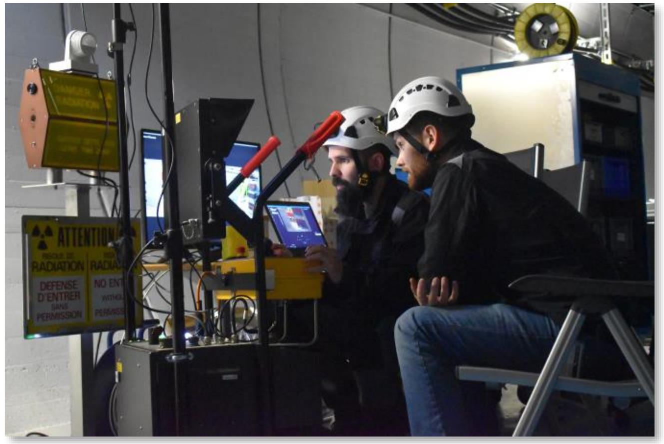
EXTRM robot (CERN made)

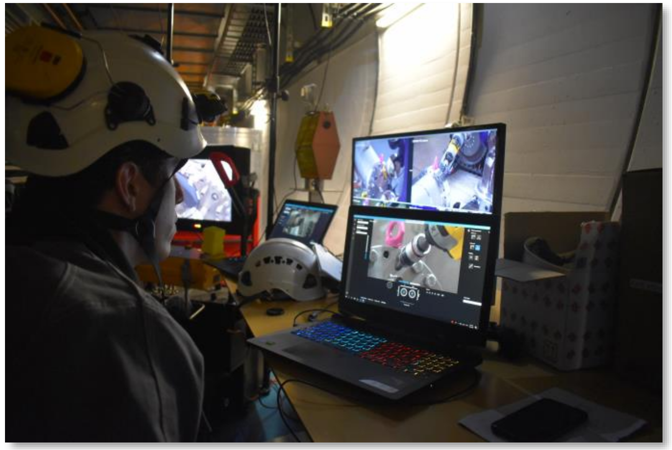


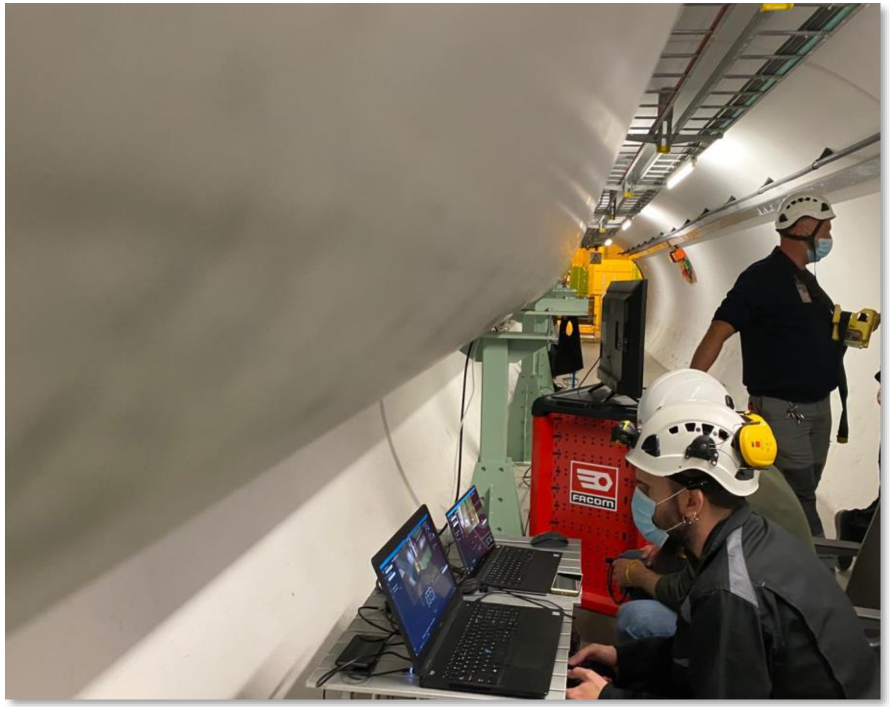
CERNBot in different configurations (CERN made)

Robotic service for remote maintenance

- ➢ Remote inspection and teleoperation (for EP and ATS)
  - ✓ Robotic controls (kinematics + feedbacks) and operation

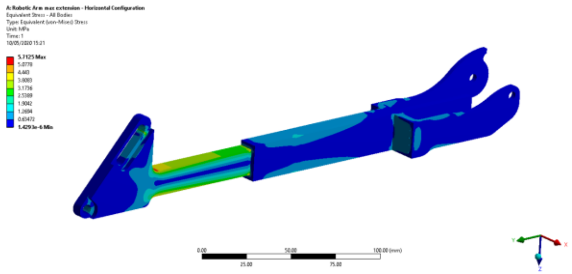


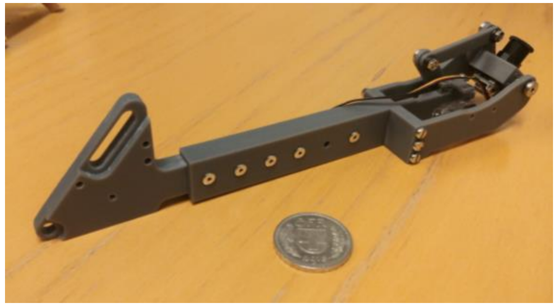




Robotic Lab #1, building 937

- Robotic prototyping
- 3D printing
- Robotic arm control, tools vision and algorithms testing (autonomy and teleoperation)
- Participation in the HSSIP and Italian teacher programs to host and mentor high-school students

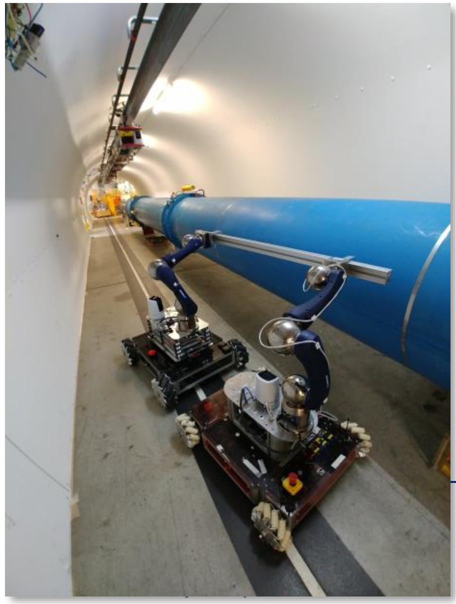


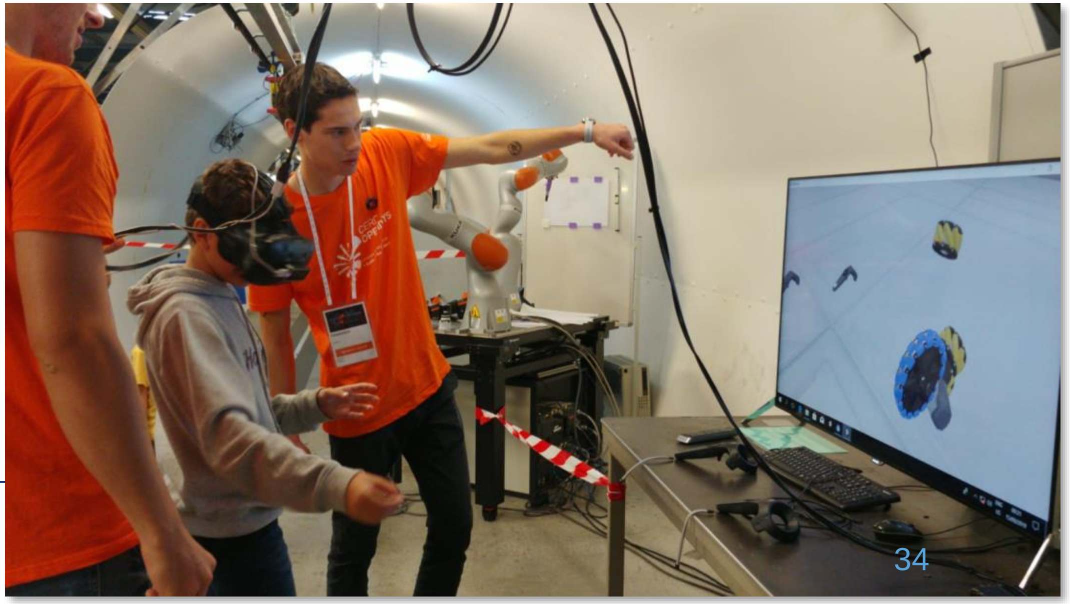


Design,FEM analysis and 3D printing prototype for the RF cavity inspection robot

Robotic Lab #2, building 927

- Robots testing and commissioning
- Intervention procedures and recovery scenarios commissioning (mockups)
- LHC Tunnel mockup (~ 30 meters)
- Virtual reality zone



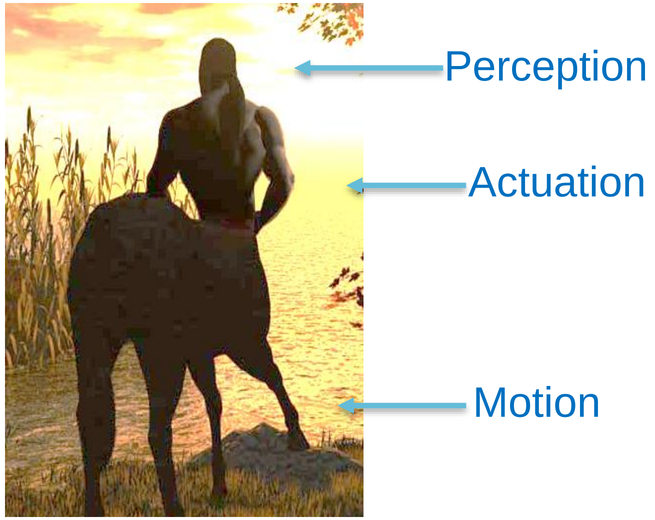


Robotics technologies are mainly used at CERN for:

- 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
- And others…

CERNTAURO framework [7]

Mechatronic System



- **New robot and robotic control developed** [9-39]
  - ✓ Human robot interface
- **New user-friendly bilateral tele-manipulation system**
  - ✓ Haptic feedback
  - ✓ Assisted teleoperation
- **Artificial intelligence [30-31-38-40]**
  - ✓ Perception and autonomy
  - ✓ Deep learning
- **Operator and robot training system [41]**
  - ✓ Virtual and augmented reality
  - ✓ Learning by demonstration

Main Motivations for Custom Robotic Development

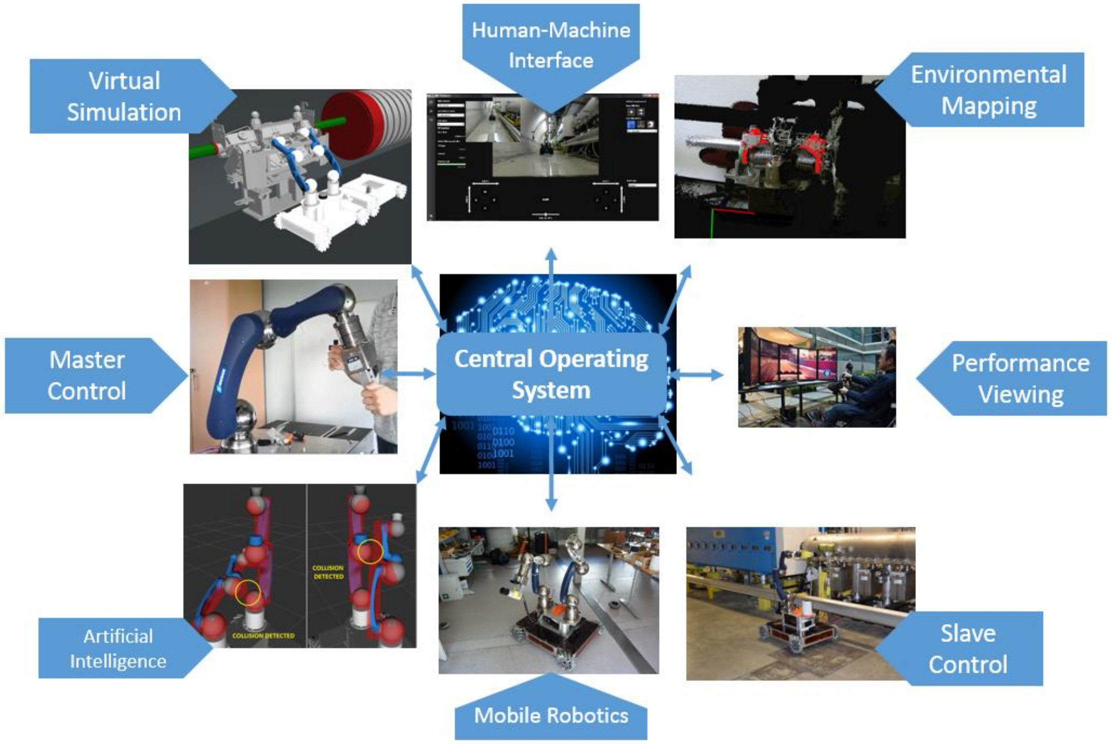
- Industrial solutions do not cover all CERN needs for remote maintenance and quality control

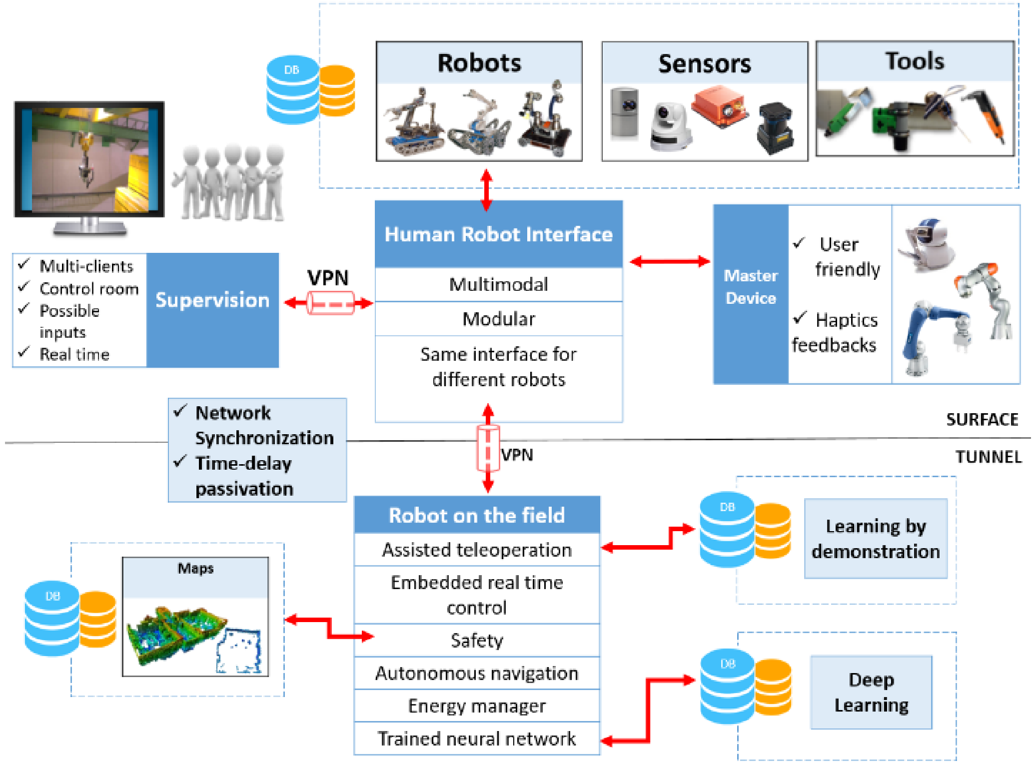
- Strong need to develop **a modular and adaptable robotic framework/system for** unstructured and harsh environments

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

CERNTAURO framework

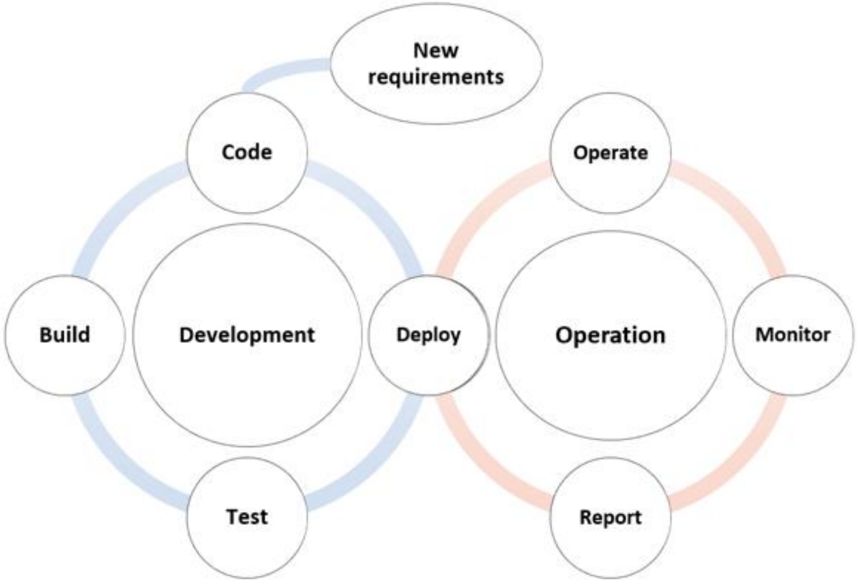
- In house robotic control system [7]
- No use of ROS [8]
- Sensor acquisition, fusion, measurements etc.





CERNTAURO Control Framework Overview

- The novel CERNTAURO continuous integration model, fundamental in Big Science Facilities to adapt to requirement change
  - ✓ The developed modules are **deployed** in operation once they have been judged to be robust enough to allow **a safe and reliable robotic application on the field**
  - ✓ Modular architecture enhances **fast integration** on new requirements and new hardware
  - ✓ **Different from the classical scheme used in service robots**



C++

C++17 support with GCC9
Compiler & Build Tools: GCC9 & CMake
Unit Testing: Google Test
Code Style: Google Style

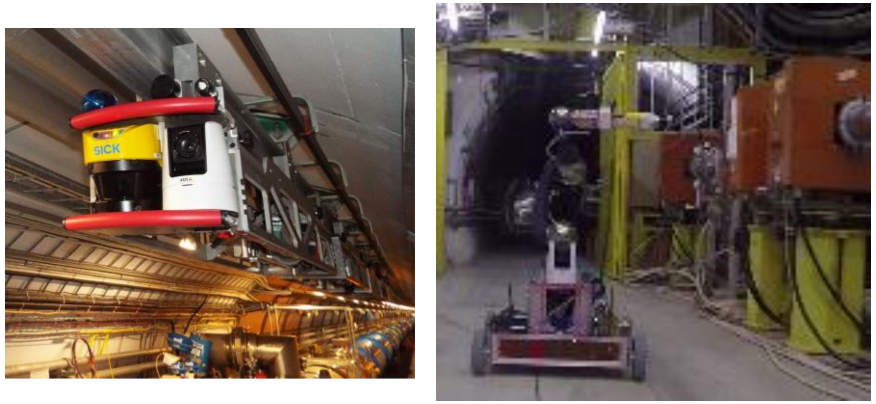
Python

Python 3
Unit Test: Pytest
Code Style: Pylint

The continuous integration model designed for the CERNTAURO framework implementation.

Robotic preventive maintenance and inspection

SPS MKP oilers refill

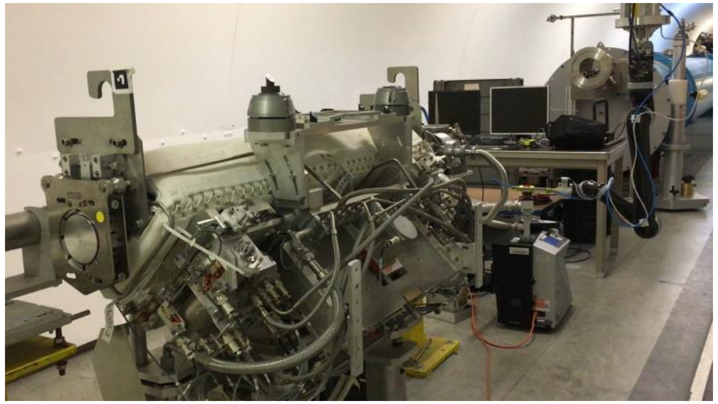


Remote radioprotection surveys

Cabling status inspection

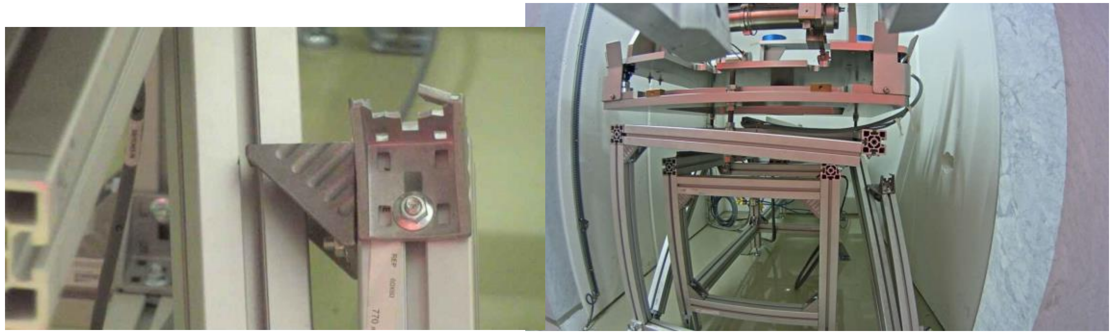
Temperature sensor installation on AD target

Tunnel structure monitoring

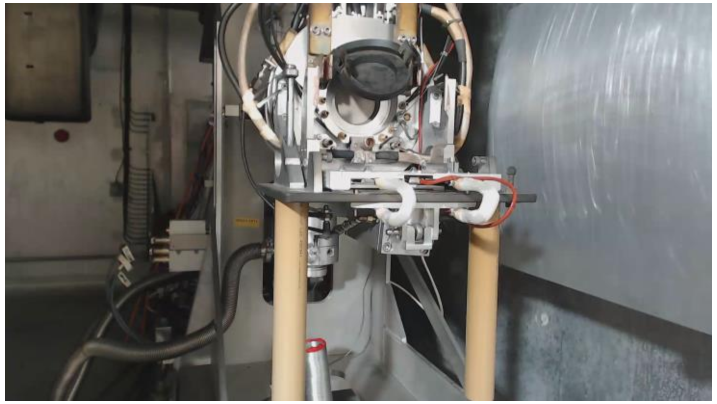


Remote Vacuum Leak detection

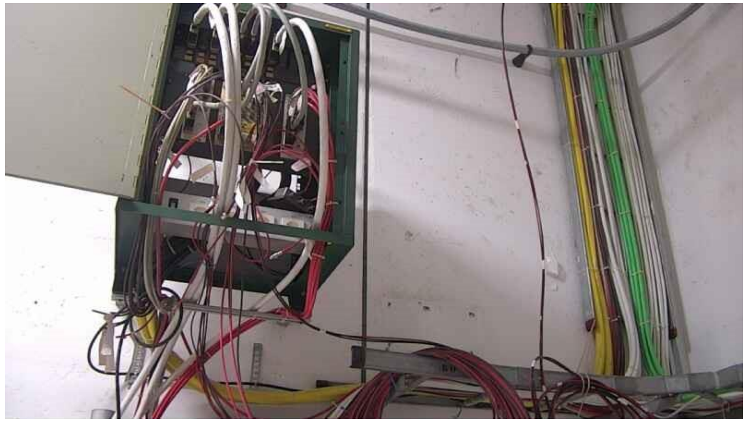
Fast reaction to equipment failures in radioactive areas



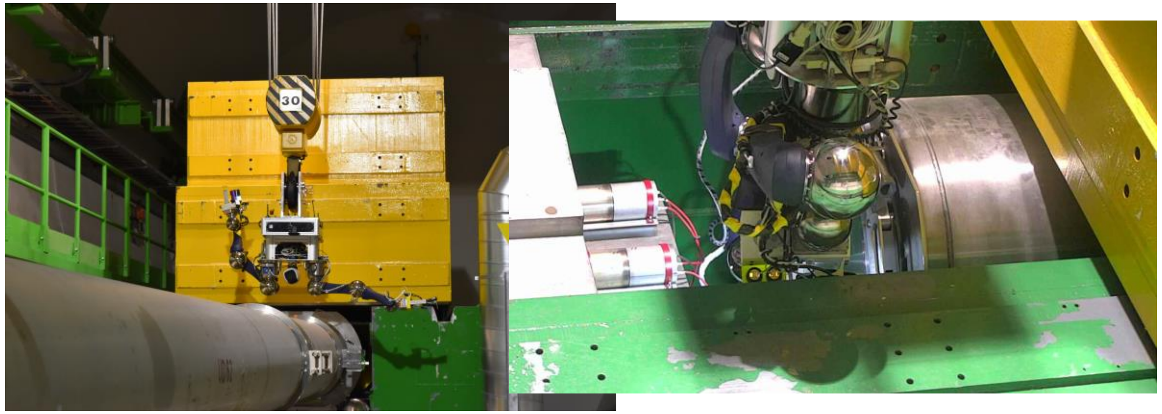
CHARM Target movable table problem
In place 1 hour after the problem



ISOLDE HRS Front-End problem
In place 2 hours after the problem

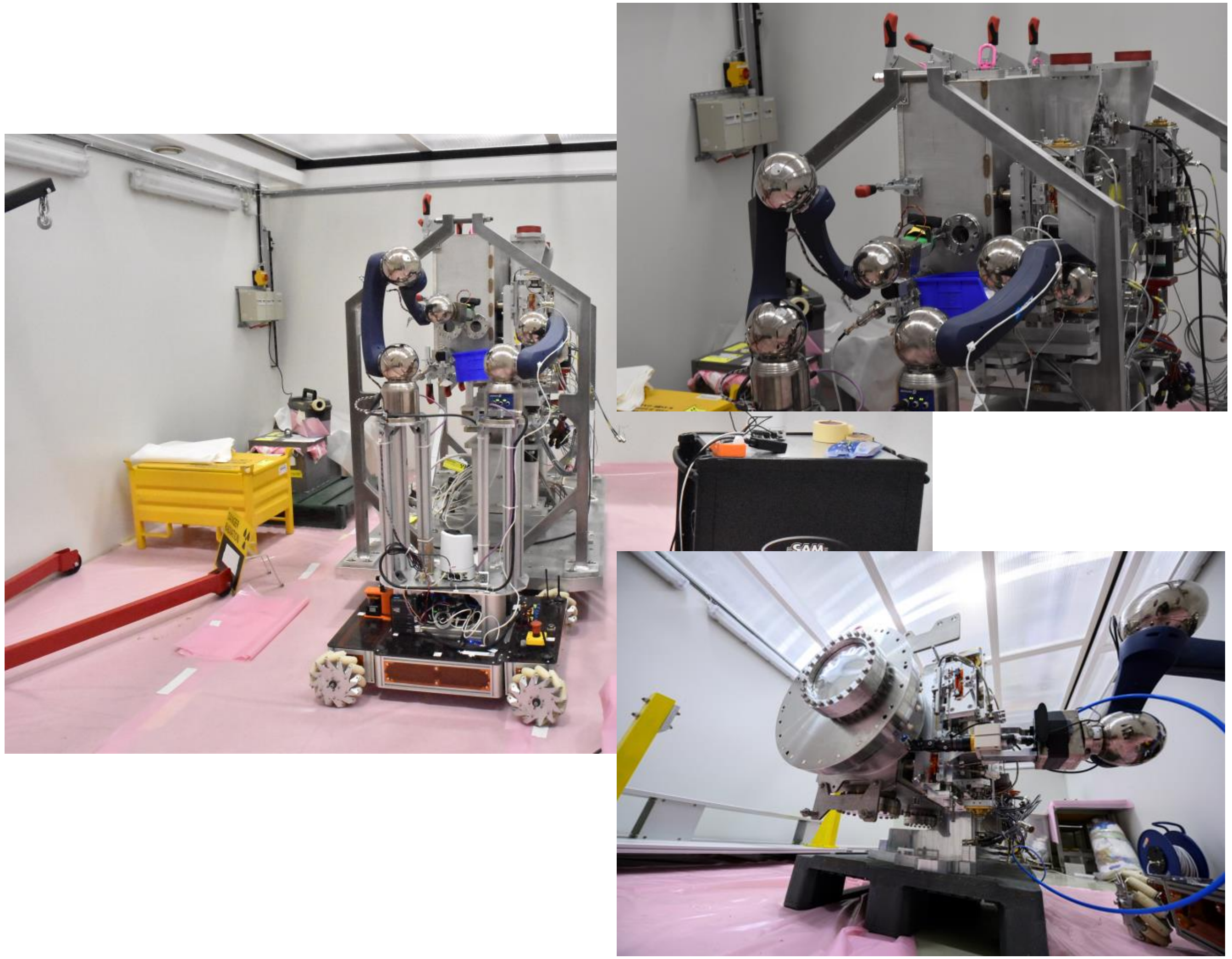


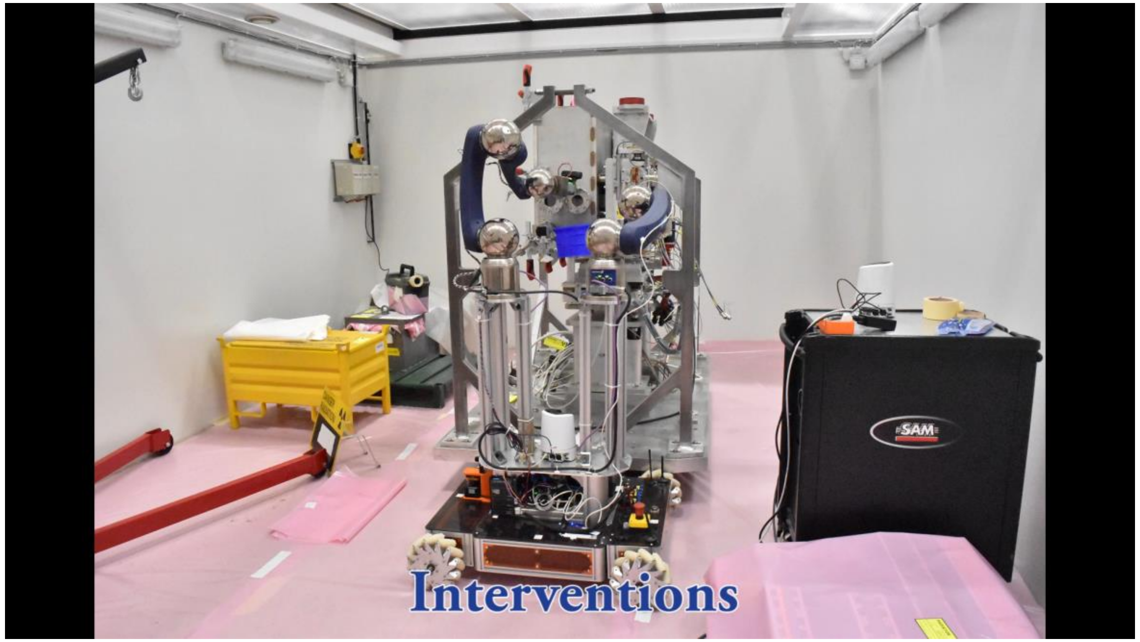
North Area BLM problem
In place 50 minutes after the problem



LHC TDE Leak problem
New robot built in 3 days

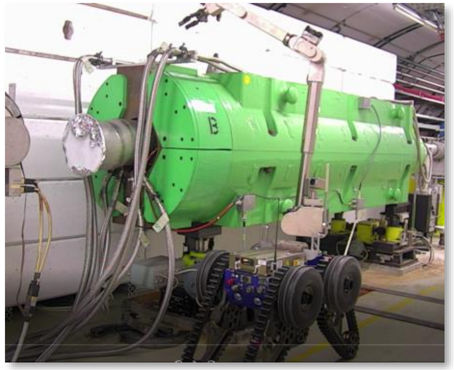
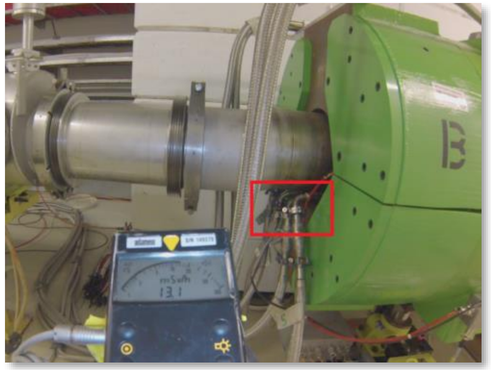
Post-Mortem Analysis



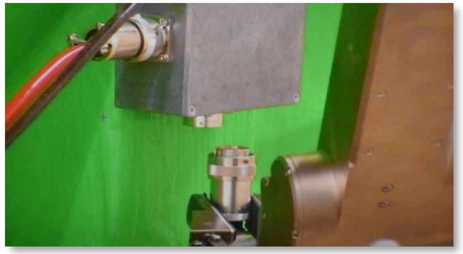


Importance of the design phase,

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





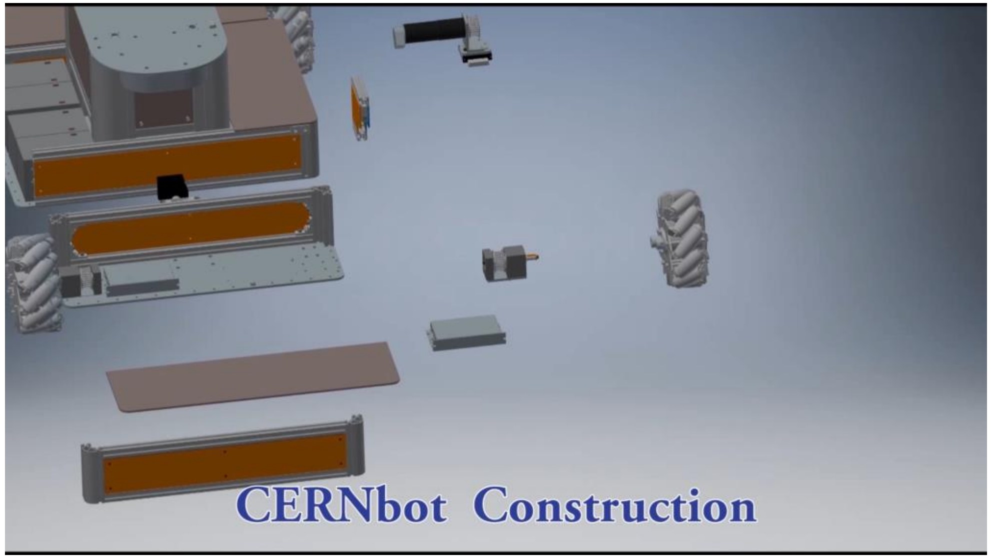


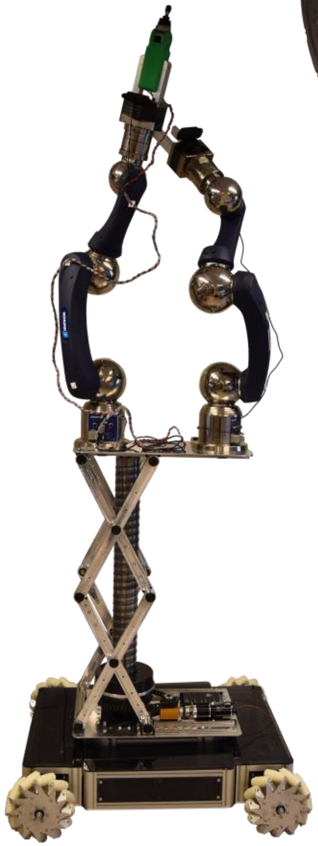
Easier remote or hands-on manipulation than chain-type connection

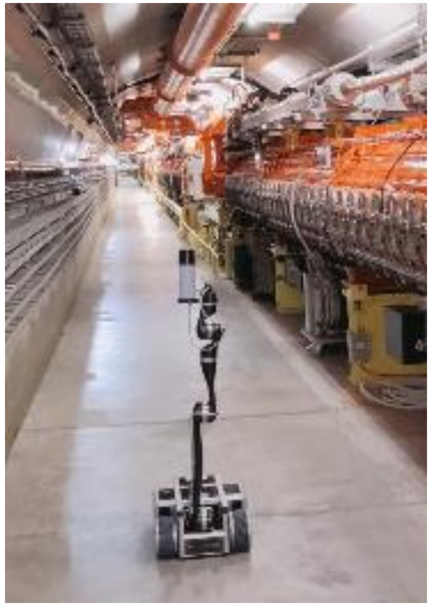
Procedures and Tools

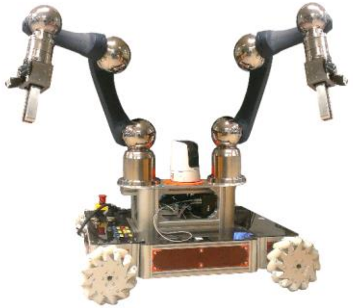
- Several time consuming and costly tools, procedures and Mockups done for intervention on non-robotic friendly interfaces during the last years (several done also in emergency situations)
  - ✓ Intervention procedures, recovery scenarios, tools and mock-ups are as important as the robot/device that does the remote intervention
  - ✓ Standardization of interfaces → standardized tools and procedures, reduce costs and intervention time

Modular Robot/Concept (CERNbot)





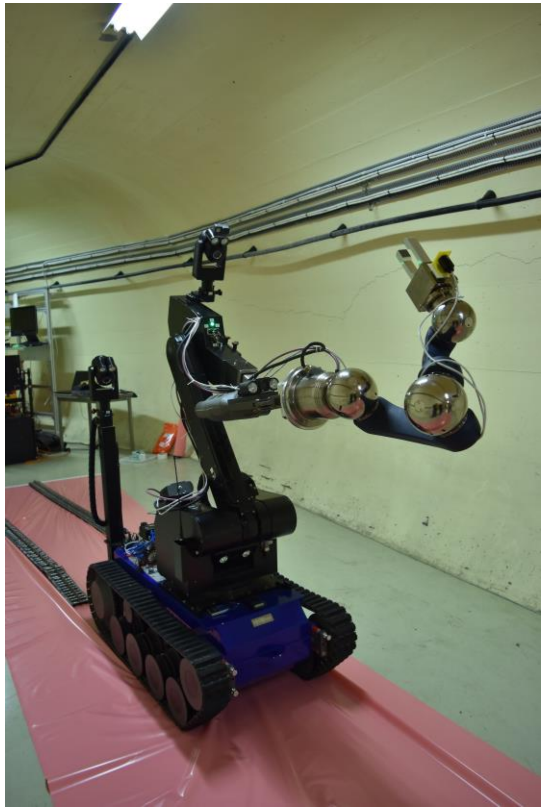


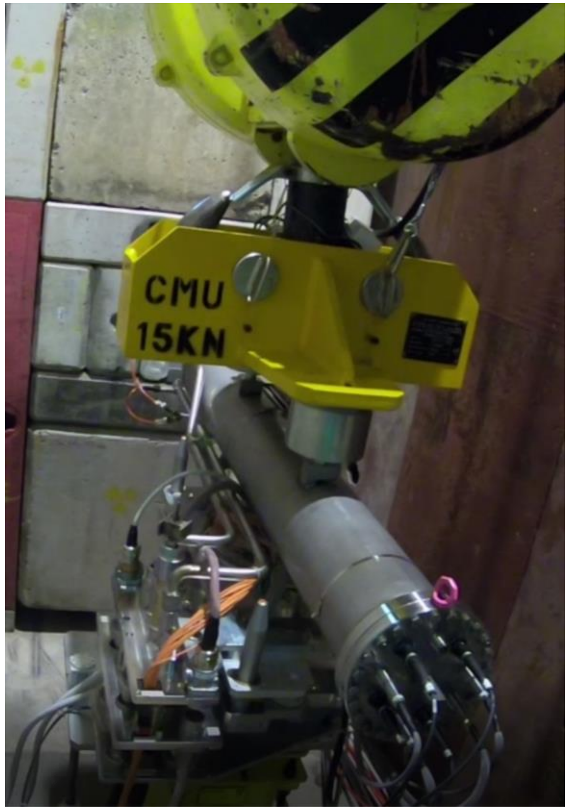


CERNbot, CERNbot2, CHARMbot, MIRA, CRANEbot

Modular Controls

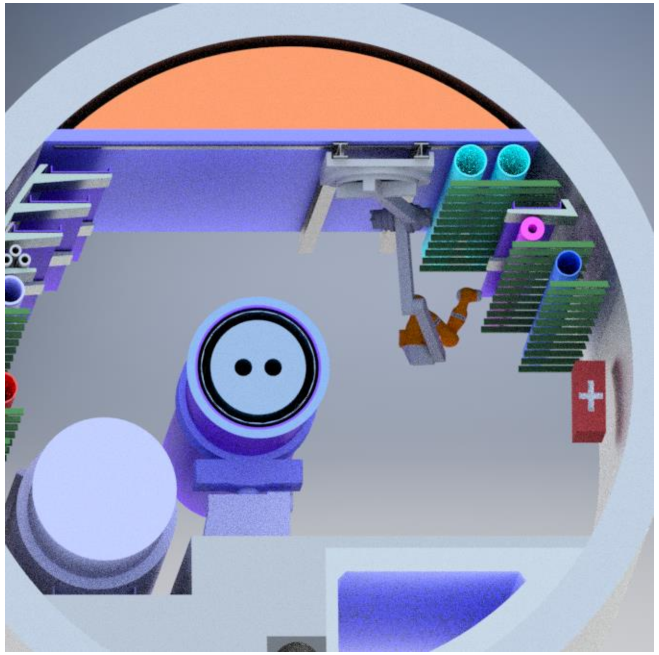
- Particle beam target maintenance, **integration of CERNTAURO on industrial robot**
  - ✓ **CERNTAURO adaptability → seamless control of multi-robots**
  - ✓ Manipulation from unstable support

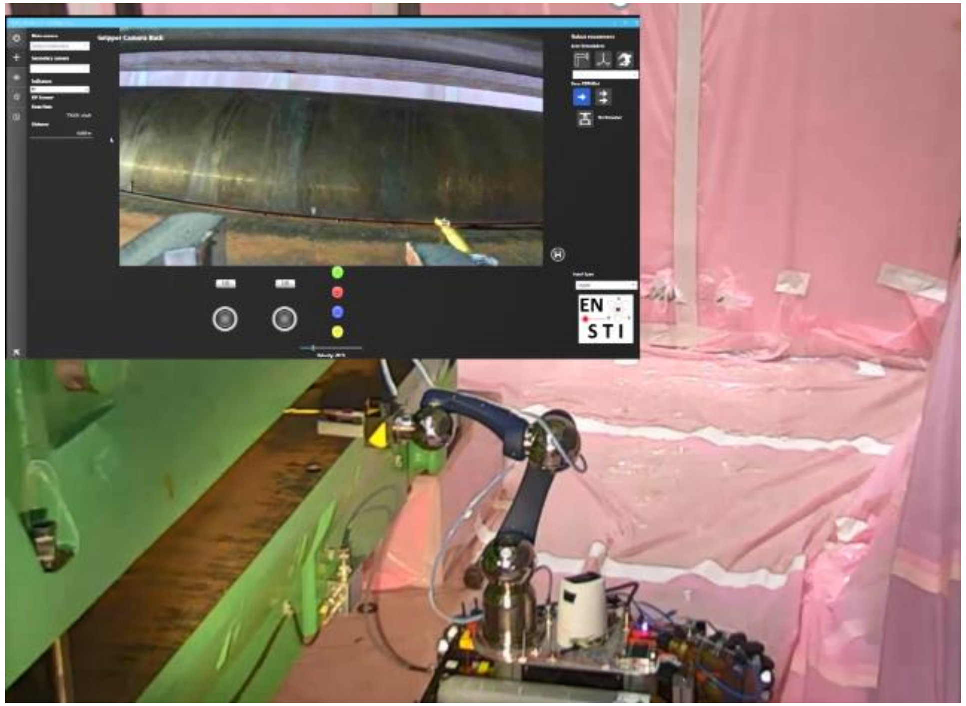




Some Considerations

- Ideally Robots or any remote maintenance device should be “part” of the machine
- Preventive maintenance with regular inspection tasks reduces the risk of unavailability
- Post-mortem analysis and understandings of failure help in increasing future machine robustness

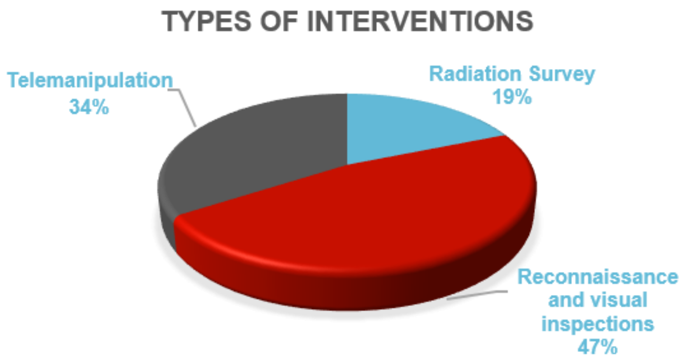


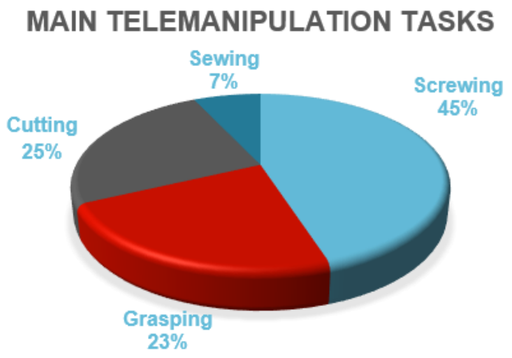


Robotic Interventions

Nr. of Interventions since 2014	Nr. of tasks performed	Robot operation time in harsh environment [h]	Dose Saved [mSv] *	Dose Taken by robots [mSv]
150	~500	~ 500	**~ 700**	**~7000**

* Calculated on estimated human intervention time

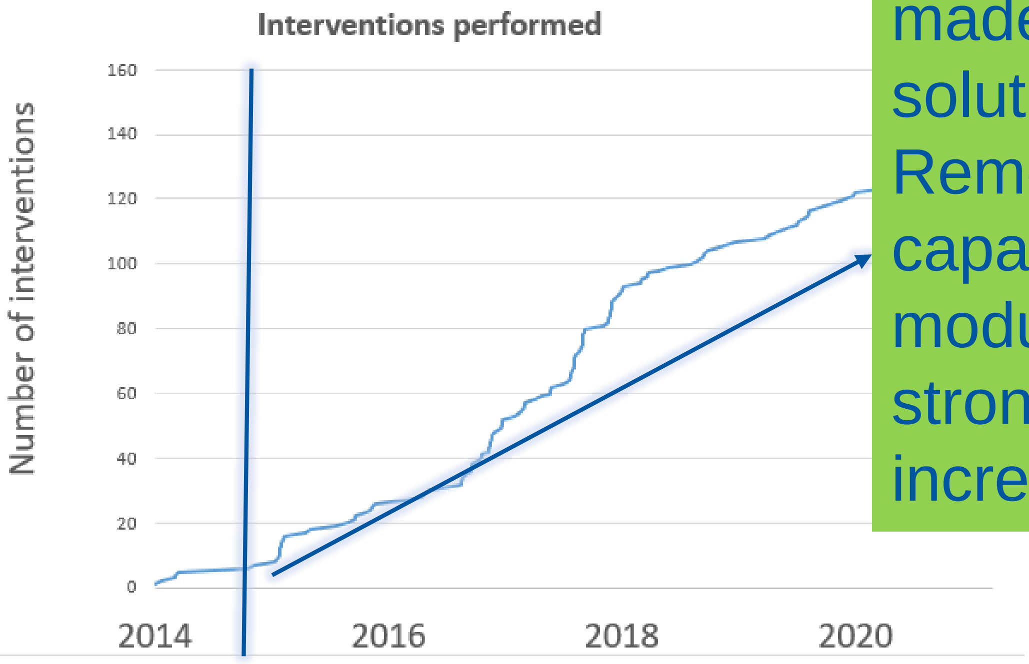




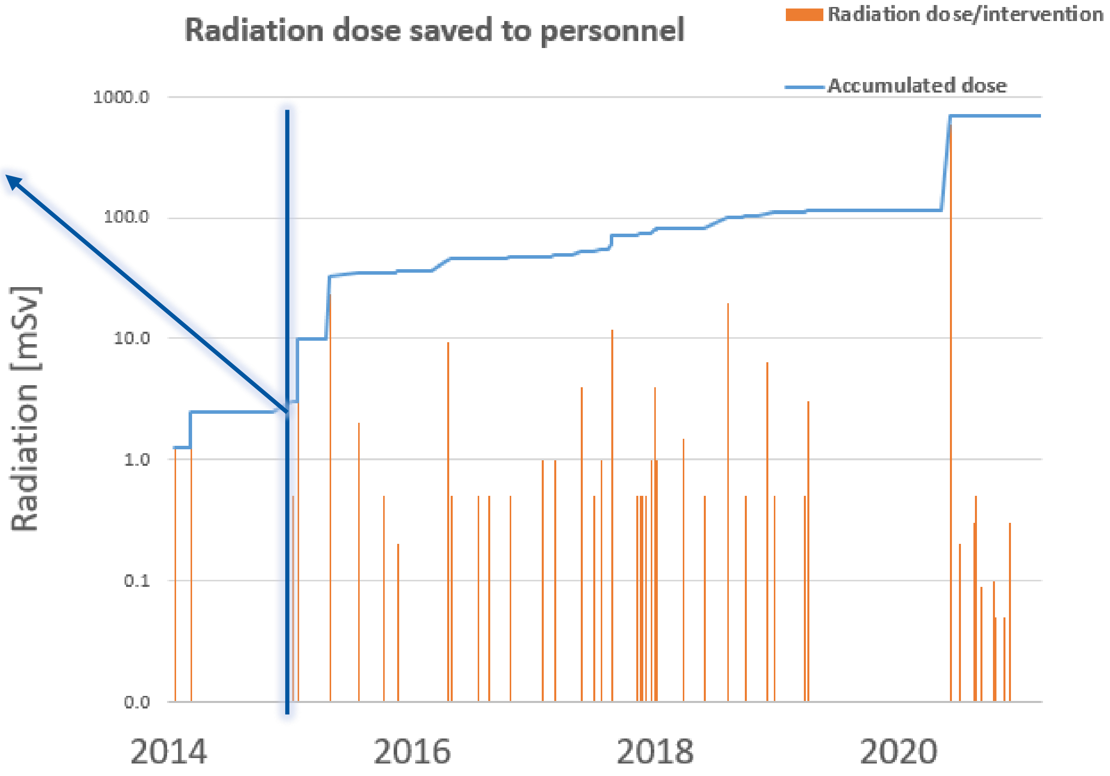
Remote maintenance test facility (b927)

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

Robotic Support at CERN

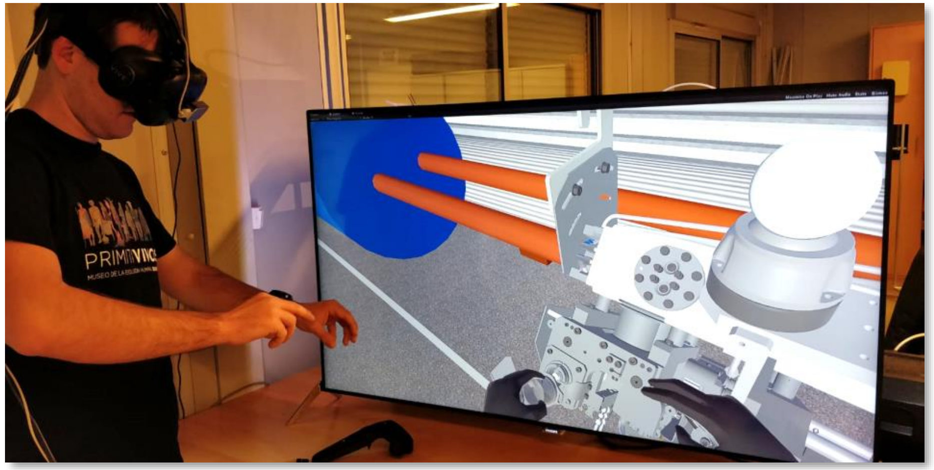


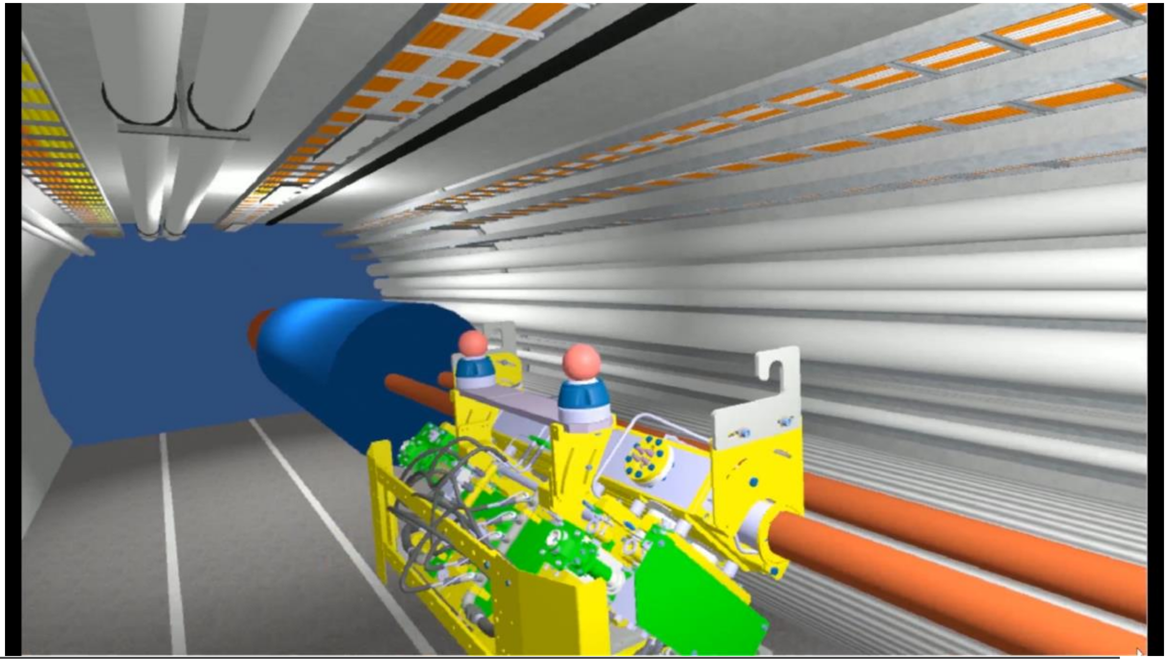
Started to apply CERN custom made robotic solutions. Remote handling capabilities and modularity strongly increased!



Current use of Enhanced Reality in BE-CEM

- Simulation of robotic interventions
  - ✓ Integration of robots in the environment and choice of robots
  - ✓ Intervention procedures
  - ✓ Tools design and test
  - ✓ Machines risk assessment
  - ✓ Robots training by demonstration
  - ✓ Operators training and teleoperations
  - ✓ Risk analysis
  - ✓ Recovery procedures
- Simulation of human intervention
  - ✓ Human intervention procedures
  - ✓ Live radiation levels and cumulated dose while training in VR (Augmented reality in virtual reality)
  - ✓ Intervention training
  - ✓ Risk analysis
  - ✓ Feedbacks for future remote-handling-friendly machines

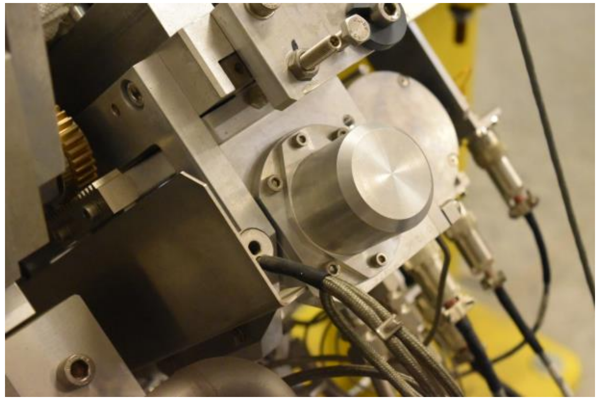




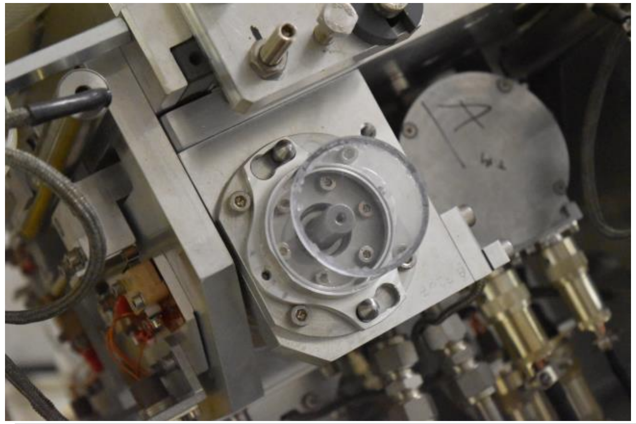
Steering New Machines Design

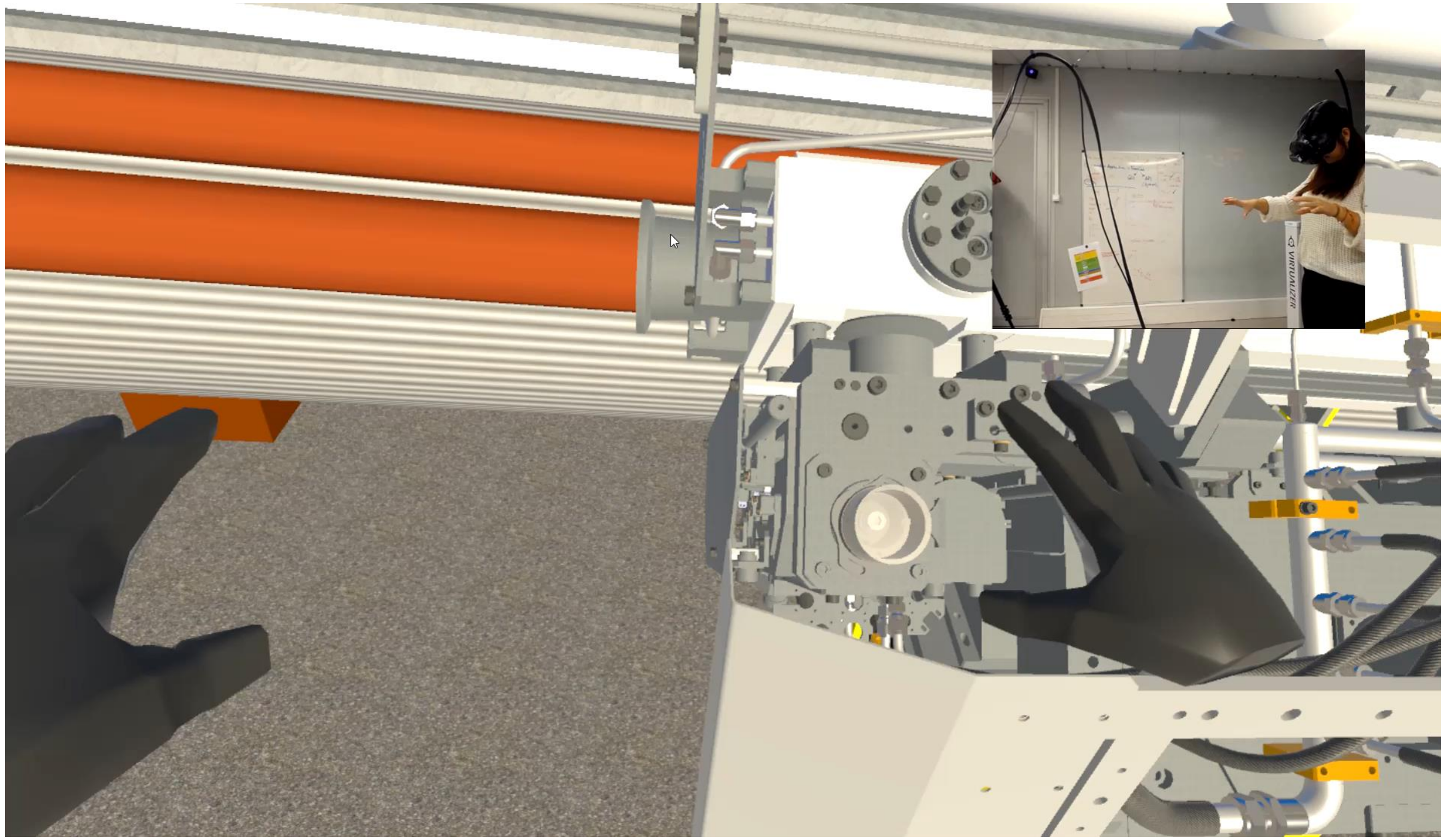
- For example, design of the new LHC Collimators motor screw cap
    - ✓ Simulation in VR to check hands on handling and “robot friendliness”

Current solution



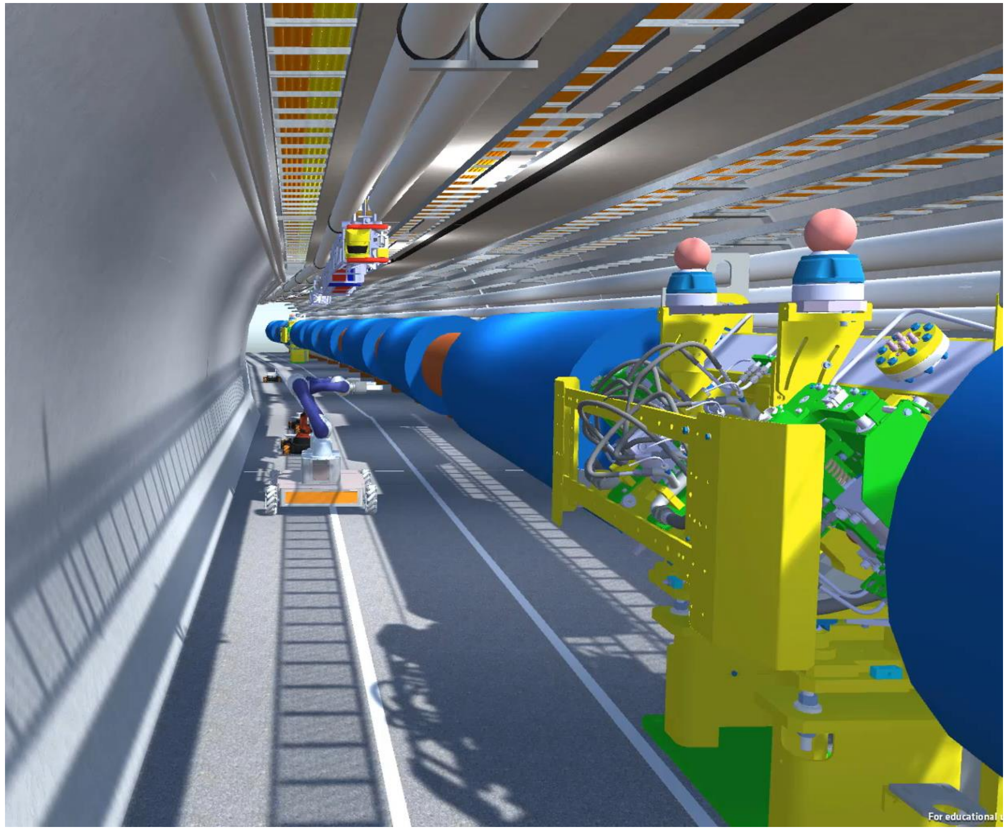
New solution





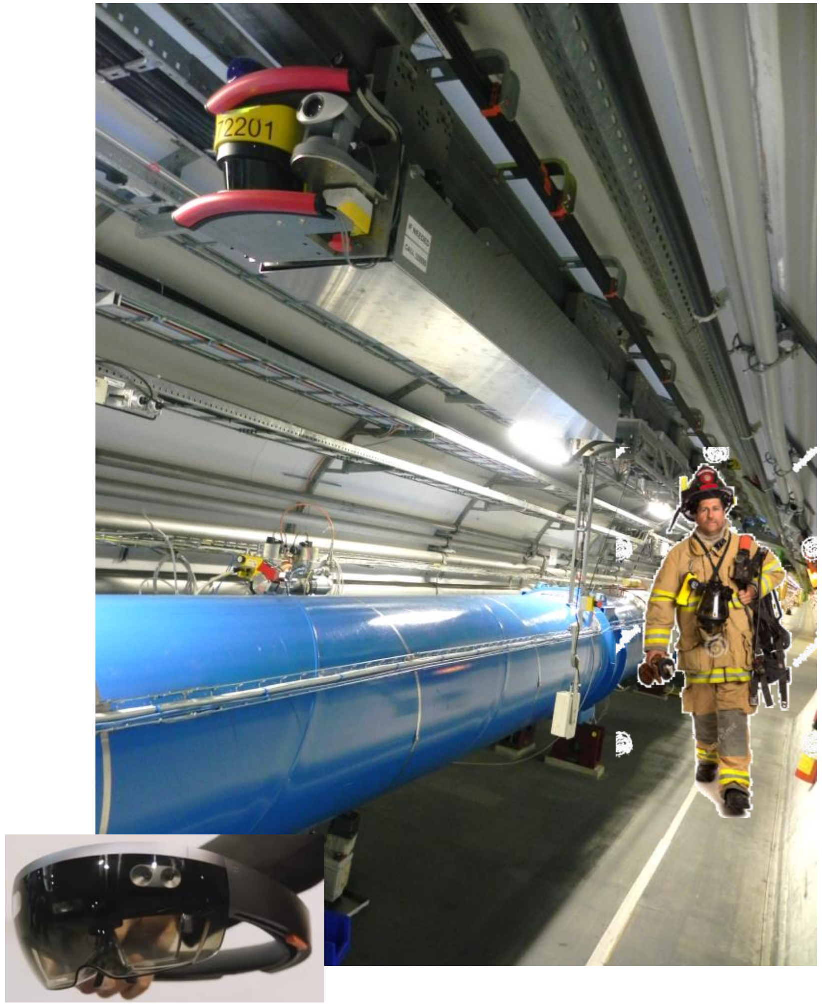
Virtual and Augmented Reality

- **Multiple autonomous robot collaborations**
  - ✓ **Several viewing angles for supervision and teleoperation are essentials**



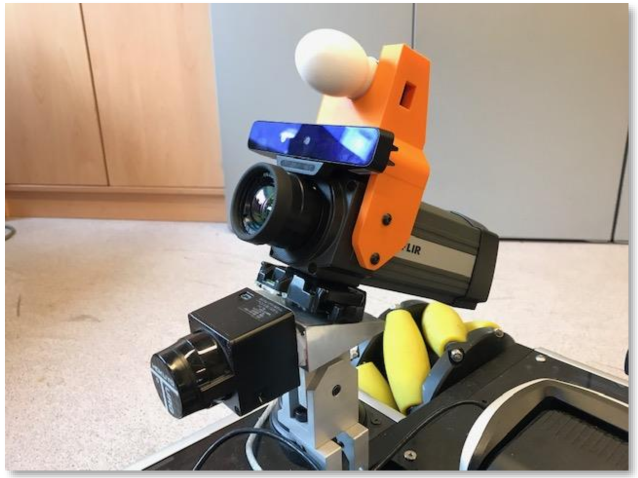
Early intervention robots

- **With such large distances, early intervention systems are necessary for example in case of accident or fire**
  - ✓ **Human fire response** (Fire Service) in accelerator facilities is judged **fundamental but not enough** due to response delay, personal risk assessment and reliability.
    - **Robotic** firefighting allows fire **inspection**, **victim** search and initial fire **suppression**.
    - **Robotic** firefighting could guide fire service giving environmental information
      - Augmented reality wearable systems
    - **Human** firefighting remains necessary for **rescue** operations and **final extinguishing.**

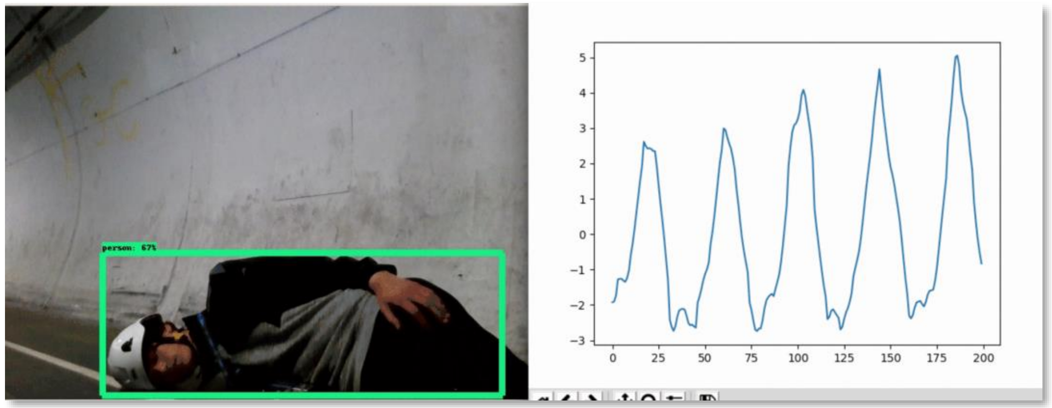


People recognition and vital monitoring

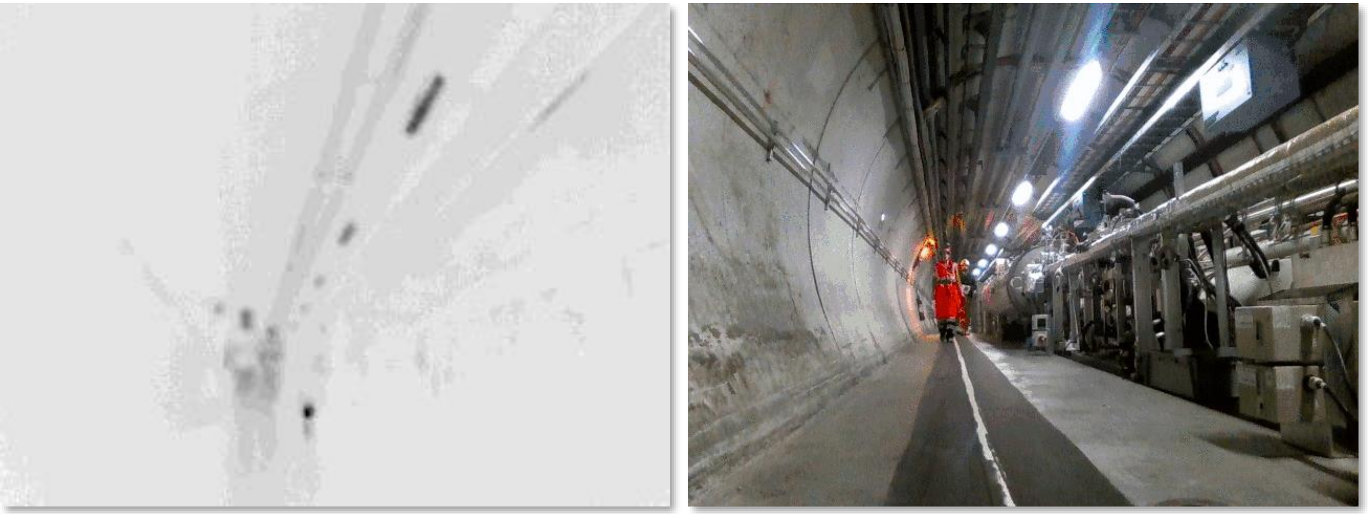
- Machine learning techniques enhance people detection and vital signals monitoring at distance
- People search and rescue is of primary interest in disaster scenarios
- People monitoring during rehabilitation



Vision system (2D Laser, radar, thermal and 2D-3D camera)

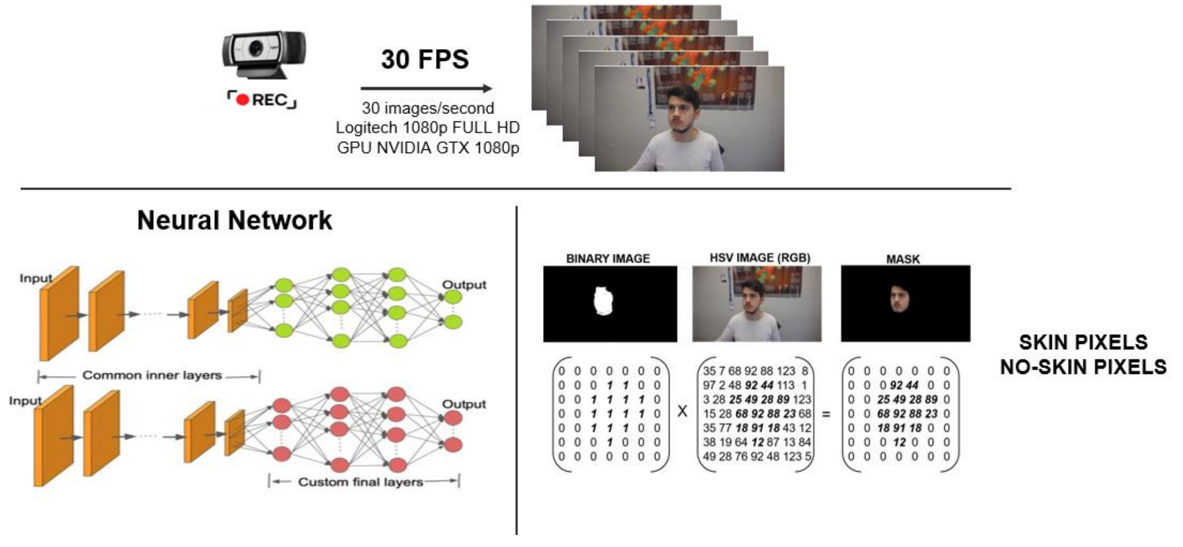


Online respiration monitoring



Online people recognition and tracking

MARCHESE project: Health Contactless Monitoring

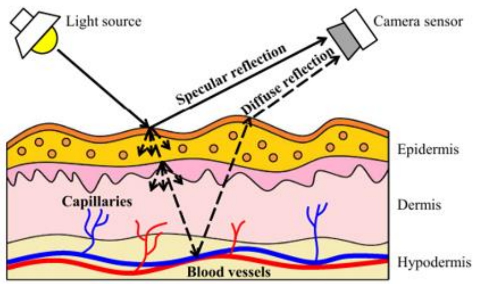


$$C_k(t) = I(t) \cdot [v_s(t) + v_d(t)] + v_n(t)$$

Reflection of each skin pixel in an image sequence in RGB channels

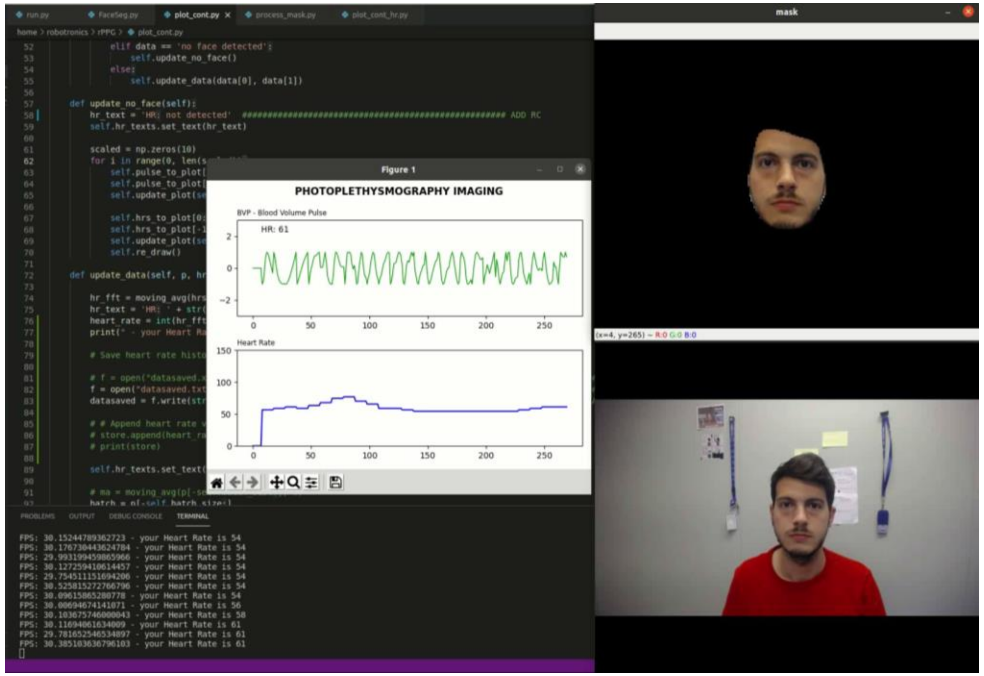
SPECULAR REFLECTION is a mirror-like light reflection from the skin surface (not contain any pulsatile information). Time dependent: body motion influence.

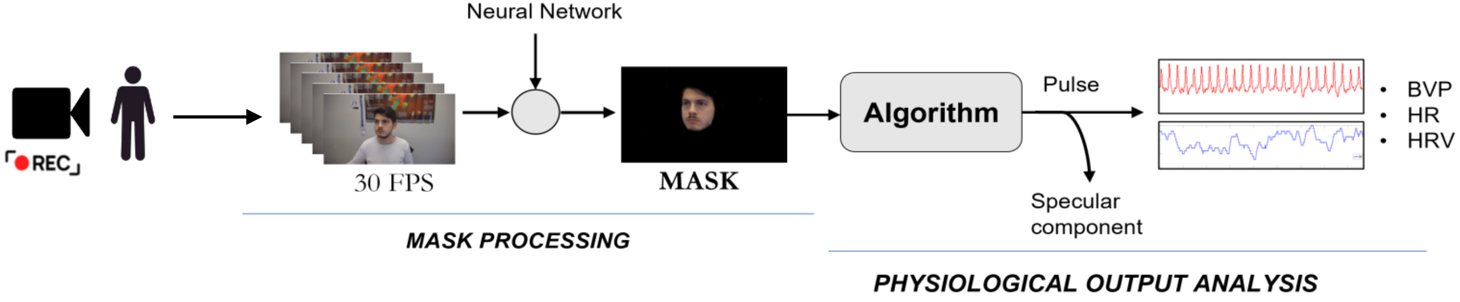
DIFFUSE REFLECTION is associated with the absorption of the light in skin tissues. The hemoglobin contents in skin tissues lead to a specific chromaticity.



DICHROMATIC MODEL $\rightarrow C_k(t) \sim I_0(1 + i(t)) \cdot [u_c \cdot c_0 + u_s \cdot s(t) + u_p \cdot p(t)]$

Constant — Specular — **Pulse**





Comparative Analysis: Performance Test

- Telemanipulation experiment comparing Telemax robot (industrial solution) and CERNTAURO framework running on CERNbot using a master arm
  - ✓ Approaching, grasping and unscrewing a cylindrical electrical connector.
  - ✓ 10 well trained/expert and 10 non trained operators

Electrical connector used for the task

System	Un-trained users set[s]	Well-trained users set[s]
CERNTAURO	412 ± 9	114 ± 2
Robotic Industrial	Failed	213 ± 31

Results obtained during the fulfilling of the task

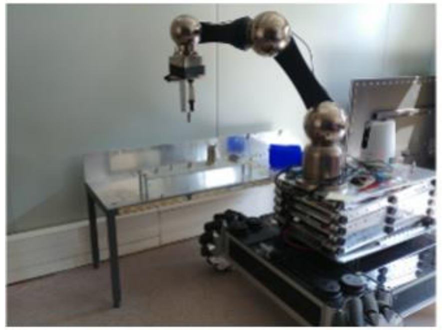
System	Un-trained users set[s]	Well-trained users set[s]
CERNTAURO	25%	10%
Robotic Industrial	50%	15%

Heartbeat percentage increase during the fulfilling of the task

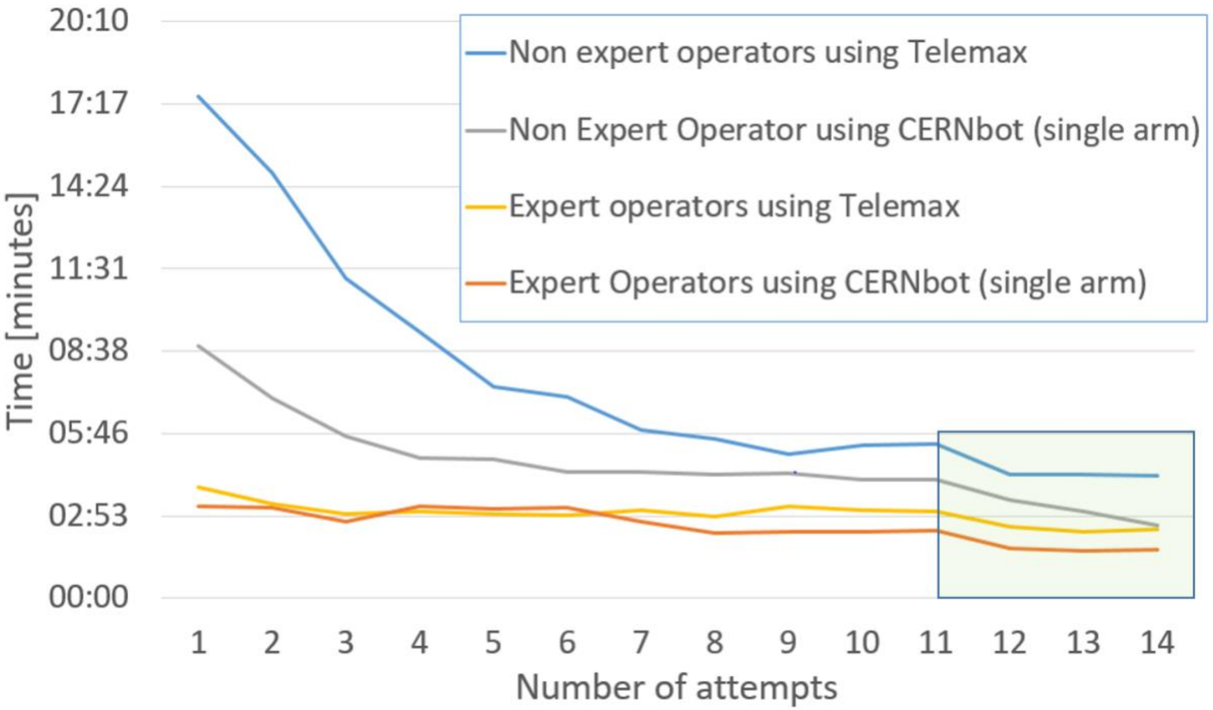
CERNTAURO Solution increases the efficiency reducing the stress of the operator

Comparative Analysis: Efficiency Test

- Telemanipulation experiment comparing Telemax robot (industrial solution) and CERNTAURO framework running on CERNbot using a master arm
  - ✓ Approaching and grasping a male connector inside a box and screwing it on a female one
  - ✓ 10 well trained/expert and 10 non trained operators



Picture of the Lemo B-type standard self-latching multipole connectors, with alignment key, used for the test (left), the connection task being performed by CERNbot in single arm configuration (center) and an operator at the master station (right).

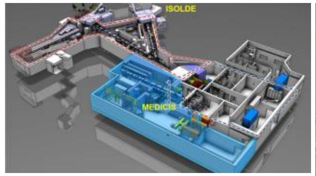


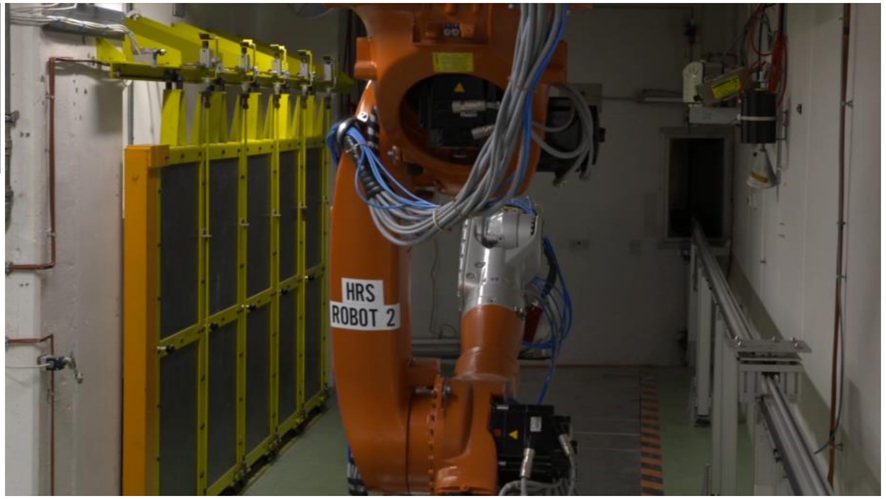
Time performance comparison between non-experts and experts operators using the Telemax and the CERNbot robot in doing the Lemo connection task

CERNTAURO user friendly increases the learnability of the system allowing non expert operators to reach similar performances of the expert one, after only few trials

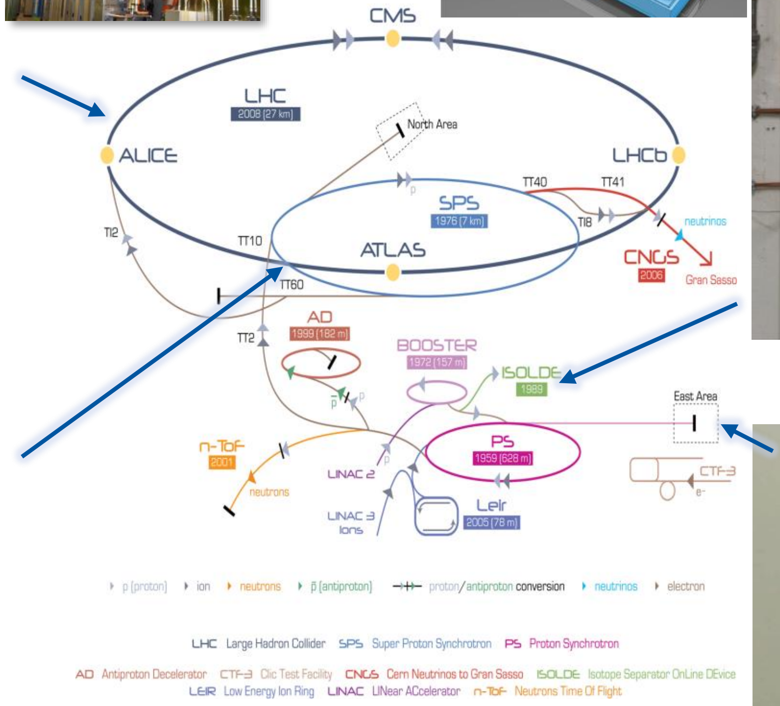
Main Robots integrated/controlled within facilities at CERN

TIM (x5)





Kuka Robots (x3)

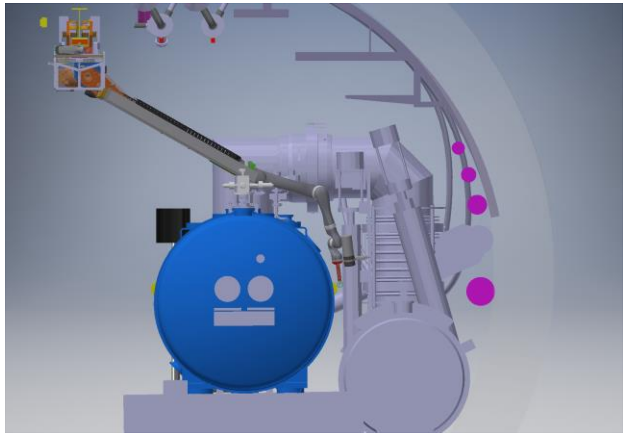


MIRA - CERNbot

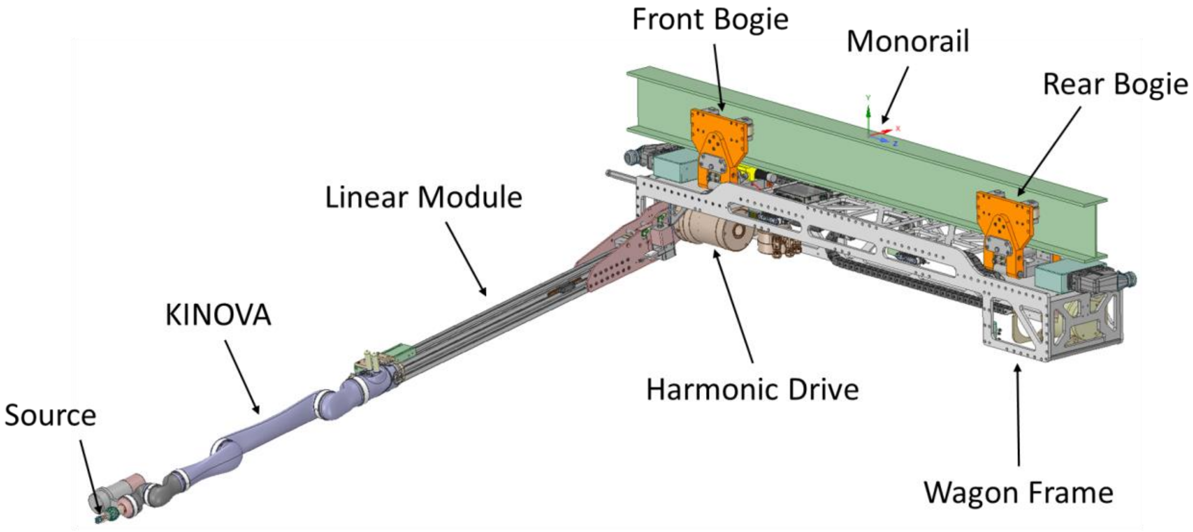
CHARMbot

Novel TIM robotic wagon

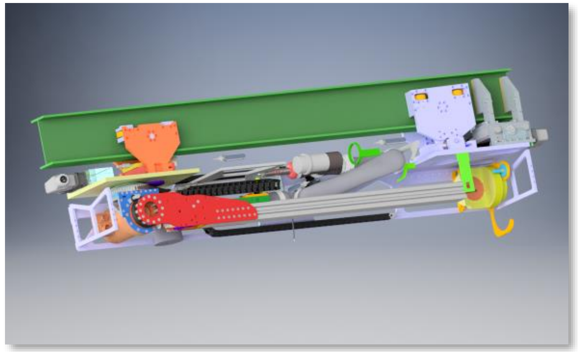
- 6 DoF (rotational axis) + 1DoF (linear axis) for dexterity
- 2 DoF (harmonic drive, backlash-free) for transversal positioning
- 1 stabilization axis
- 5 cameras



3D view for transversal positioning



New TIM robotic wagon with extracted arm

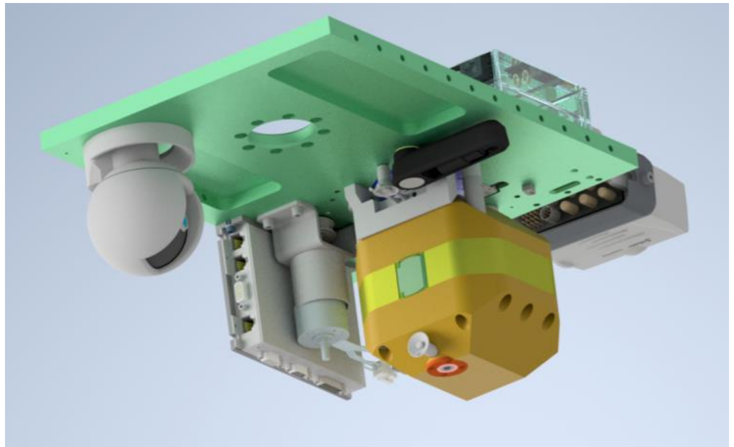


New TIM robotic wagon with source container and retracted arm

Novel radioactive source shielding system

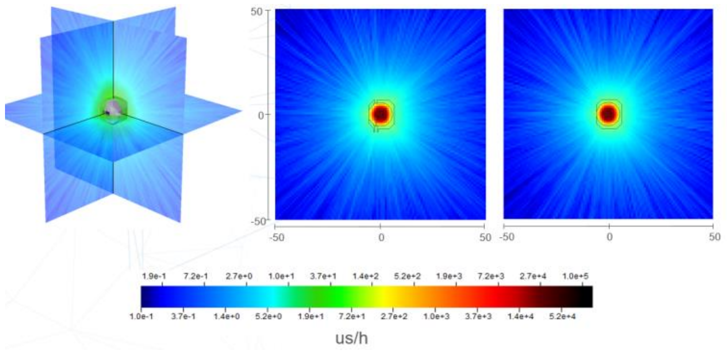
- Motorized system (Carousel-based design)
- Core/shielding part in tungsten
- Absolute positioning encoder on the core
- Locking system with handle and safety pin
- Sensor redundancy for the source state
- **<u>Cs-137 Source: 1.85 GBq</u>**
- Radiation levels with source in shielding:

  1.1 µSv/h at 40 cm

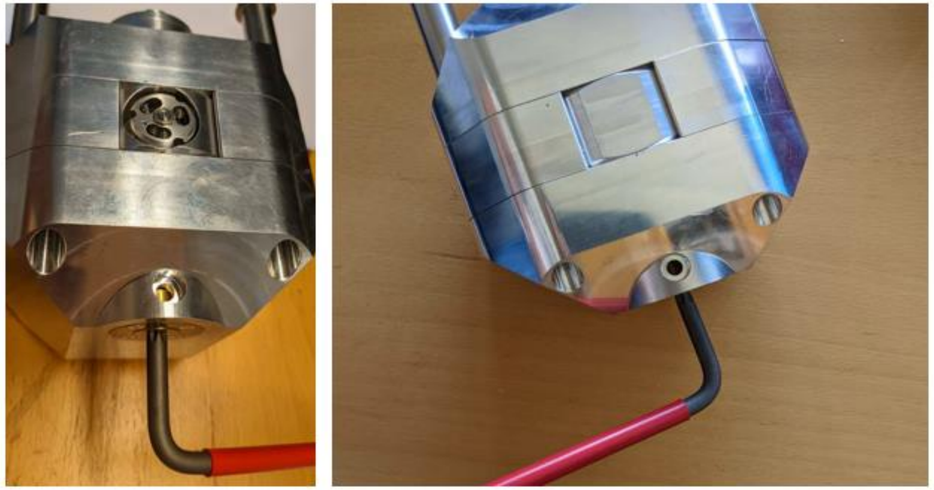


Design

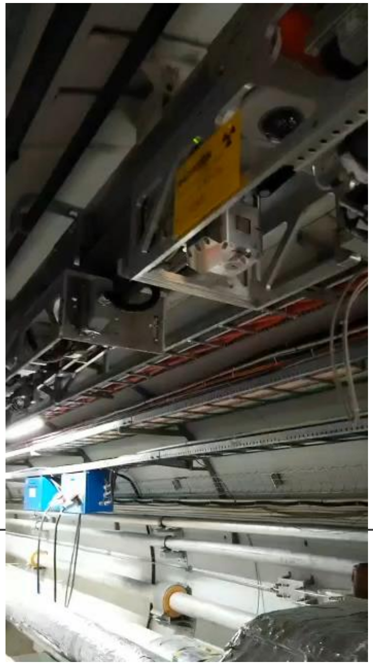
Shielding installed in the robotic wagon



RP simulation in symmetry planes (courtesy of HSE-RP)

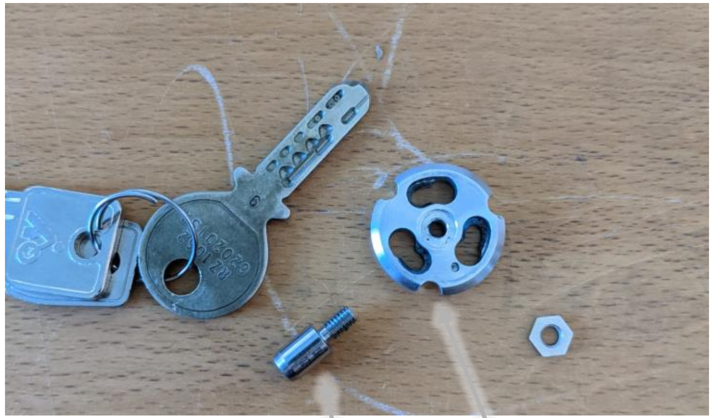


Shielding



Installation of the radioactive source in shielding (x2)

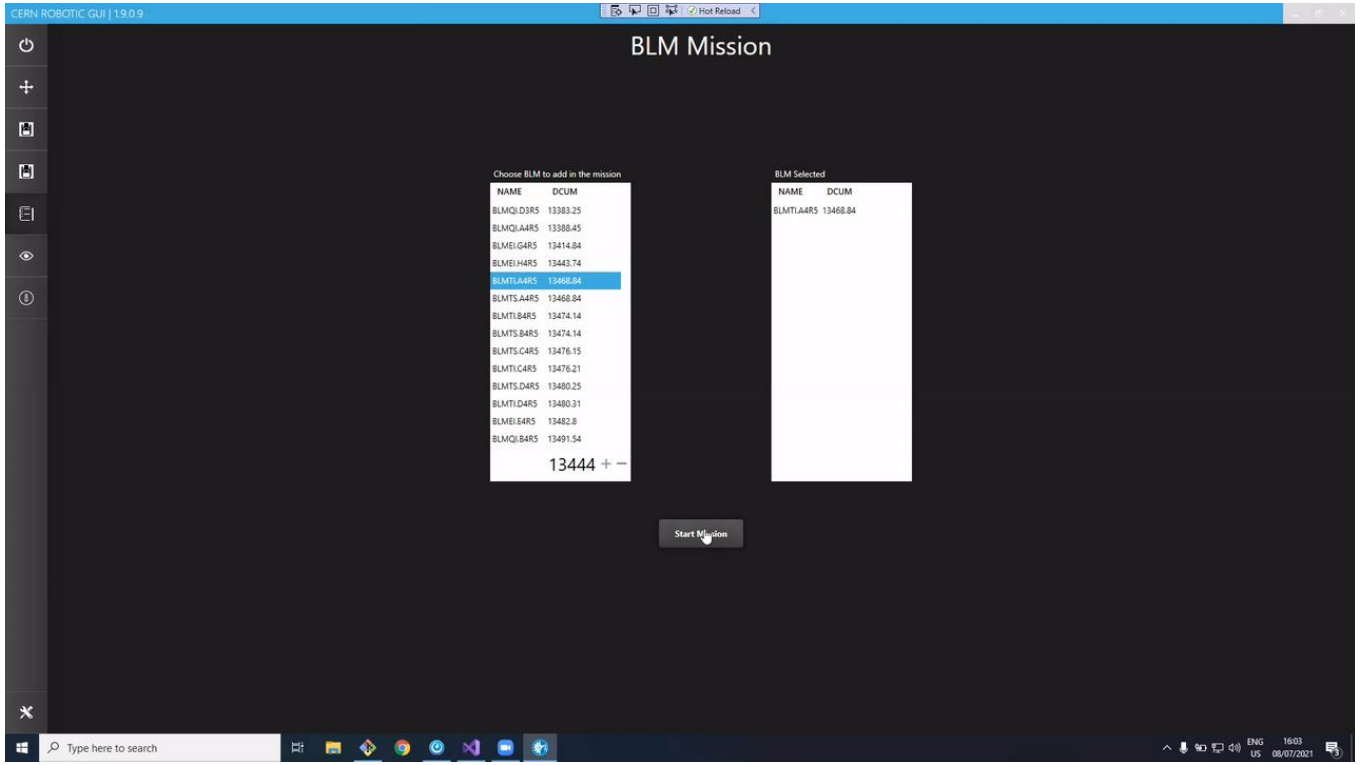
- Operation performed fully remotely in ISR
  - ✓ Source extracted from transport container and safely installed in shielding using robots

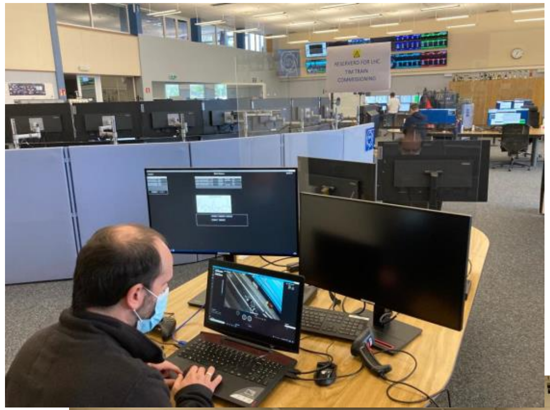


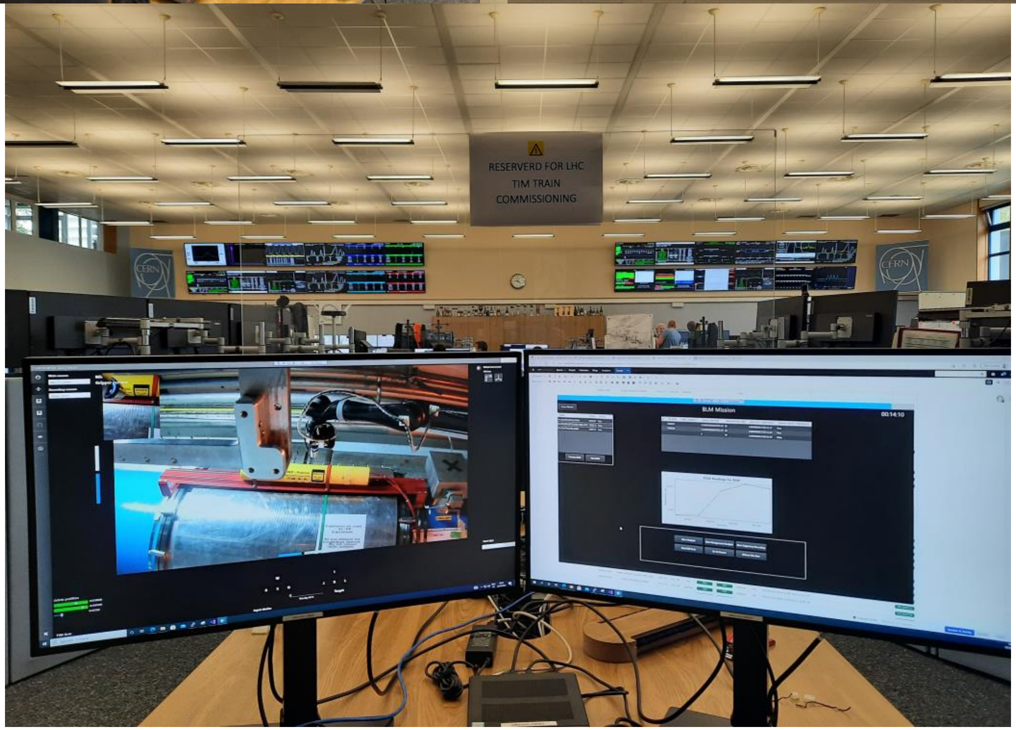
Radioactive source and holder

Measurements with source in shielding

Human-robot interface and operation

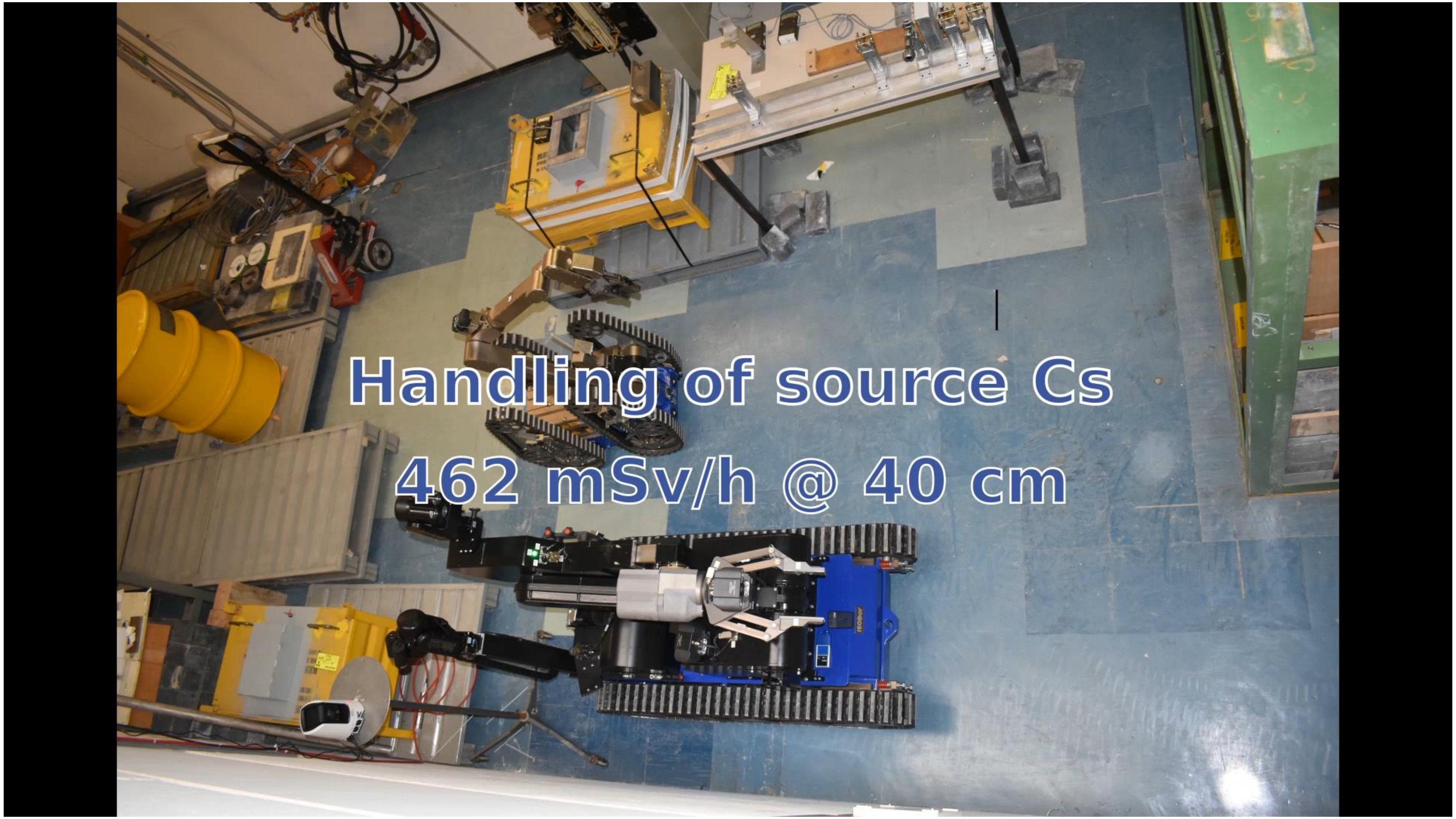






Intervention done in 2015

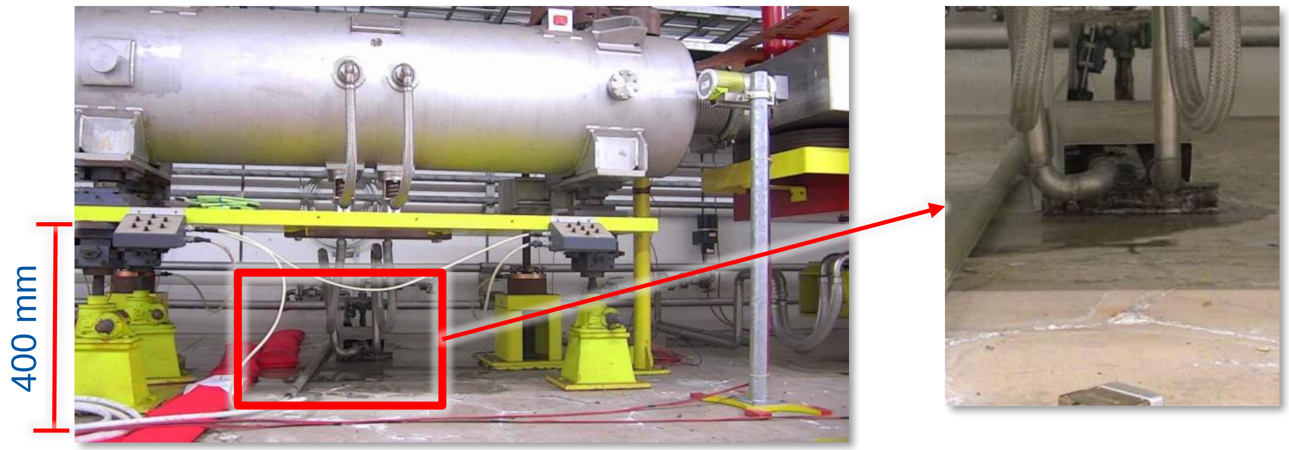
Intervention done in 2015, b172



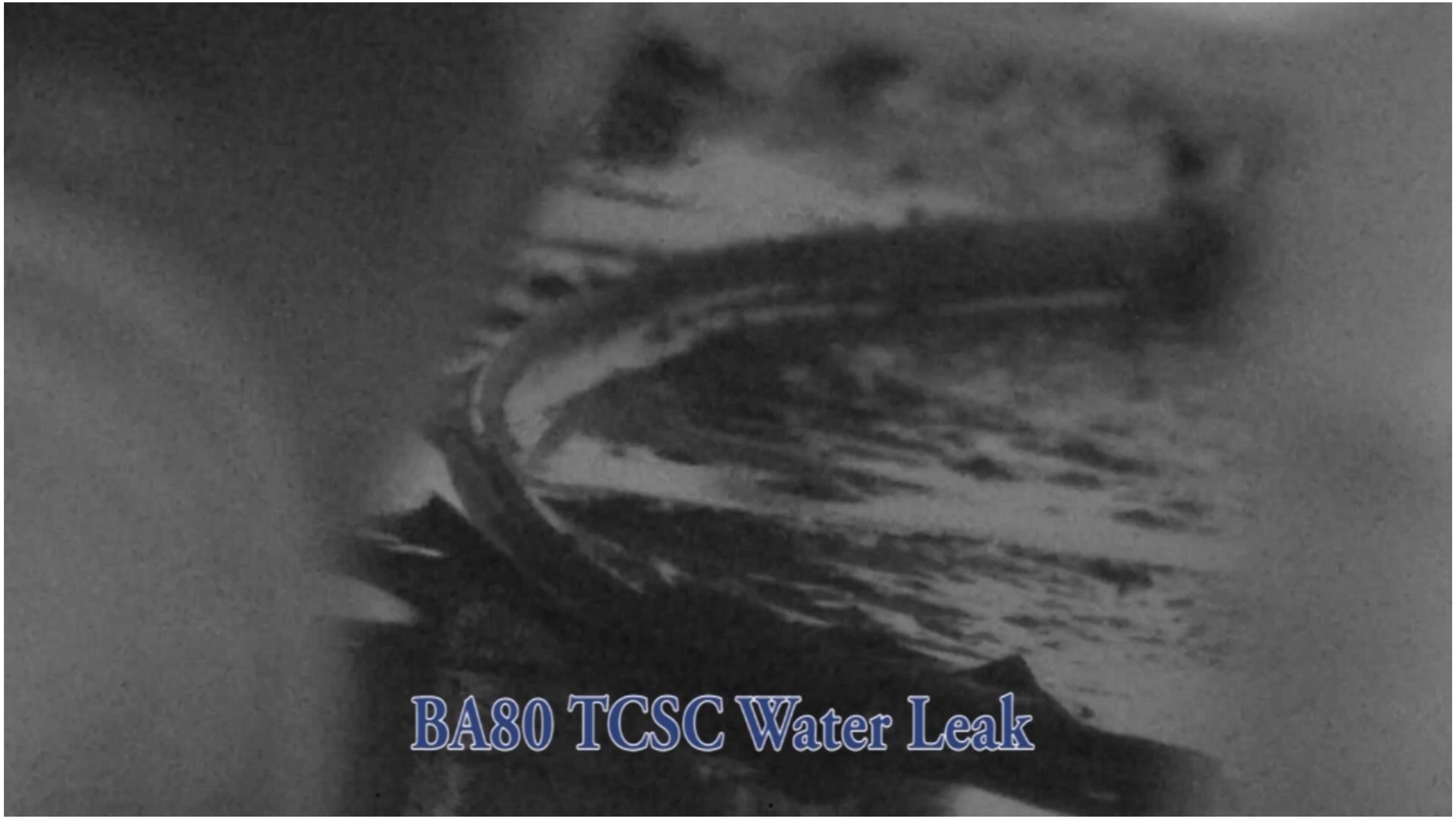
Main Robotics Interventions in 2020

Challenging Teleoperation Example#1

- Water leak inspection and fix in extremely radioactive area
  - **Access particularly difficult**
  - 1 km inside 1st beamline access
  - Teleoperated from human safe area
  - CERNbot for teleoperation and EXTRM for support
  - 10 hours of operation
- **CERNTAURO modularity allowed quick robot reconfiguration, sensors and tools integration to environmental changes**

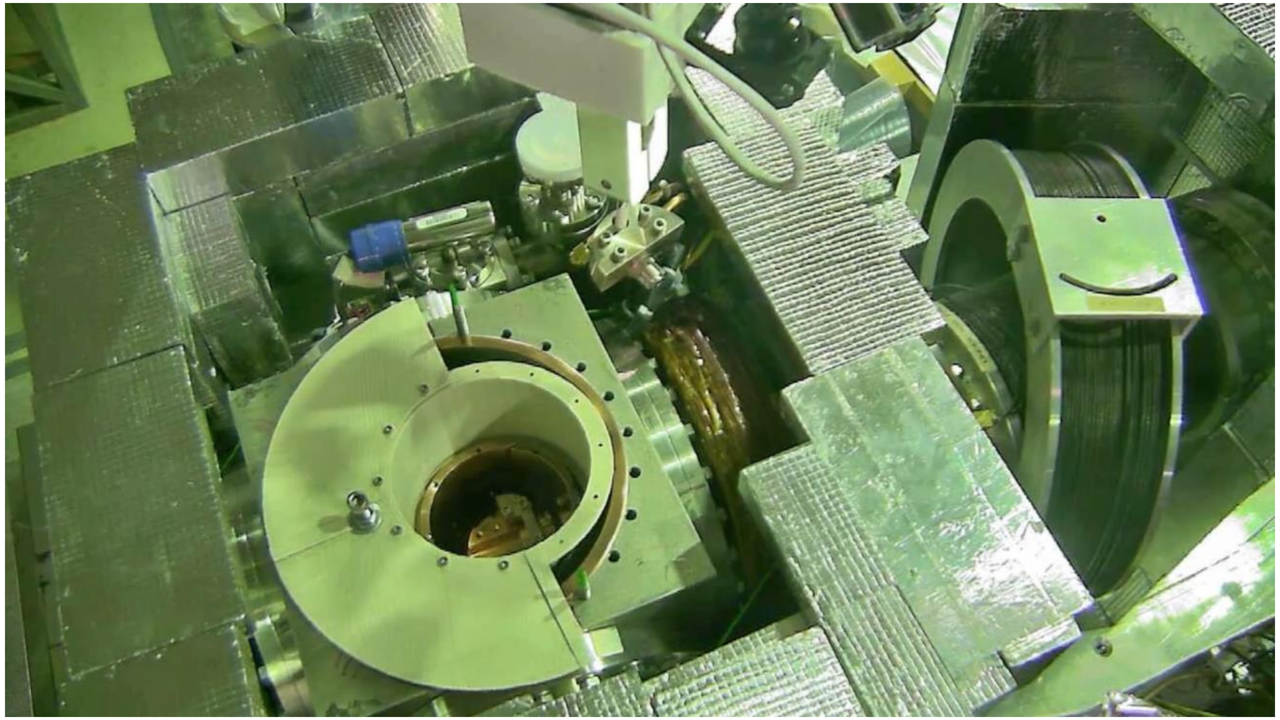
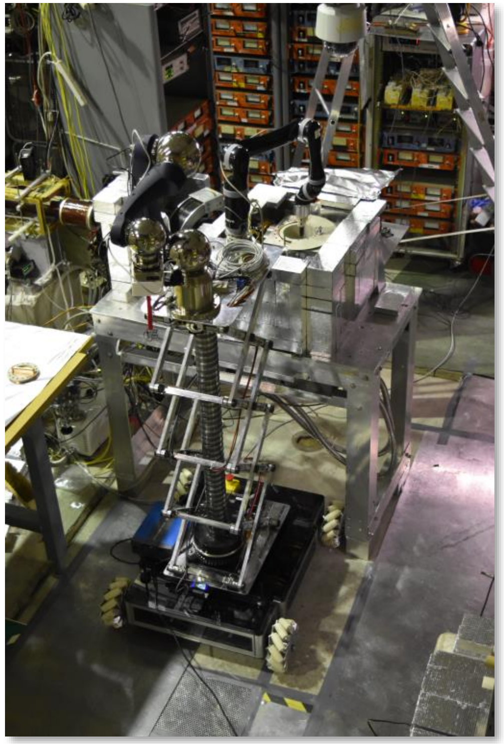
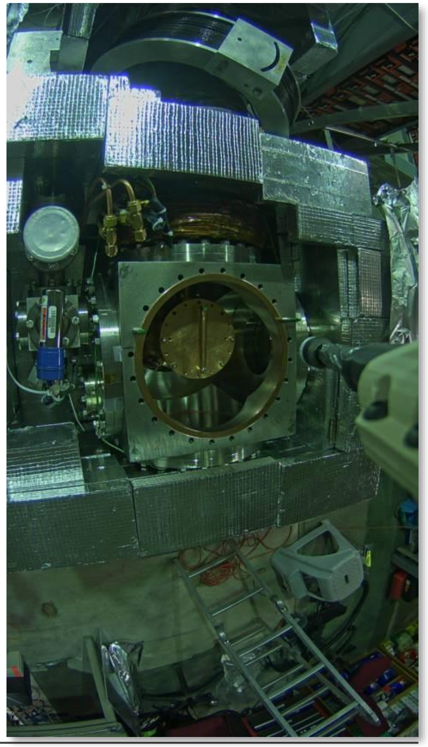


Challenging Teleoperation Example#1

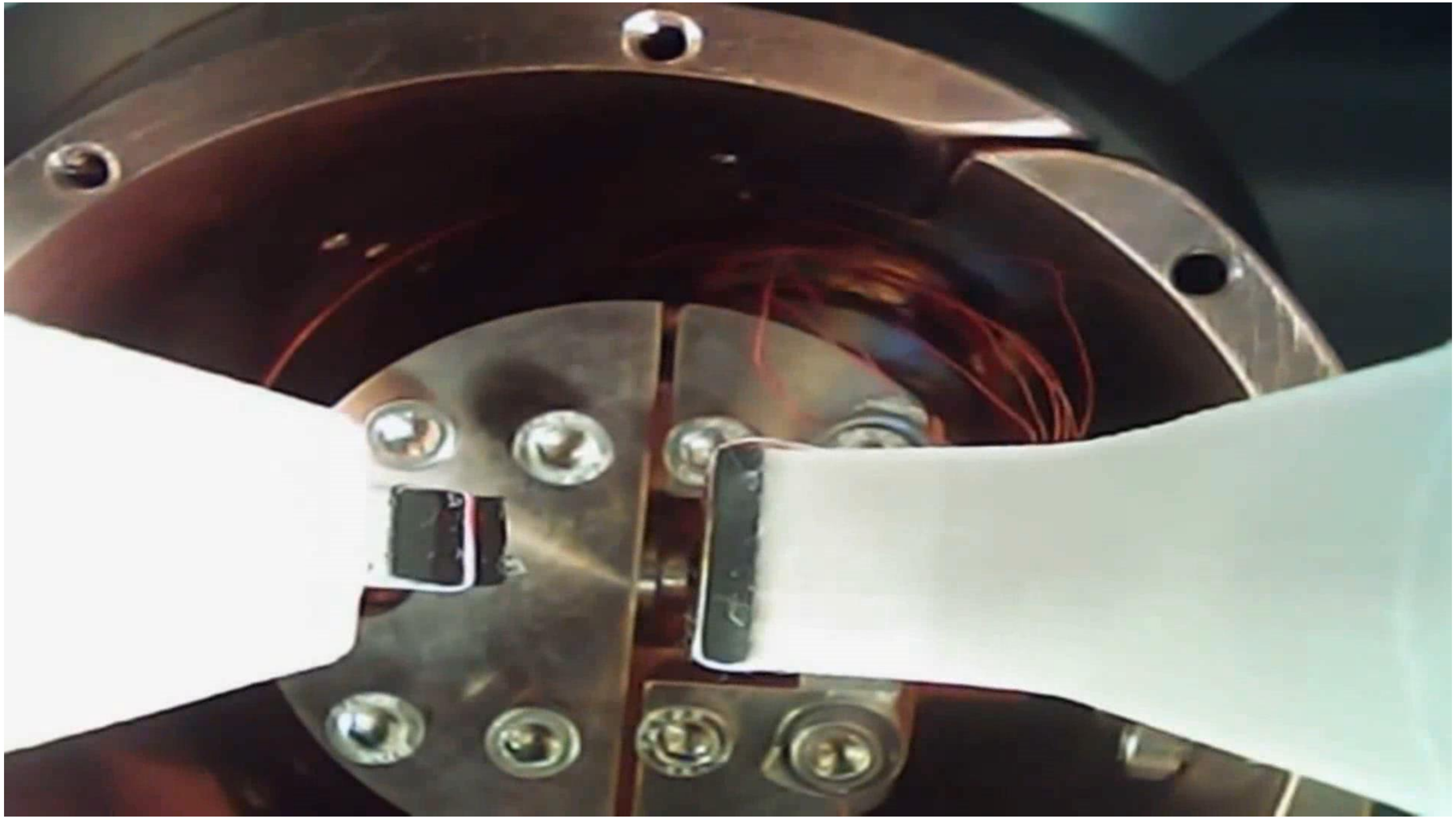


Challenging Teleoperation Example#2

- Radioactive source handling at 2.5 m height using CERNbot 2
  - ✓ **Intervention not possible to be performed by humans**
  - ✓ Bimanual operation, novel procedures and tooling
  - ✓ **CERNTAURO RH procedures and recovery scenarios allowed intervention acceptance by big science facility management**
  - ✓ **CERNTAURO bilateral master-slave control allowed precise telemanipulation of delicate objects**

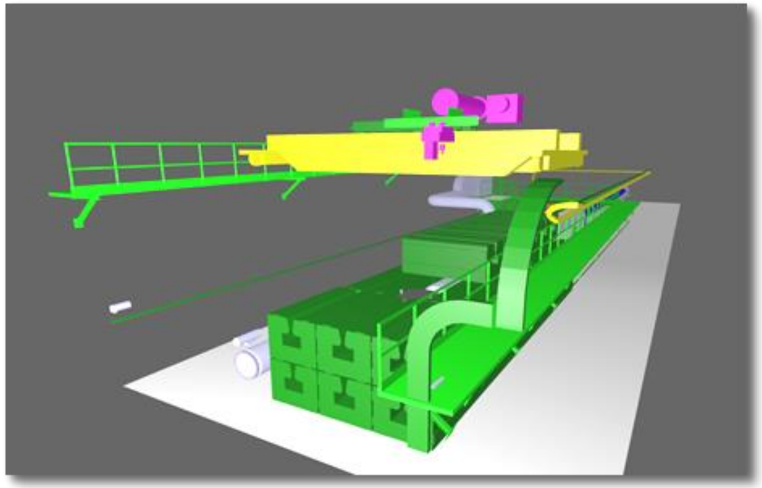
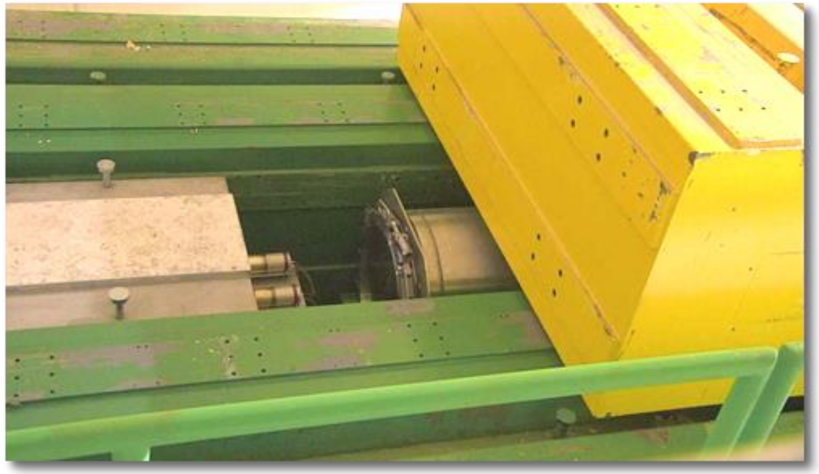
Challenging Teleoperation Example#2

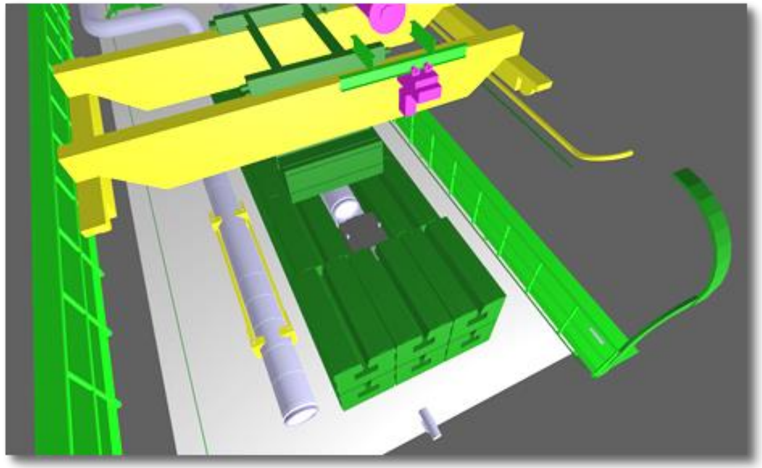
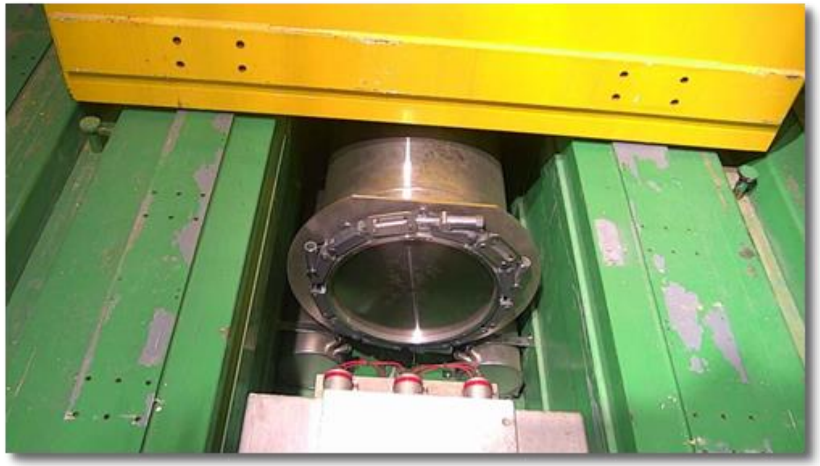


Challenging Teleoperation Example#4

- LHC TDE inspection

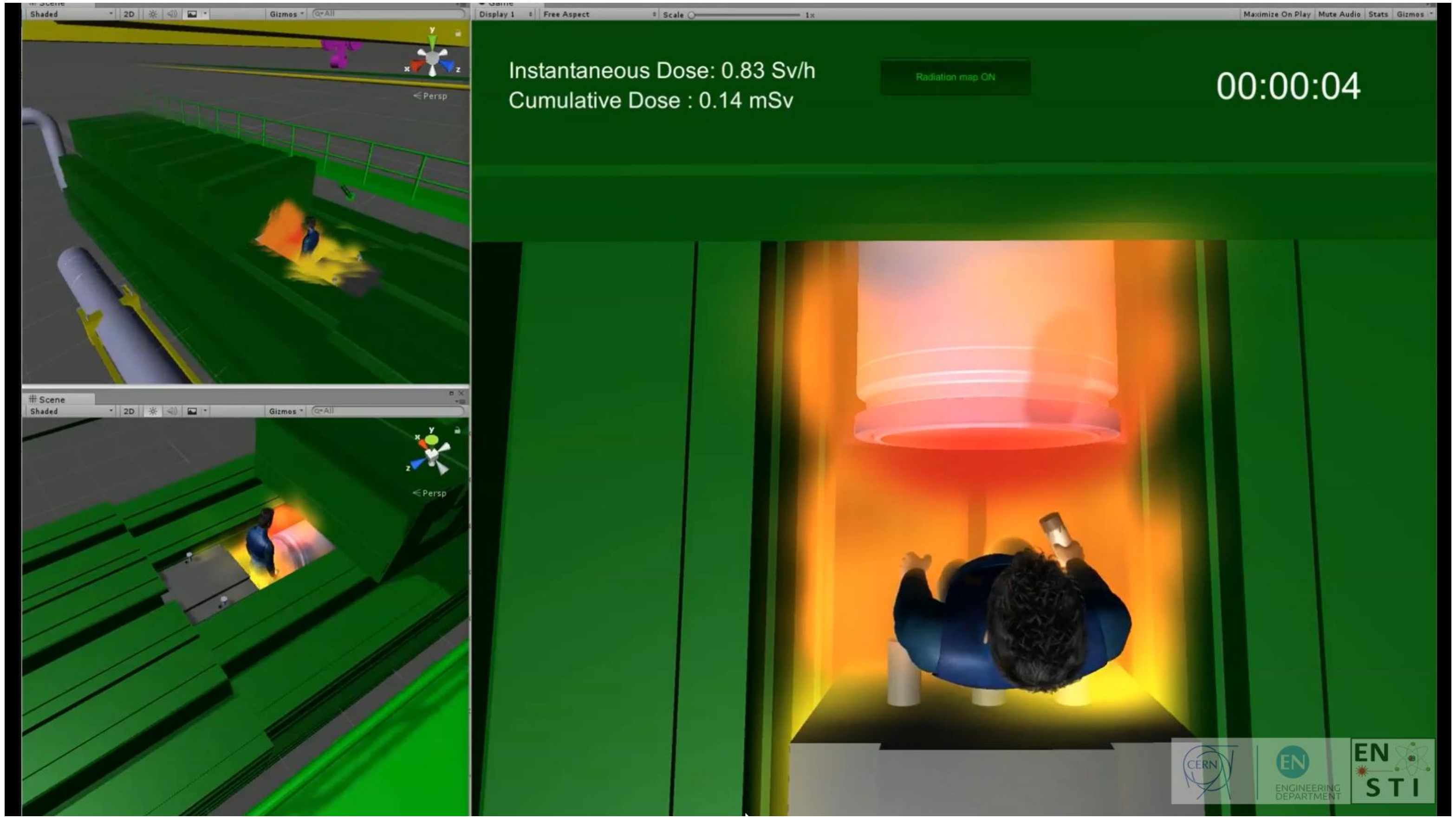
CERNbot v1.0 core

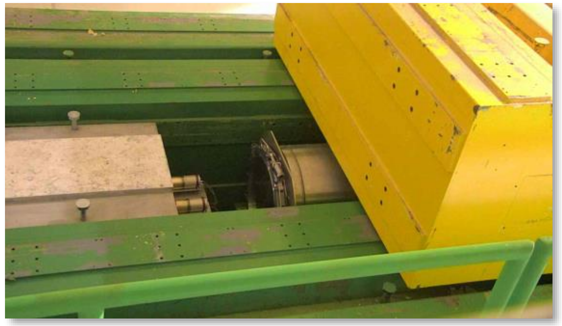



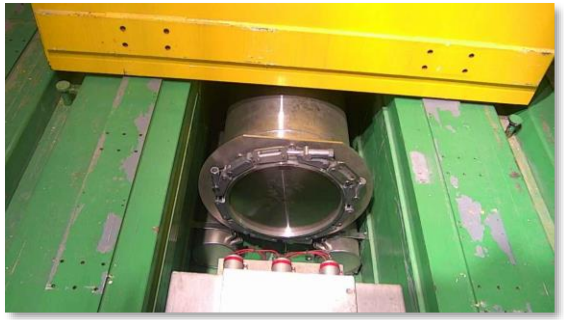



Challenging Teleoperation Example#4

- LHC TDE inspection

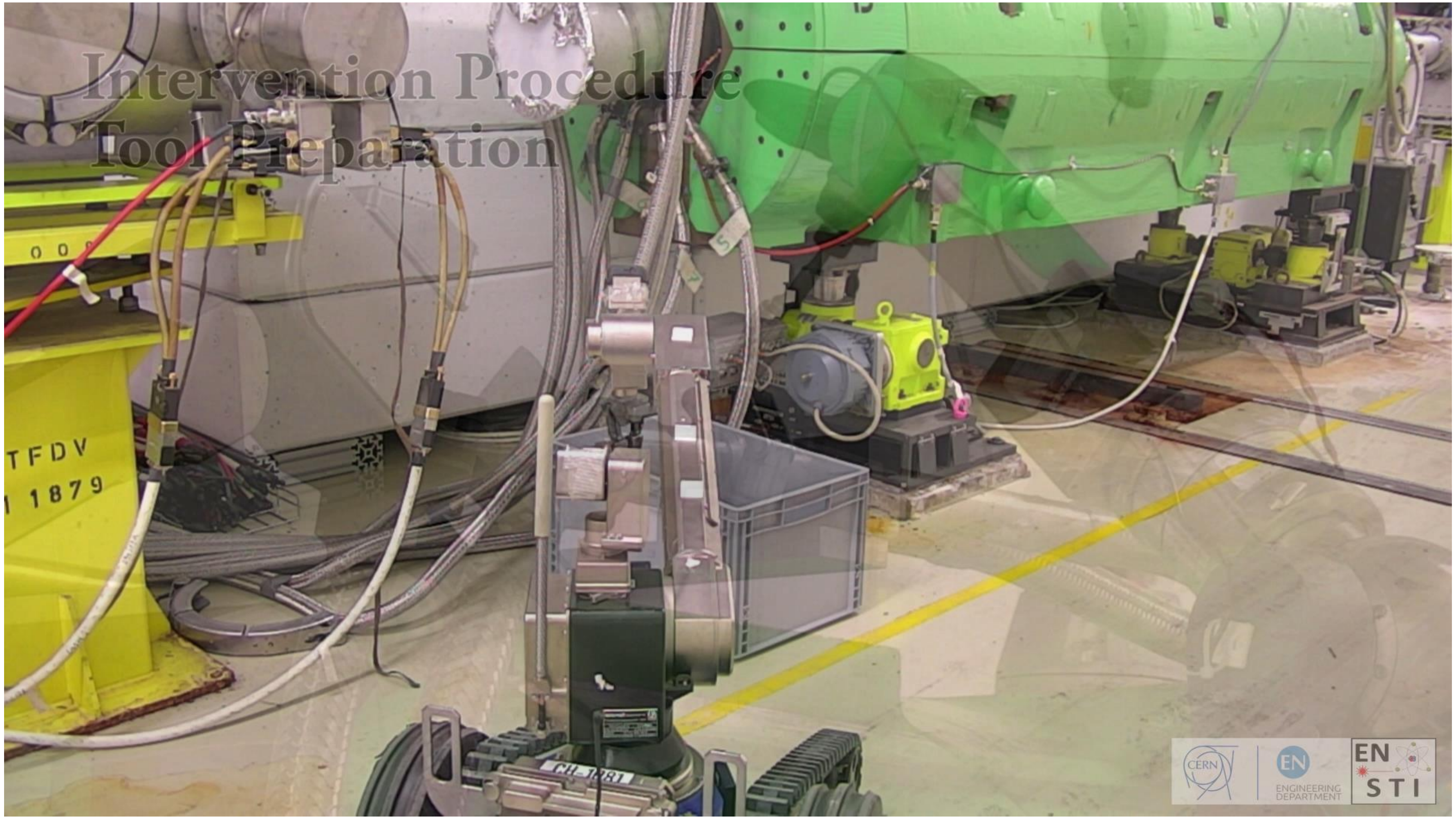






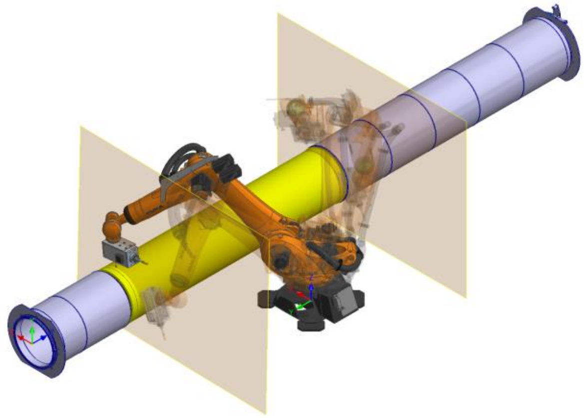
Challenging Teleoperation Example#5
Dismantling of n_ToF target

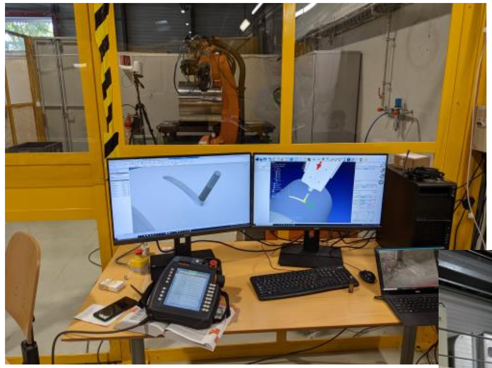
Robotics used for postmortem analysis (SPS - TIDVG)

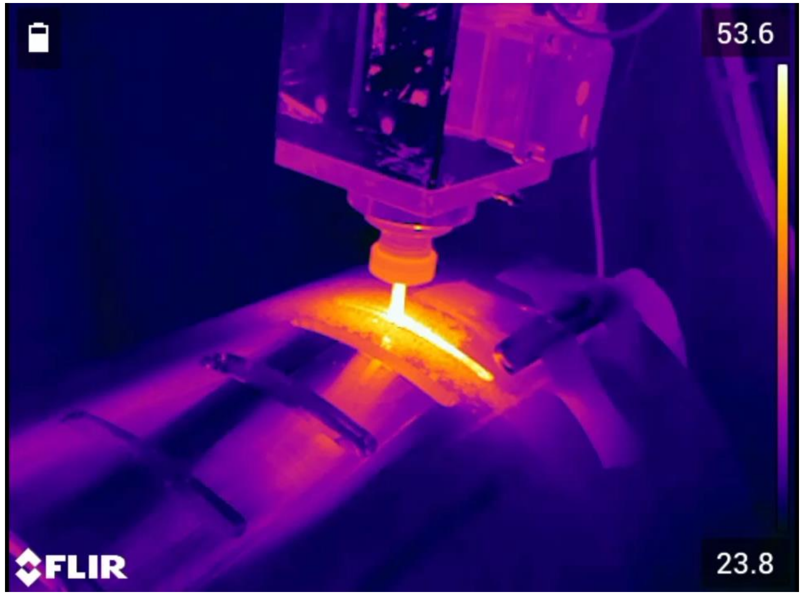


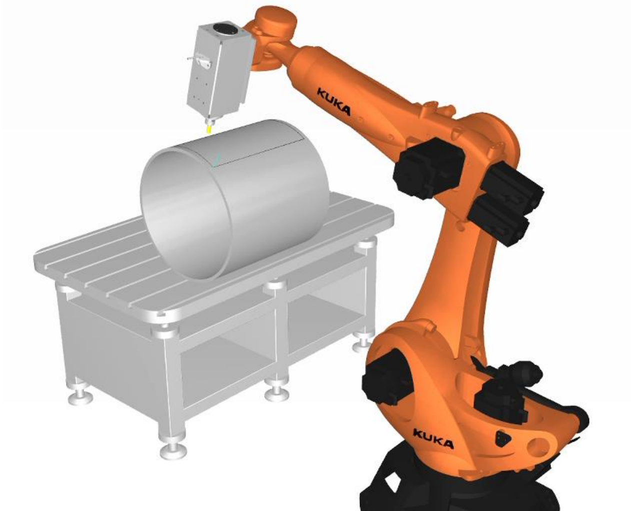
Robotics used for postmortem analysis (LHC - TDE)

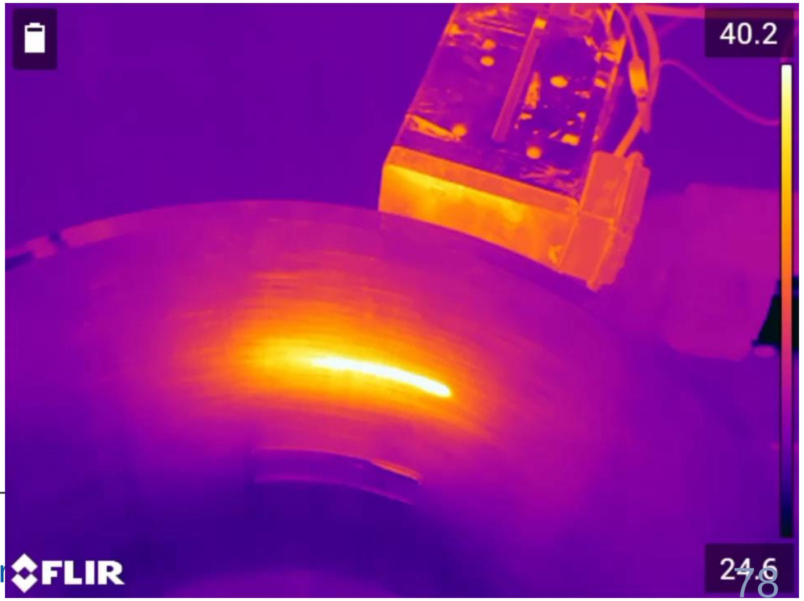
- Robotic milling to open the old TDE shell in ss 318LN



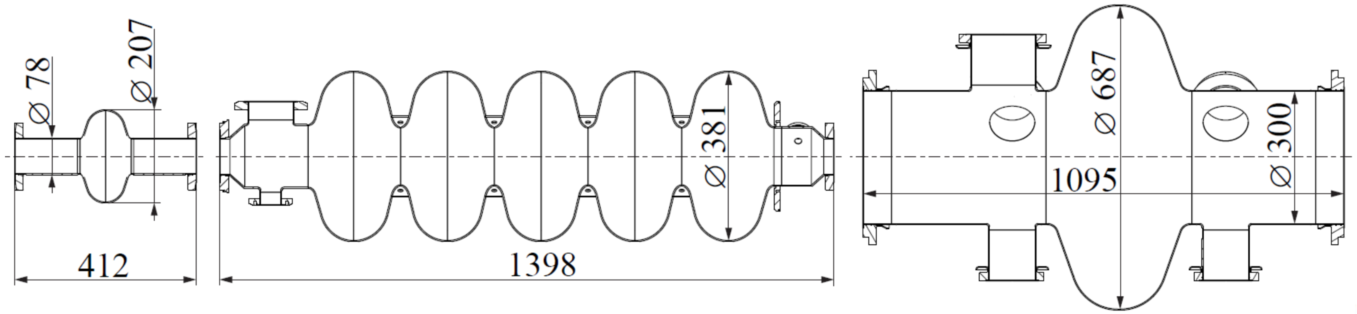


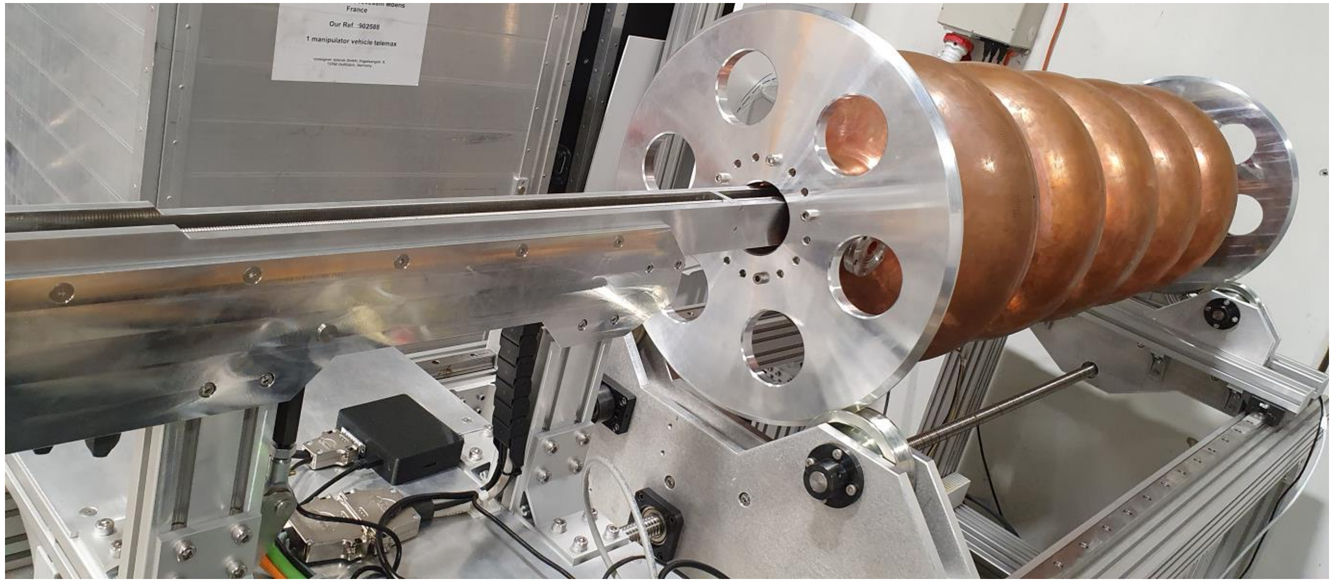


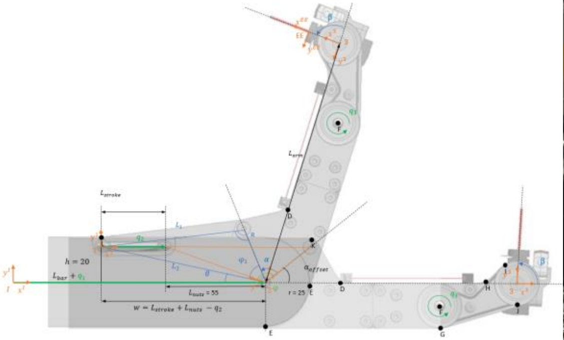


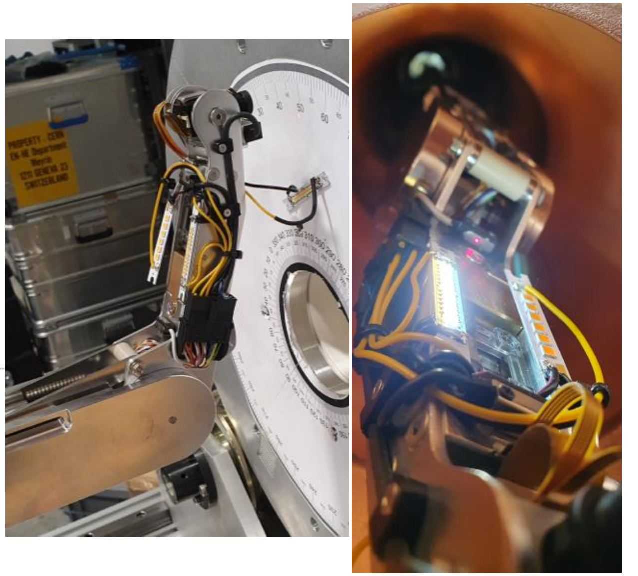


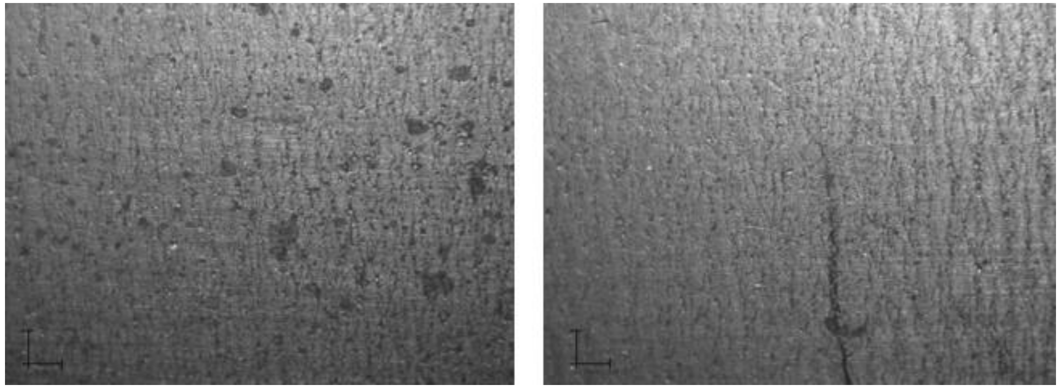
Robots used for Quality assurance: RF cavity visual inner inspection











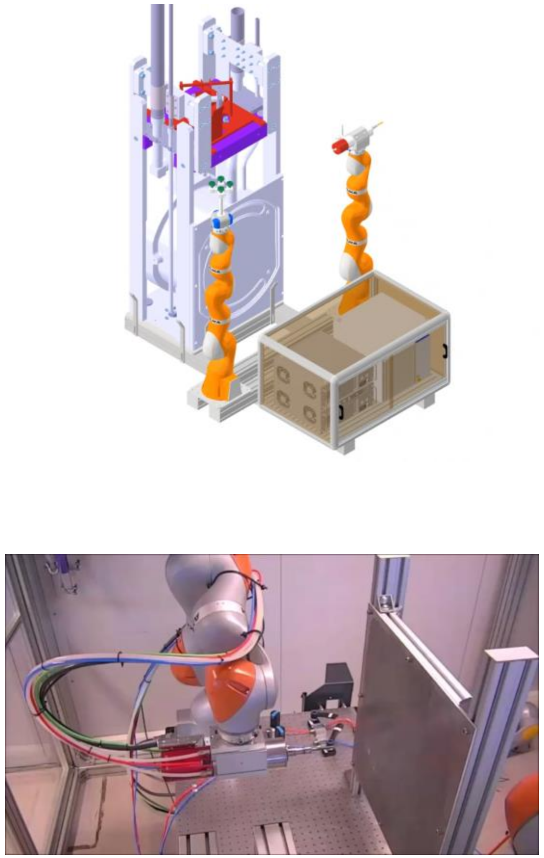
Images size: 1 x 1 cm taken at 23 mm distance

Content

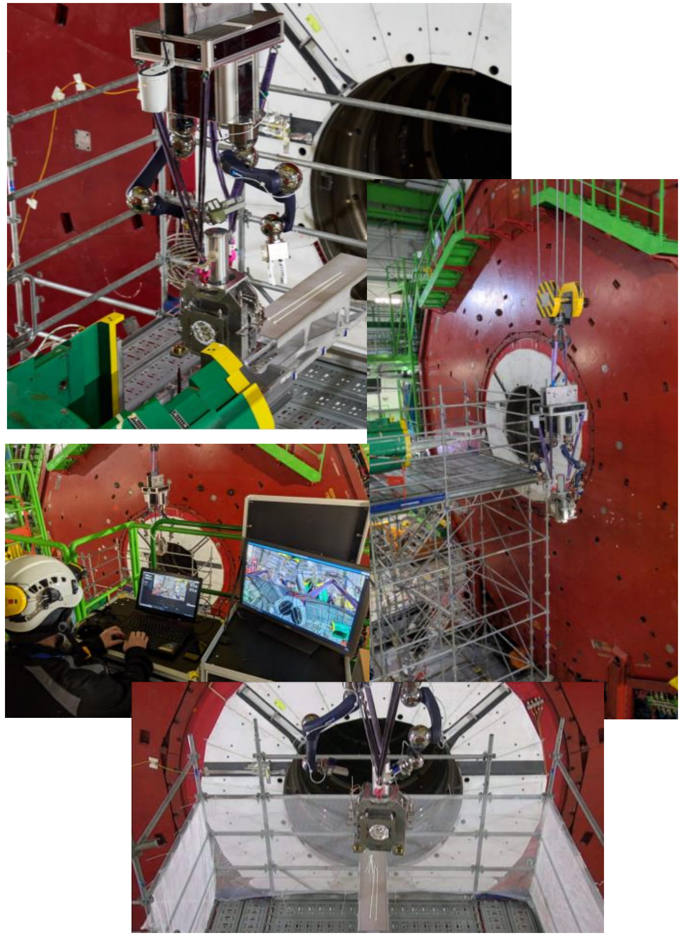
- Introduction and state of the art
- Needs and challenges for robotics at CERN
- The robotic service in BE-CEM
- Future objectives
- Conclusions

Future main missions

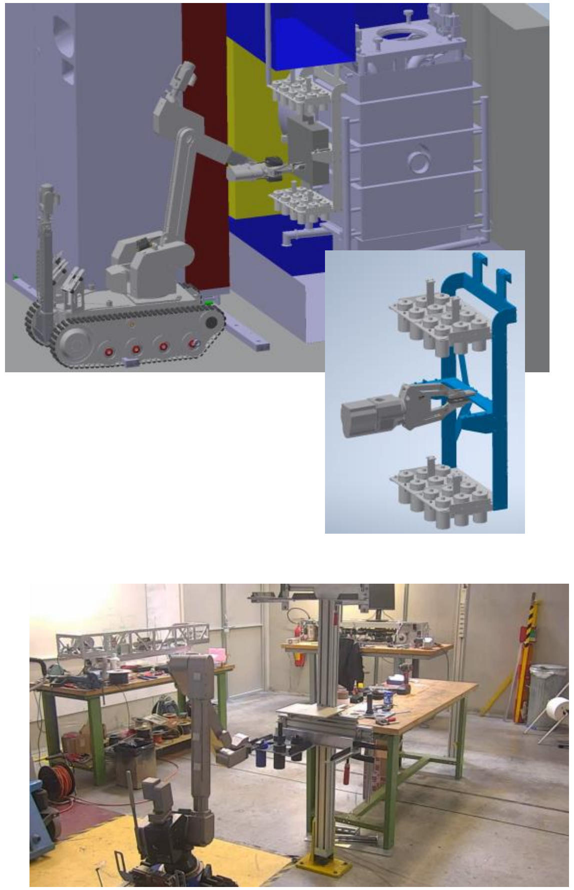
- old nToF target opening, robots for NA (TCCD), ntoF NEAR target exchange, new CMS VAX maintenance with CRANEbot, ATLAS shielding doors robotic milling



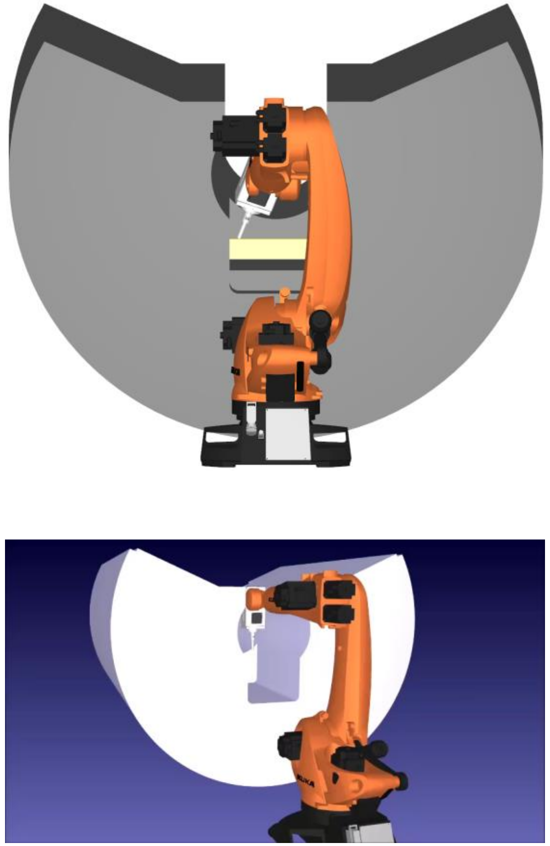
old nToF target opening



CMS VAX Maintenance



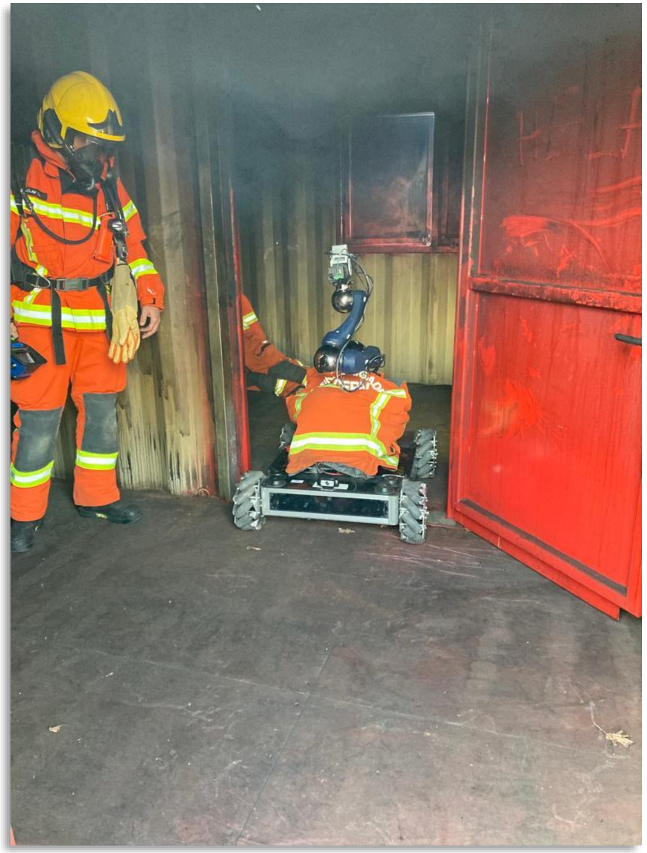
n_ToF NEAR targets exchange

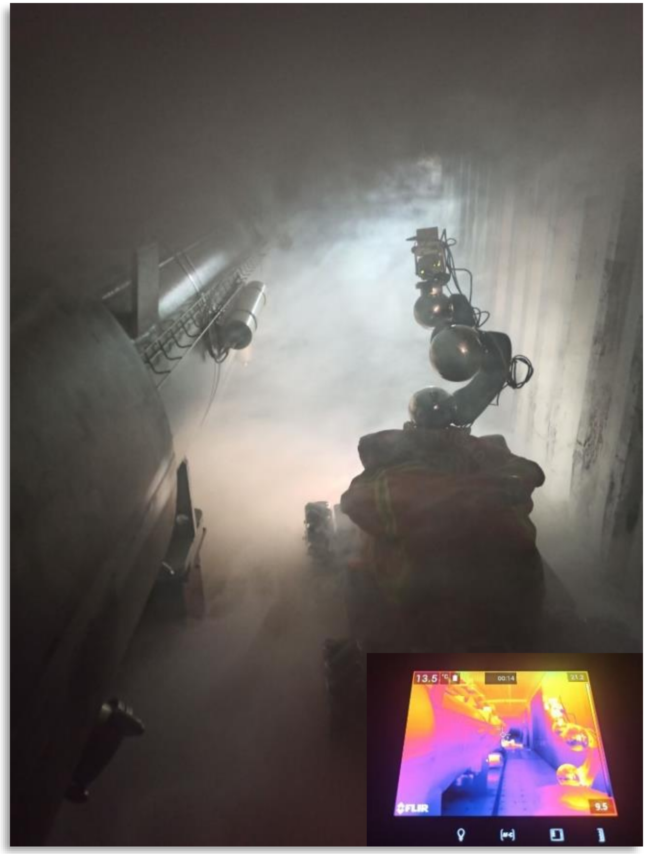
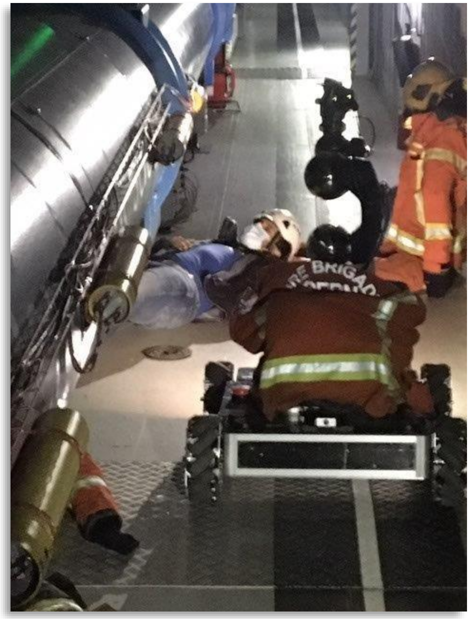


ATLAS shielding doors modifications

Robots for Search and Rescue

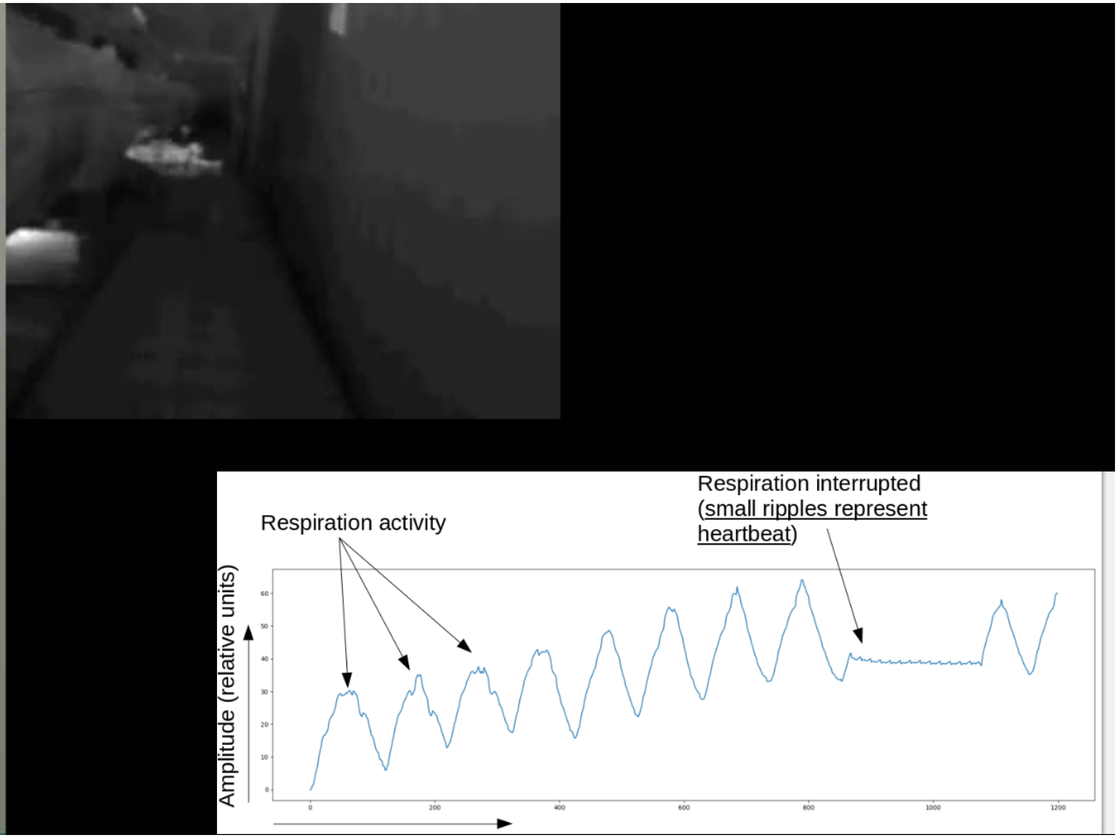
- First test of for **FB-CERNbot** collaboration for search and rescue in disaster zones



Robots for Search and Rescue

2D IMAGE

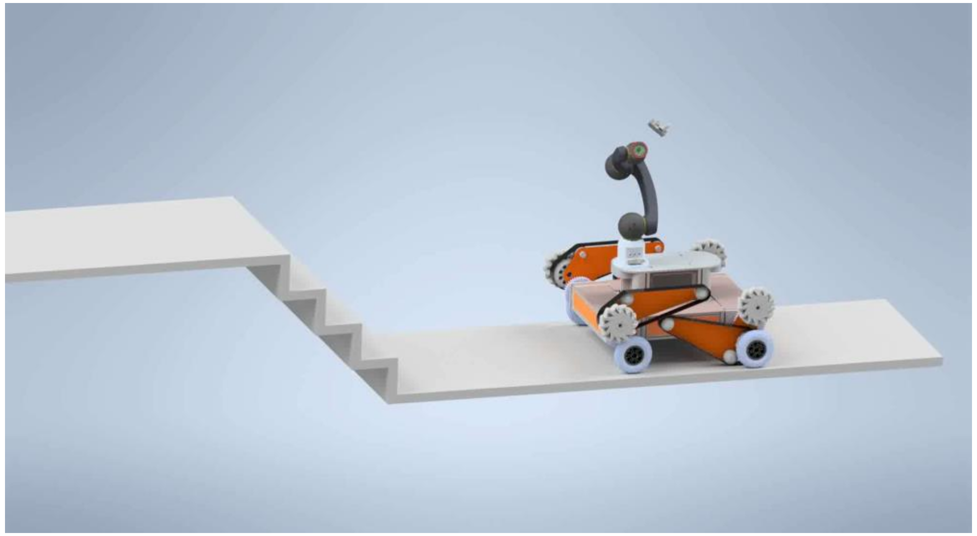


IR+RADAR (for respiration and heart beat monitoring

Video of CERNbot searching for victims in disaster zones with presence of heavy smoke, comparison of standard 2D image with IR+RADAR

Modular Robots

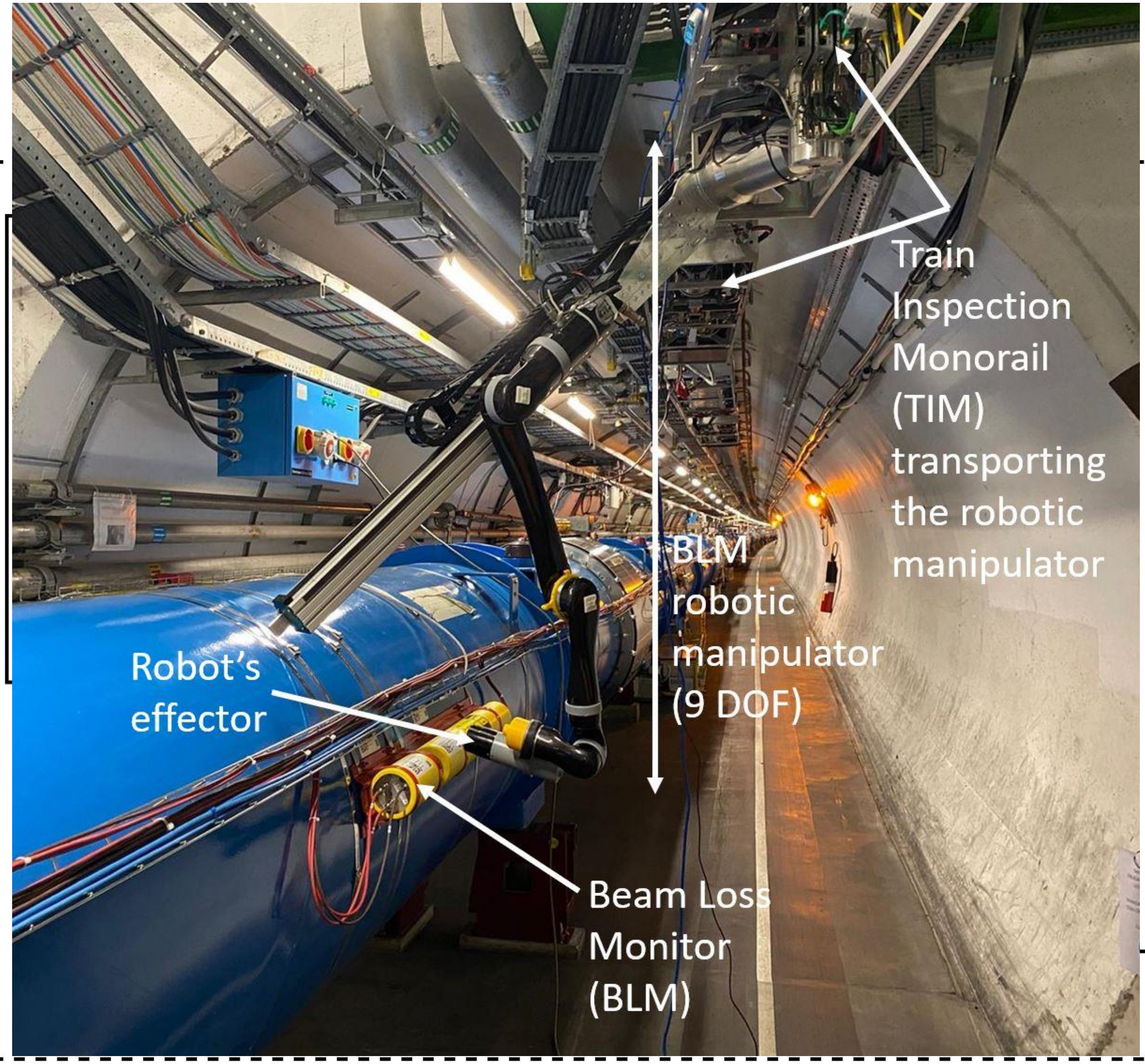
- Adaptive traction system for ground robots
- Drones and hyper-redundant (snake) robot for inspection and teleoperation support (third eye) in confined space (including beam pipe inspection)
- Fusing hydraulic and mechanic technologies for a novel robotic arm (more precision and payload) for portable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



User-friendly teleoperation system

- Novel Master device equipped with haptic devices to increase operators proprioception
- Autonomous operation based on learning by demonstration technology
- Integration and commissioning of Machine Learning technologies for operator awareness and autonomy improvements (70% of LHC BLMs validated autonomously with TIM in LS3)

Mixed Reality Human-Robot Interface



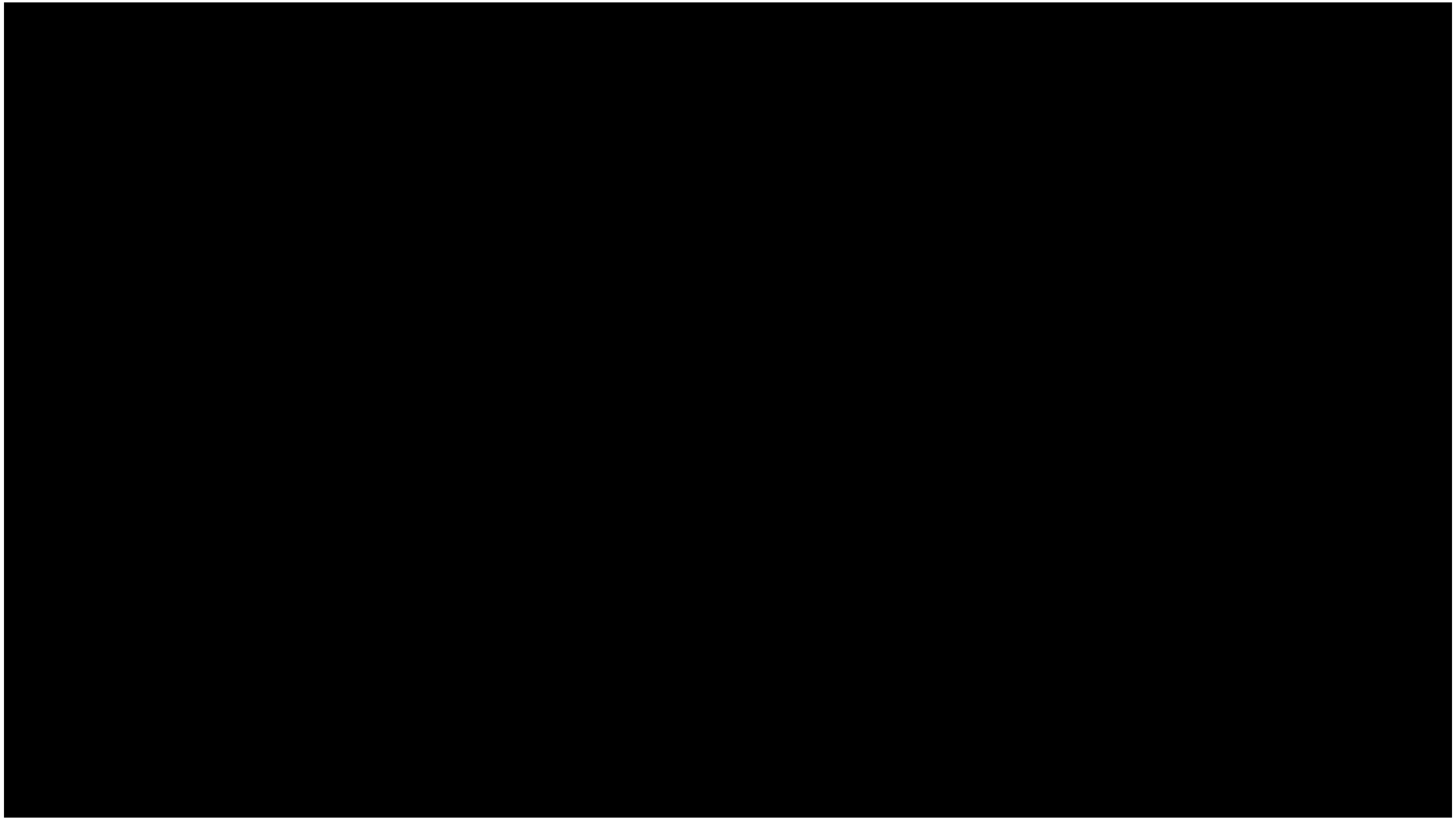
Communication over mobile 4G network, WiFi or CERN internal network

2D GUI (Windows Presentation Foundation, C#)

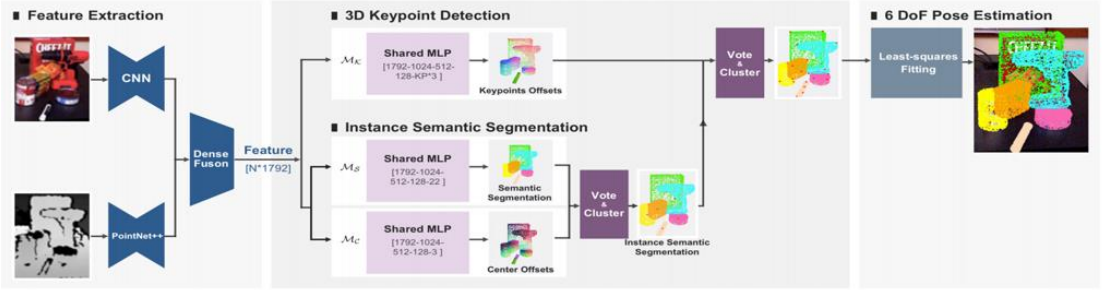
3D (Mixed Reality) GUI (Unity, C#)

LOCAL OPERATOR'S COMPUTER

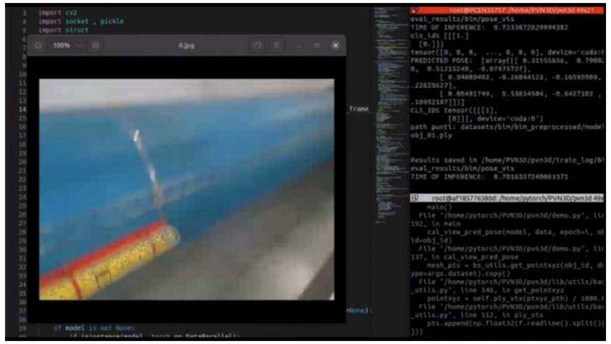
Mixed Reality Human-Robot Interface

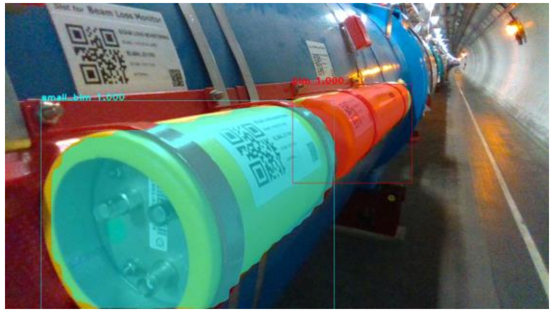


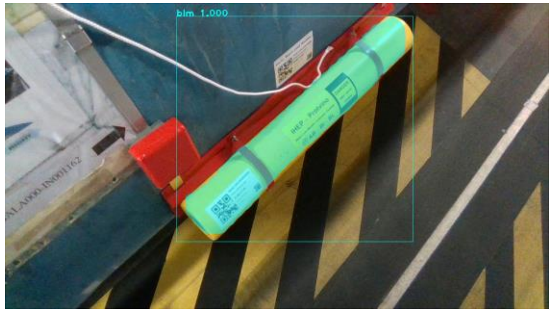
BLMs detection and 6 DoF pose estimation using ML

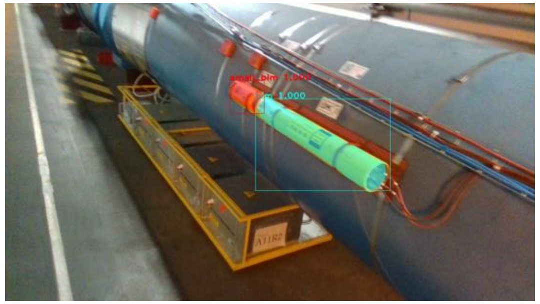


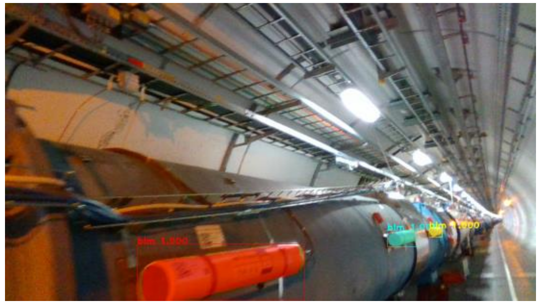
BLMs detection and pose estimation framework

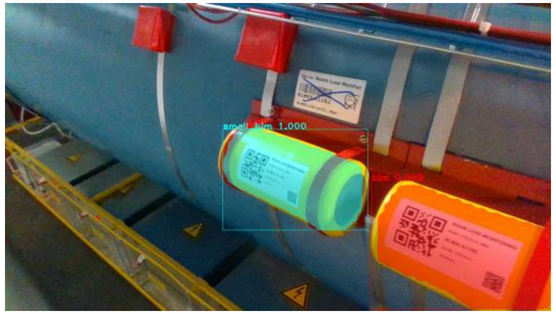


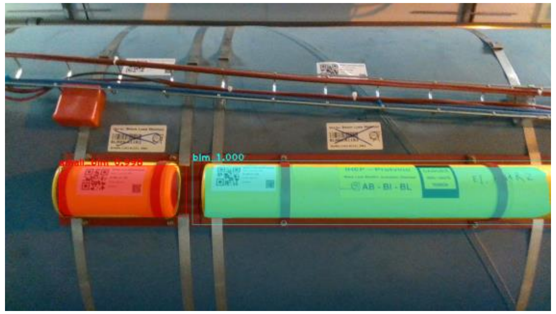


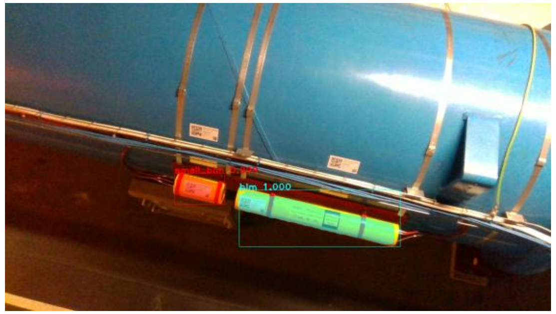








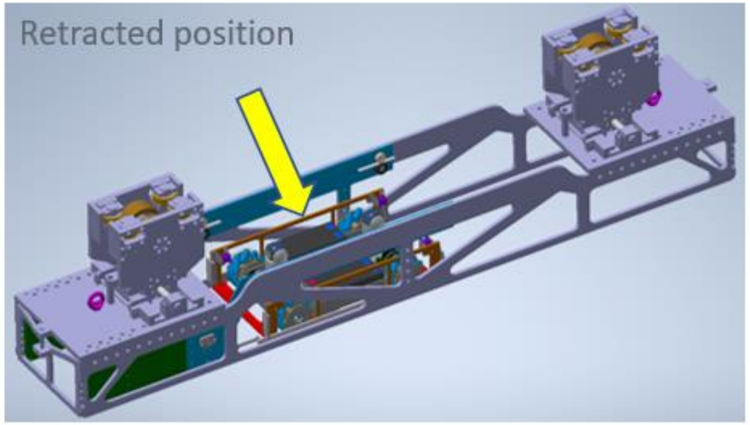


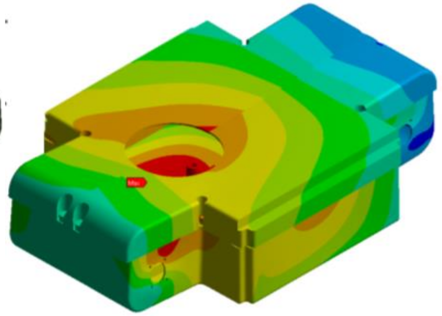


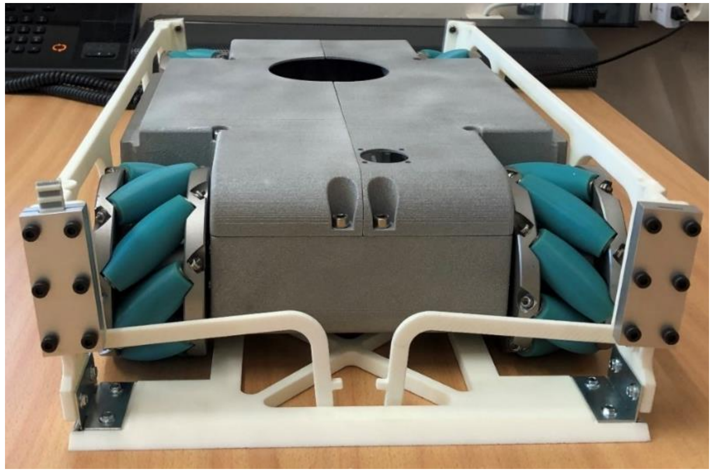
Examples of BLMs detection/segmentation using ML

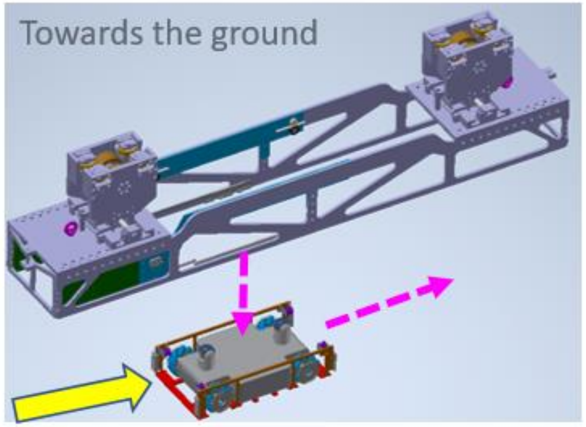
TIM Junior

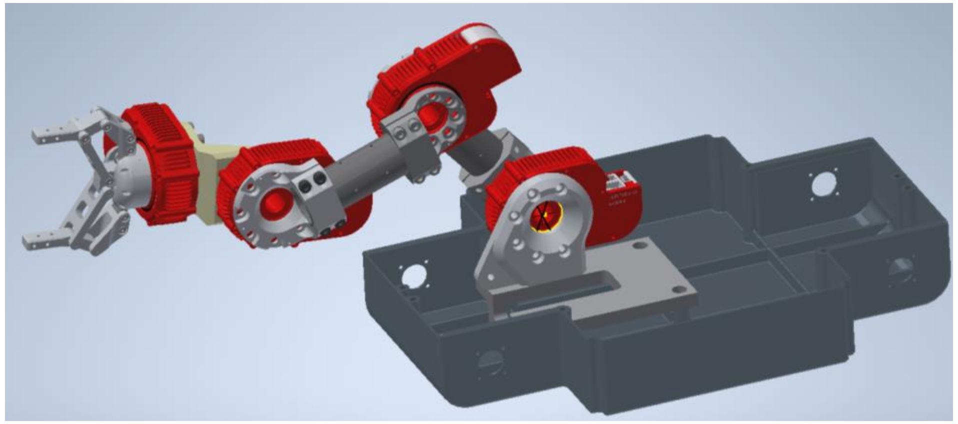
- ROV inside TIM wagon to be lowered down in the LHC

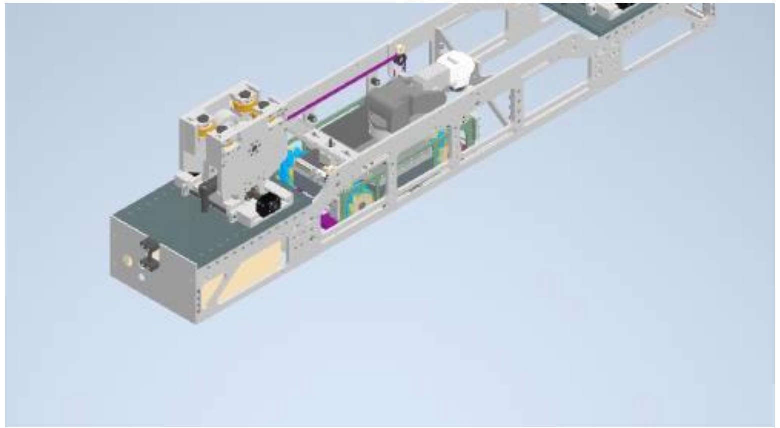






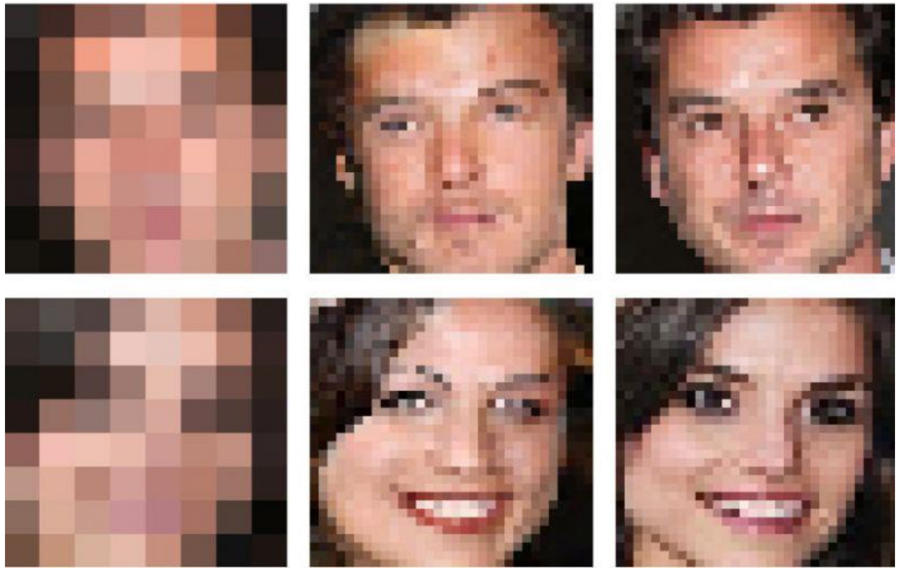


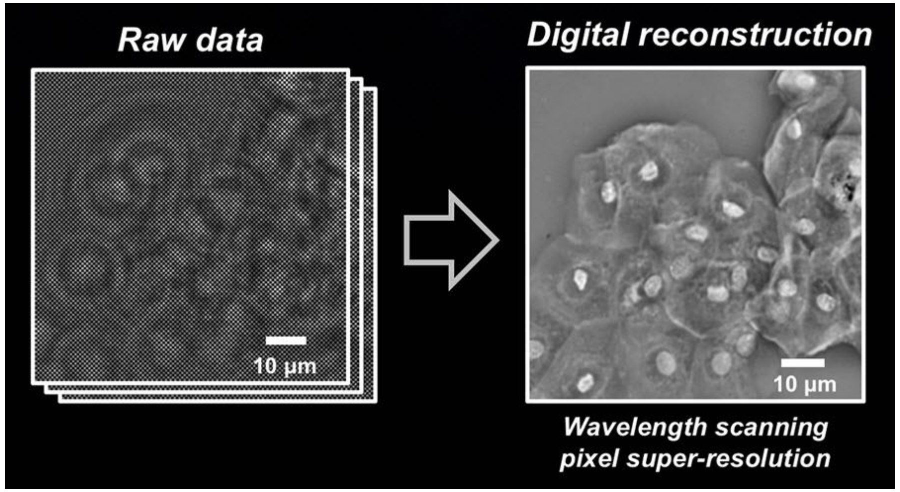


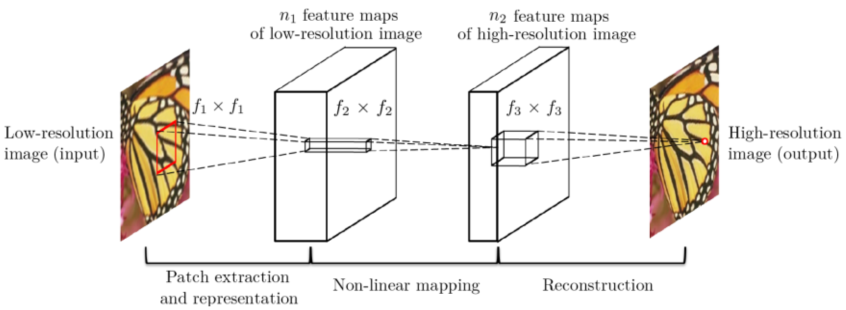


Super resolution for visual online monitoring #1

- Generates higher resolution less noisy images from small resolution compressed images
- Two categories:
  - Single image super-resolution [7]
  - Multiple image super-resolution [8]
- State-of-the-art neural networks produce great results but are not suitable for real-time display

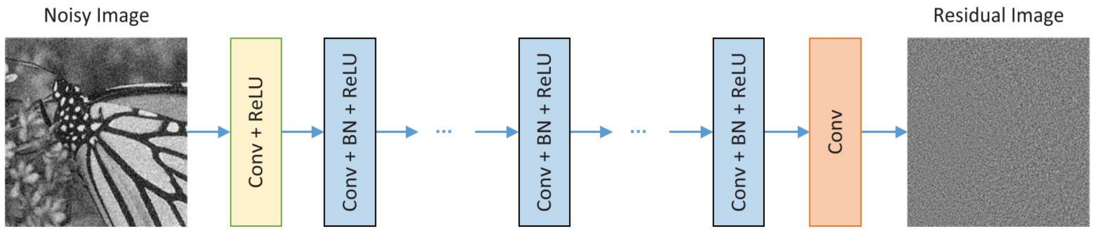


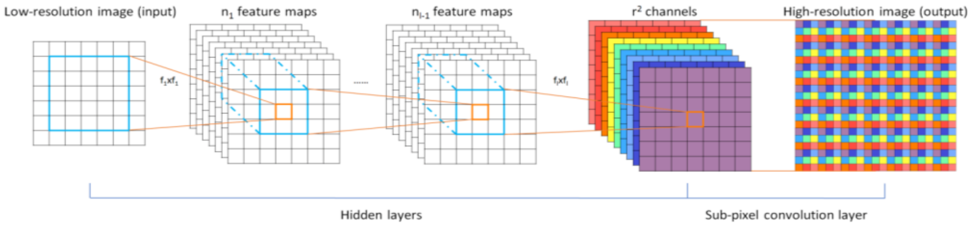




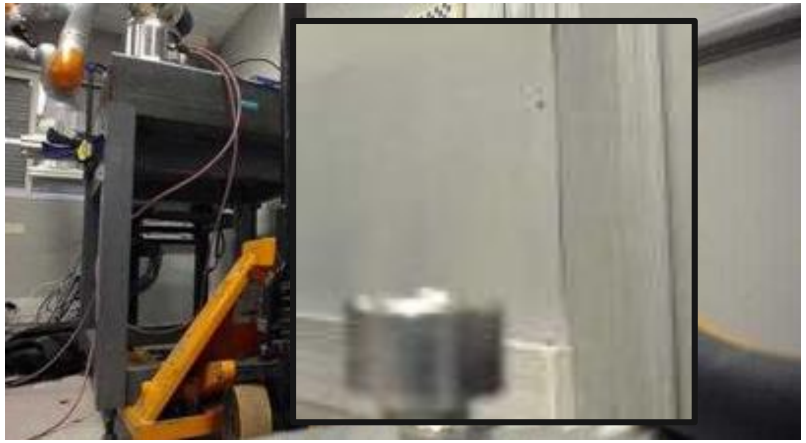
Super resolution for visual online monitoring #2

- We merged 2 neural networks : compression noise reduction and resolution enhancement [9]
- Reduce 4G bandwidth consumption for transmitting images
- Generates no lag thanks to real-time capabilities
- Little defects in some images are not critical as images are displayed to the operator at 15 fps
- Multiscale super resolution available (2x, 4x, 8x etc.)

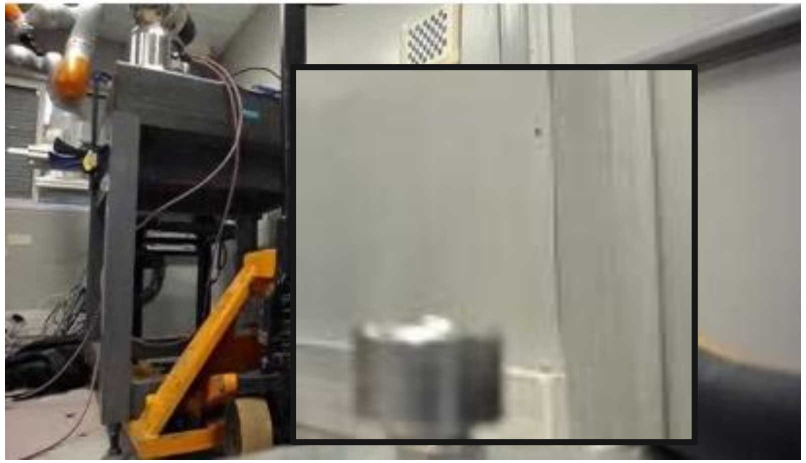




PYTORCH



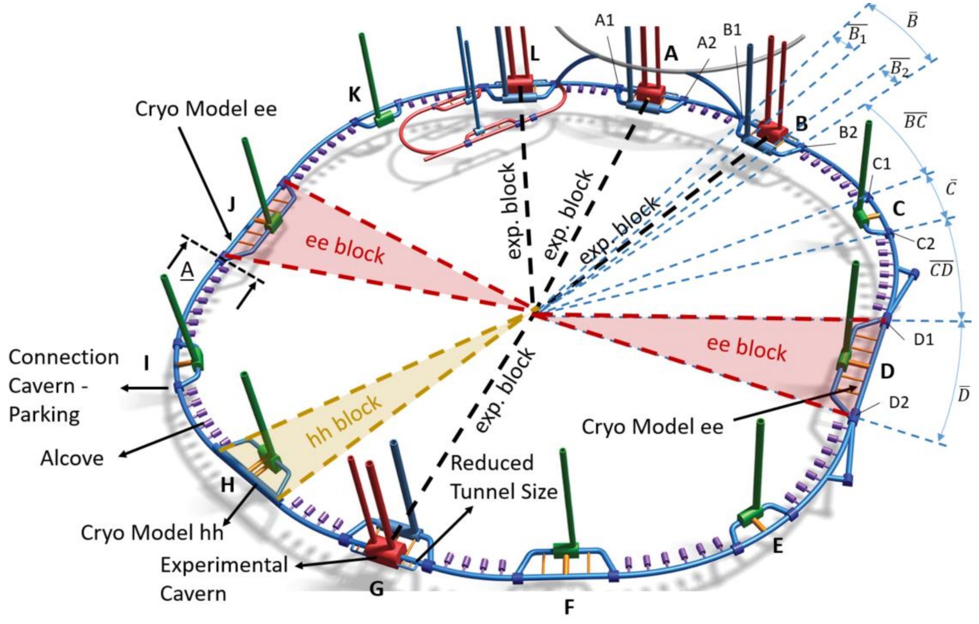
50% jpeg compression; 14 kb

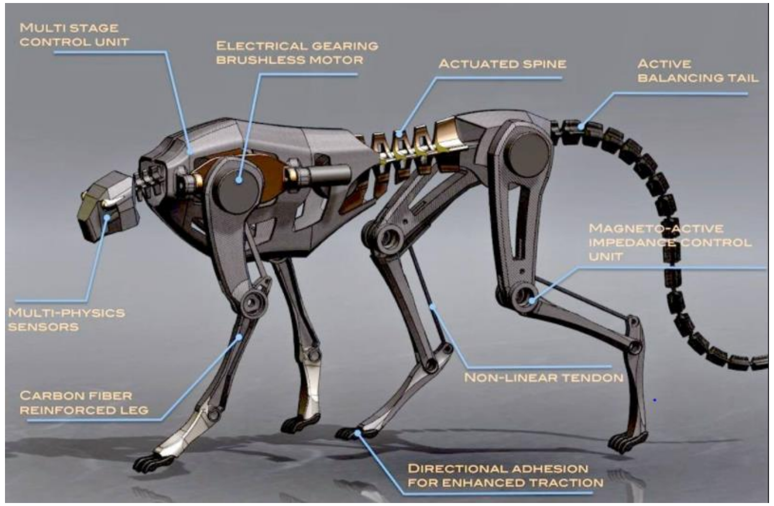


4X resolution enhancement + noise reduction; 282 kb; computation time 4 ms

Robots for Future Accelerators (FCC)

- Novel robotics platforms and controls for remote maintenance and interventions





Robots for Future Accelerators (FCC)

$$
\begin{aligned}
\min_{\mathbf{x},\ \mathbf{p}_l} \quad & J(\mathbf{x},\ \mathbf{p}_l) \\
\text{s.t.} \quad & \mathbf{f}(\mathbf{x},\ \mathbf{p}_l) - \mathbf{z}_{des} = \mathbf{0} \\
& -\mathbf{c}(\mathbf{x},\ \mathbf{p}_l) \leq \mathbf{0} \\
& \mathbf{ub}(\mathbf{x},\ \mathbf{p}_l) \leq \mathbf{0} \\
& \mathbf{lb}(\mathbf{x},\ \mathbf{p}_l) \leq \mathbf{0}
\end{aligned}
$$

$$
J(\mathbf{x},\ \mathbf{p}_l) = \underbrace{\mathbf{Q}^T(\mathbf{x},\ \mathbf{p}_l)\mathbf{K}_Q\mathbf{Q}(\mathbf{x},\ \mathbf{p}_l)}_{J_1} + \underbrace{\mathbf{k}_p^T \arctan(\mathbf{p}_l)}_{J_2} + \underbrace{\mathbf{k}_w^T \mathbf{w}(\mathbf{x},\ \mathbf{p}_l)}_{J_3}
$$

General version of this algorithm was used to find the optimal design of a cavity inspection manipulator

Gamper, H.; Gattringer, H.; Müller, A. and Di Castro, M. (2021). **Design Optimization of a Manipulator for CERN's Future Circular Collider (FCC)**, ICINCO 2021

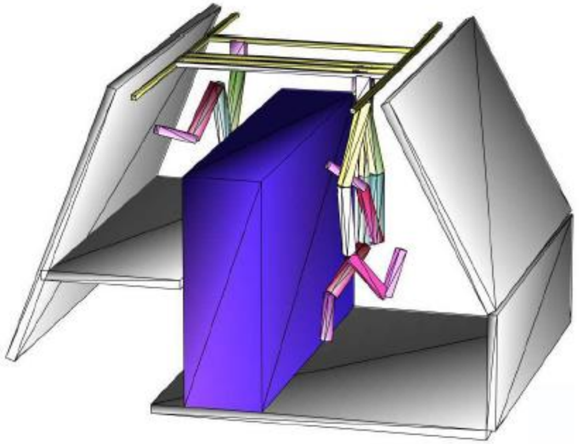


Figure 10: Optimization results FCC-ee (collision objects)

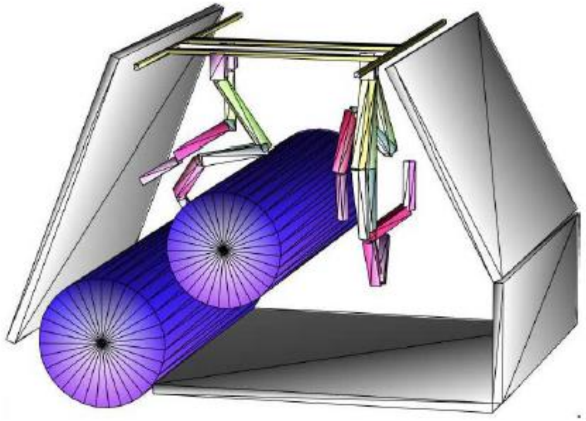
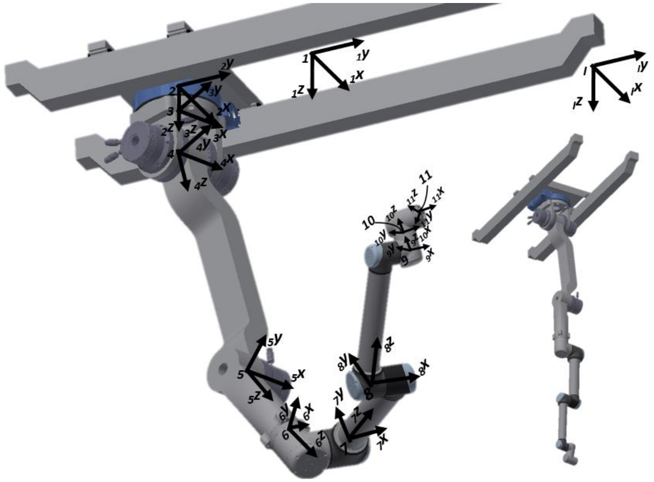
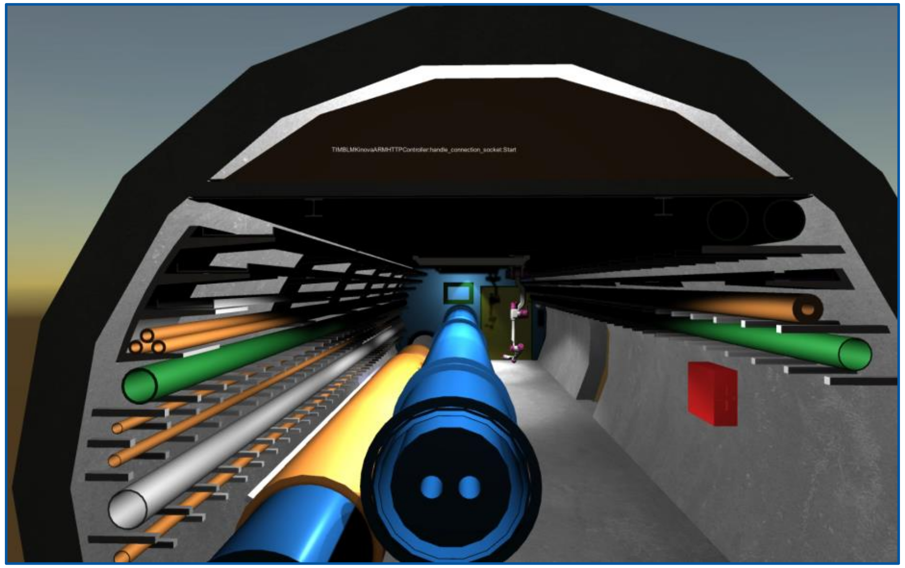


Figure 11: Optimization results FCC-hh (collision objects)





Established Collaborations

Institute		Collaboration Nr.	Contribution
UKAEA	UK Atomic Energy Authority	KN4867	sharing teleoperation expertise
CREATE	Create	KE3947	robotics operation strategies
University Federico II	Università degli Studi di Napoli Federico II	KE3630	robots control theory
Unicampus Biomedico	UCBM Università Campus Bio-Medico di Roma	KN4437	medical applications (MARCHESE)
Polytechnic Madrid	Politécnica Universidad Politécnica de Madrid	KE4297	enhanced reality and teleoperation
University Jaume I	UJI Universitat Jaume I	KE4202	human robot interface

Established partnerships for European Projects

- We are chairing the Teleoperation topic group of the EuRobotics consortium (https://www.eu-robotics.net/)

- Consortiums built for European Projects calls (RECONDITION, BIANCA, HUROSHARE, SCORE, POLE)

- Participation in the European robotic Challenge (EUROC) and Puresafe projects

Conclusions

- Particle accelerators devices are normally installed for many years and tasks of dismantling radioactive objects is inherited by the future generation of physicists/technicians/engineers

- Maintenance and dismantling tasks, over a lifetime of a particle accelerator device, must be taken into account at design phase

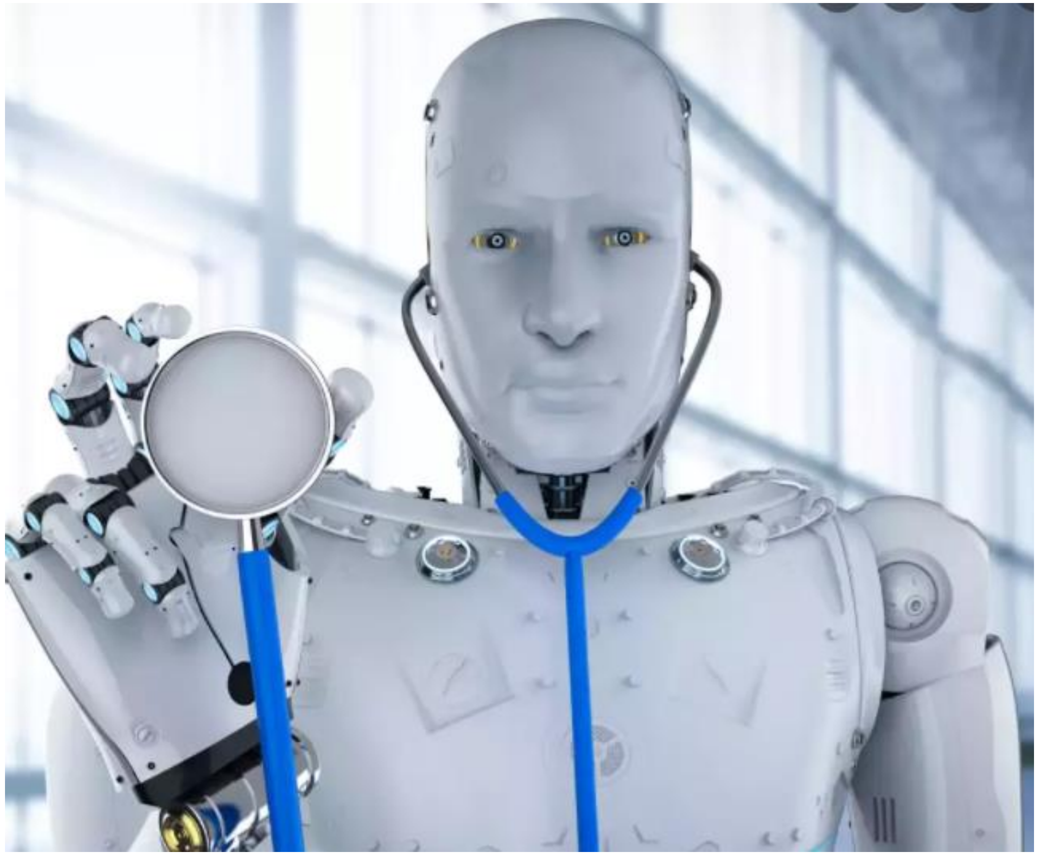
- Robotic intelligent and robust systems can increase personnel safety and machine availability in performing such tasks

- Ready-to-use industrial solutions do not exist for user friendly remote maintenance and inspection

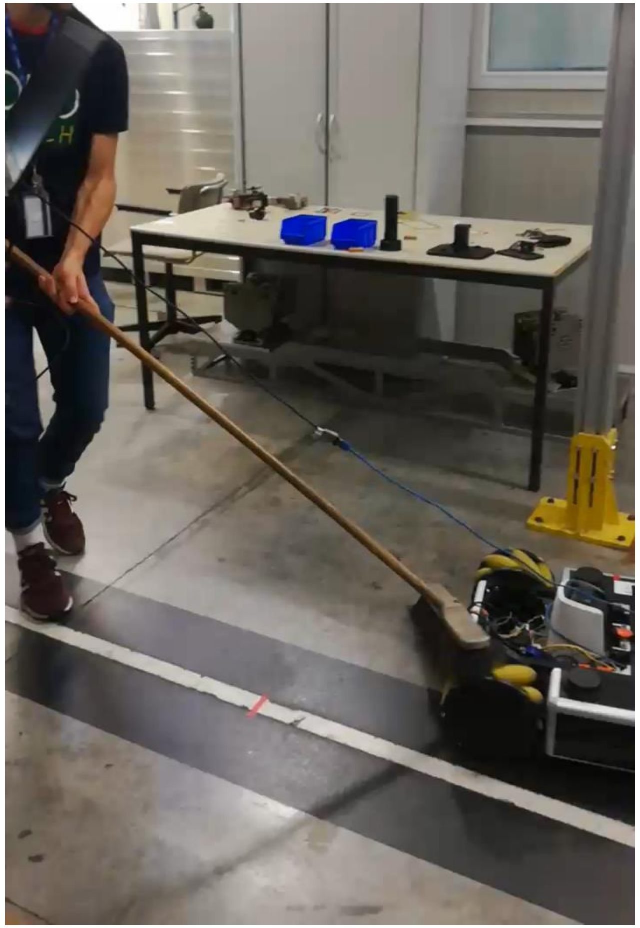
- We gained an important knowledge and experience in designing, producing and applying robots in harsh and hazardous environment

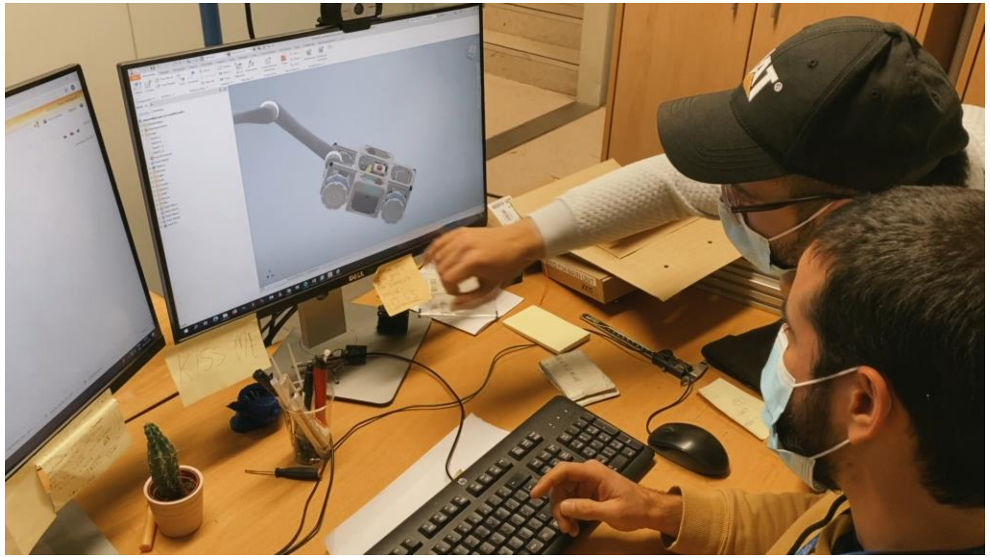
- External collaboration with Robotics Research Centres and Universities is crucial to take advantage of the cutting edge technology

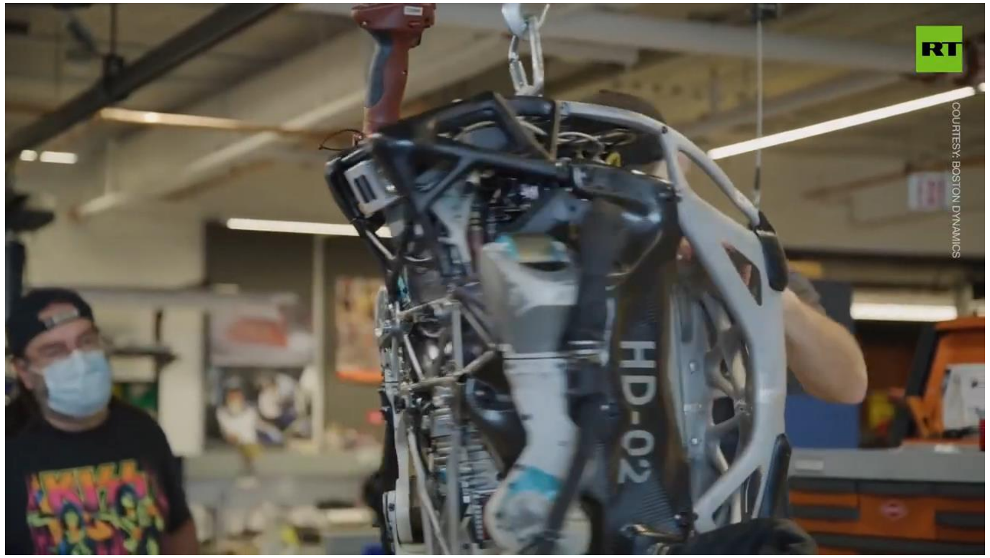
Are Robot “serving” humans?



Are Robot “serving” humans? … or we are serving robots?







Many colleagues contributed to the robotic activities during the last years ….
Lots of students (TRNEE, TECH, DOCT)

Università degli Studi di Napoli Federico II
Create
EPFL École Polytechnique Fédérale de Lausanne
ETH zürich
Università degli Studi di Genova
iit Istituto Italiano di Tecnologia
University of Zurich
JKU Institut für Telekooperation
UCBM Università Campus Bio-Medico di Roma
Loughborough University
SDU
UJI Universitat Jaume I
L-Università ta' Malta
TUM
I.U.T Montpellier-Sète
Universidad de Oviedo / Universidá d'Uviéu / University of Oviedo
Tampere University of Technology
University of the Aegean
Università di Siena 1240
Universidad Politécnica de Madrid

Robots and robotic instrumentation need a crew to use them and maintain and experts in-house to be effective

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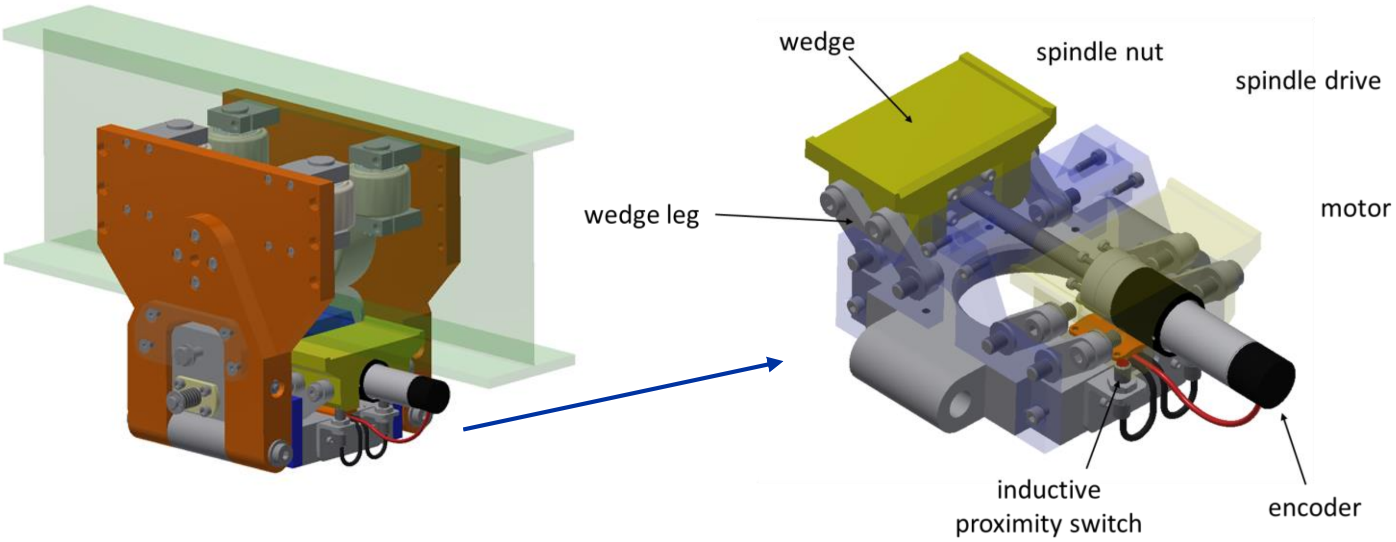
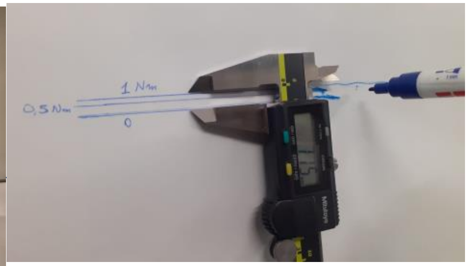
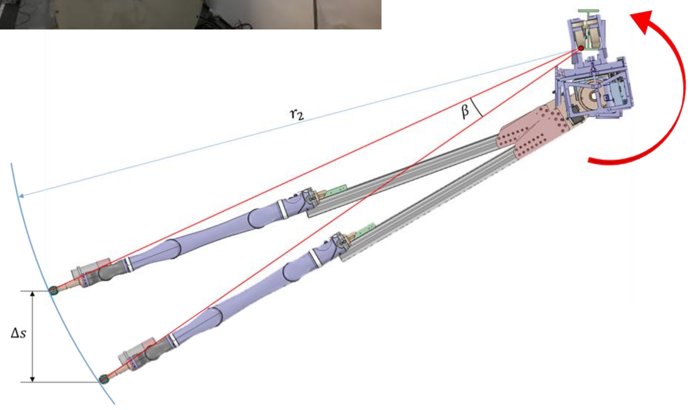
Backup Slides

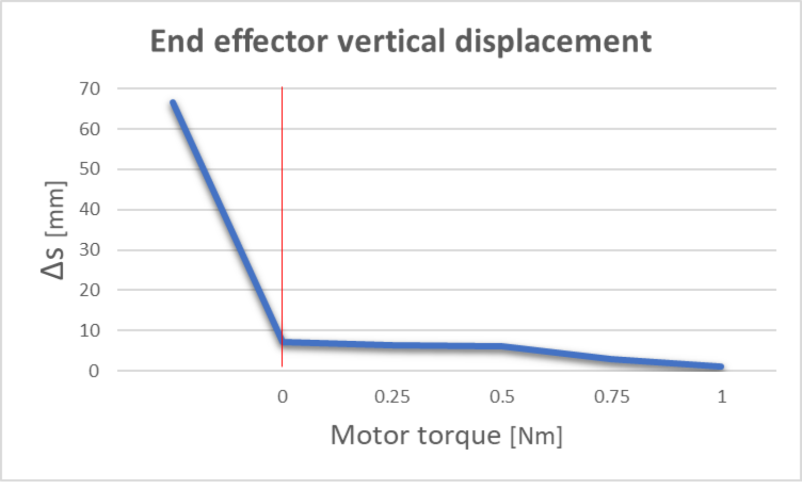
Wagon stabilisation system

➢ New Bogie with motor integrated for wagon stabilization





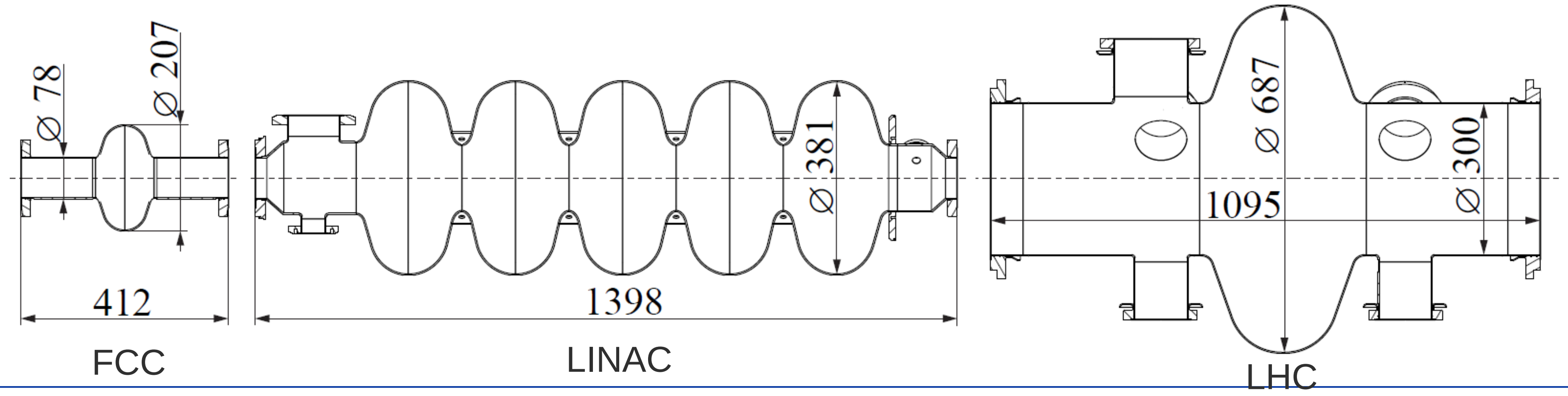




Three Cavity Type to inspect

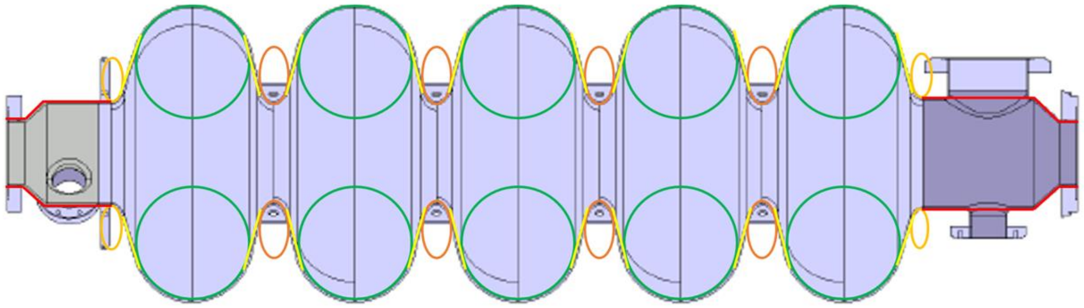
Main challenges:

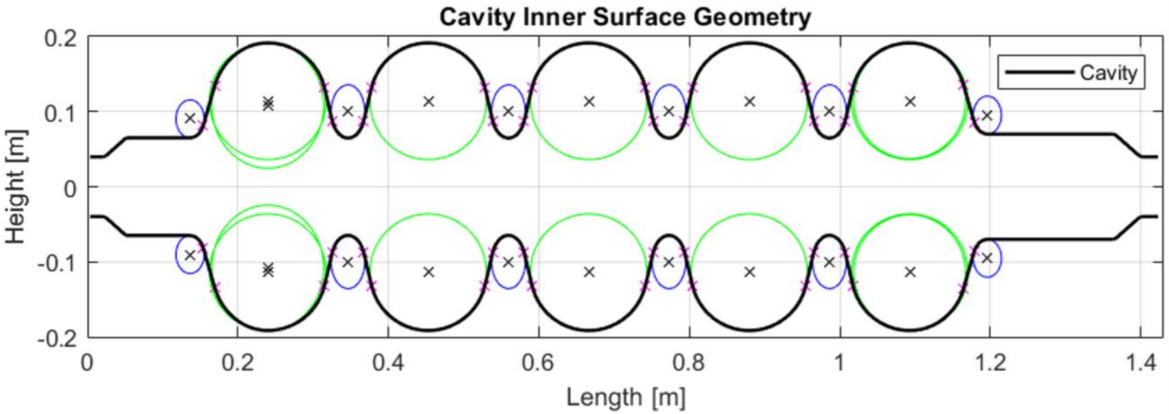
- Complex workspace: The difference in diameter of the entrance of the smallest cavity (FCC) and the point with maximum diameter of the biggest cavity (LHC).
- Autonomous system: The operator press Start and the system scan all the cavity in less than 10 hours
- System outputs: >15’000 photos (1cm x 1cm) for a total of > 3Tb
- Repeatability of the system: Be able to move to any positions based on a previous pictures by simply loading it.



Camera Positioning by Robotic Arm

Inner Surface Reconstruction

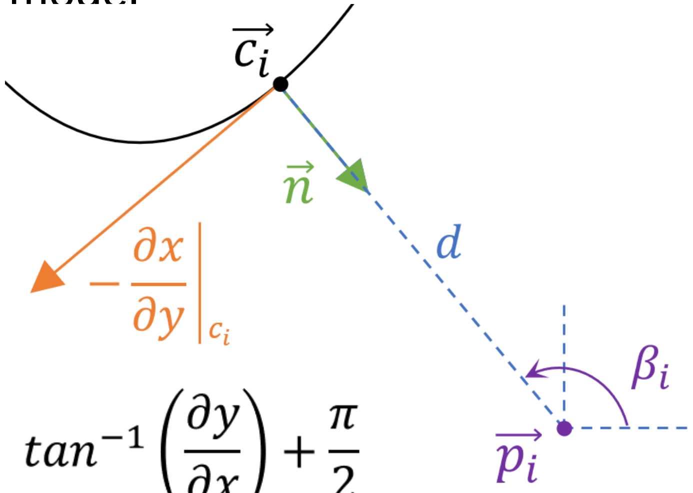




- Cavity inner surface parametrisation defined using geometric 3D model

Camera Placement Arm Path Planning

- Constant camera working distance
- Camera position at normal incidence to image point



$$\vec{p_i} = \vec{c_i} + d.\vec{n} \quad (Eq.1); \quad n = \left(\frac{\vec{c_i}'}{\|\vec{c_i}'\|}\right).R\left(\frac{\pi}{2}\right); \quad \vec{c_i}' = \begin{pmatrix} 1 \\ \partial y/\partial x \end{pmatrix}; \quad \beta_i = tan^{-1}\left(\frac{\partial y}{\partial x}\right) + \frac{\pi}{2}$$

Mathematical Model

- **Defintions**

Camera positions (end-effector): $\chi_{ee} = \begin{pmatrix} x_{ee} \\ y_{ee} \\ \psi_{ee} \end{pmatrix}$ $\psi_{ee} = \alpha + \beta$

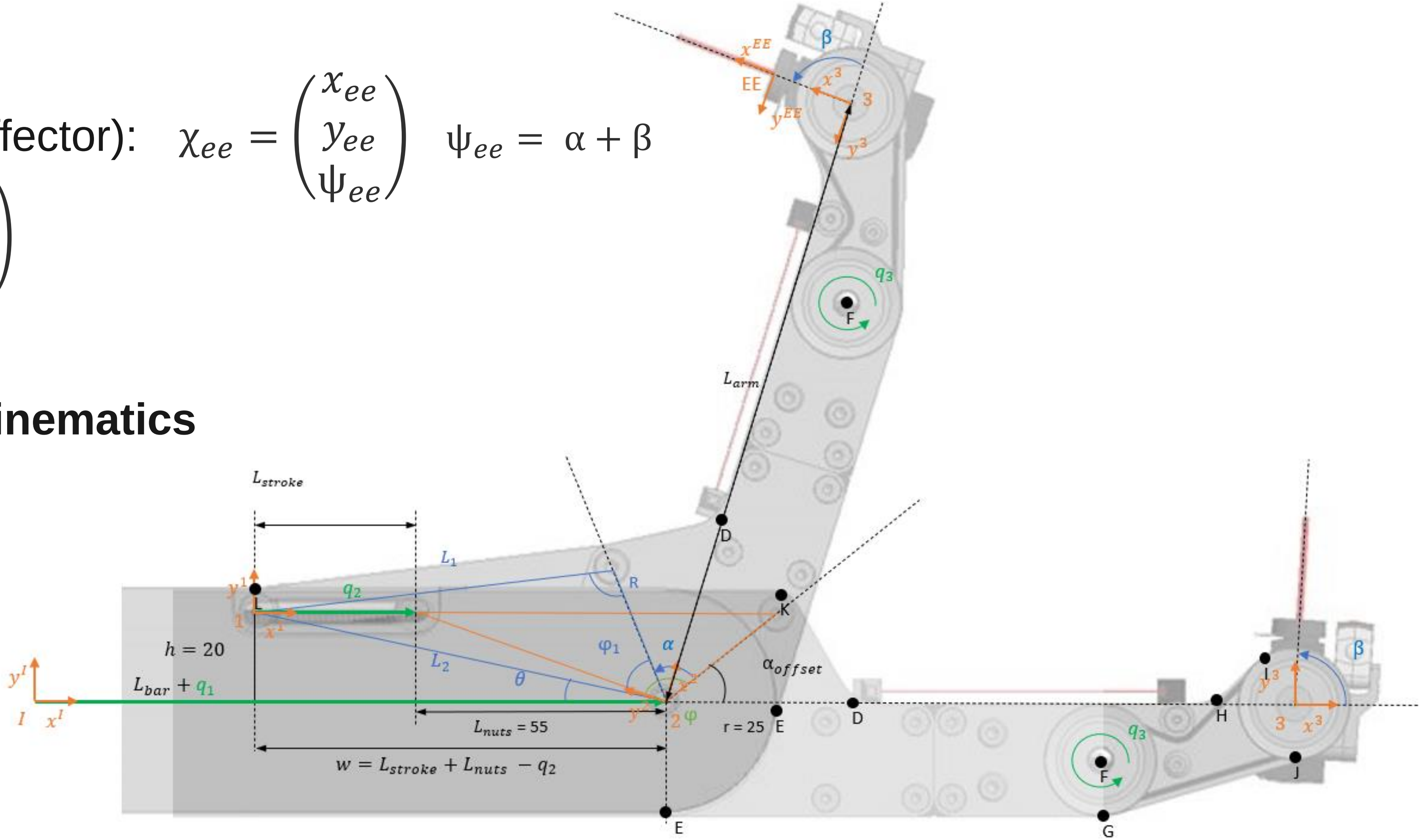
Joints space: $q_{ee} = \begin{pmatrix} q_1 \\ q_2 \\ q_3 \end{pmatrix}$

- **Forward & Inverse Kinematics**

$$\dot{\chi}_{ee} = J_A(q)\,\dot{q}$$

$$\Delta q \cong J_A(q)^{-1} \Delta\chi_{ee}$$

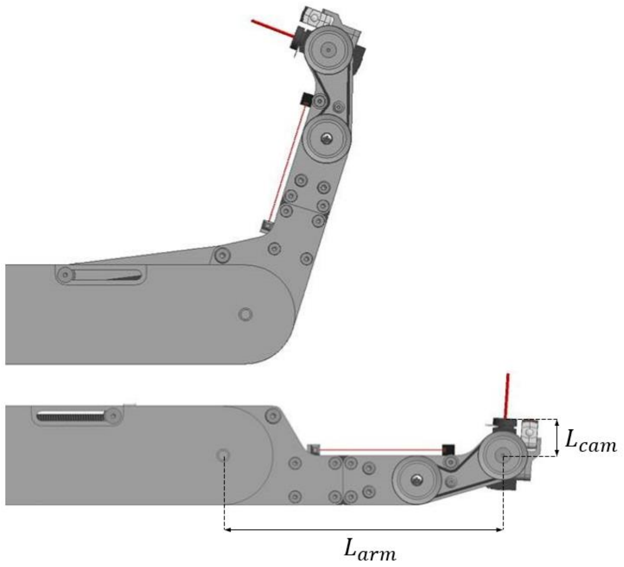
$$qNext \cong qActual + \Delta q$$



Design Validation & Optimization

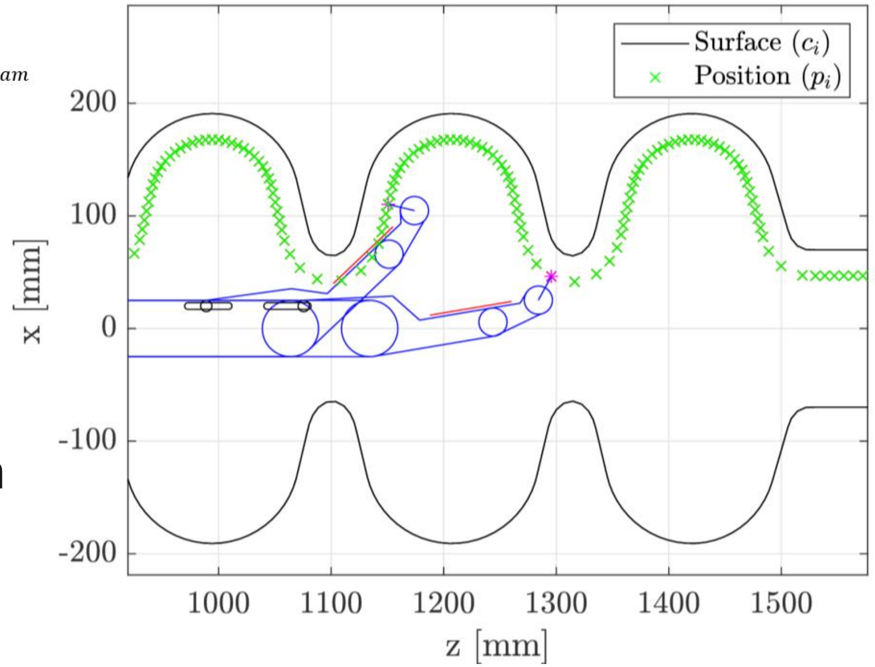
Anti-Collision System

- 1 laser sensor next to the camera
- 1 laser beam on the arm



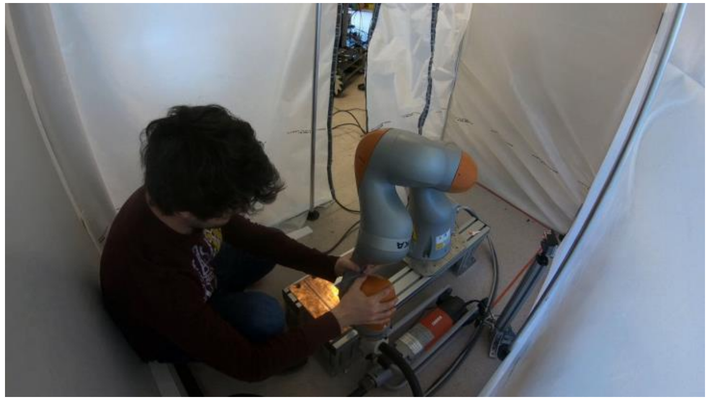
Simulation & Optimization

- L_{arm} and L_{cam} are optimised to avoid collision (lasers / cavitites)
- Maximization of the distance from the arm to the cavity
- Results: 2 arms dimensions to fit the three cavity without collision

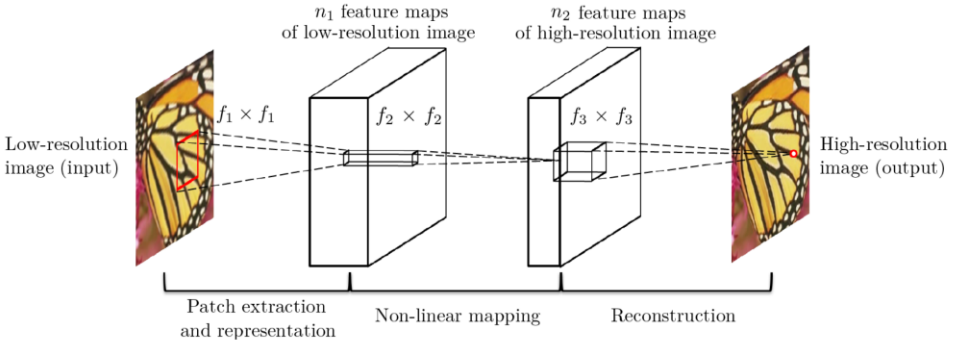


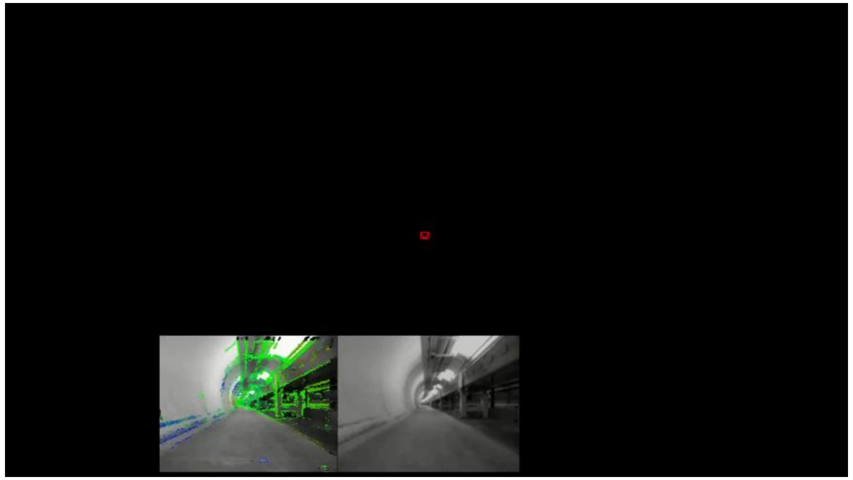
Main novel technologies/concepts introduced and applied for remote maintenance

- **Learning by demonstration**

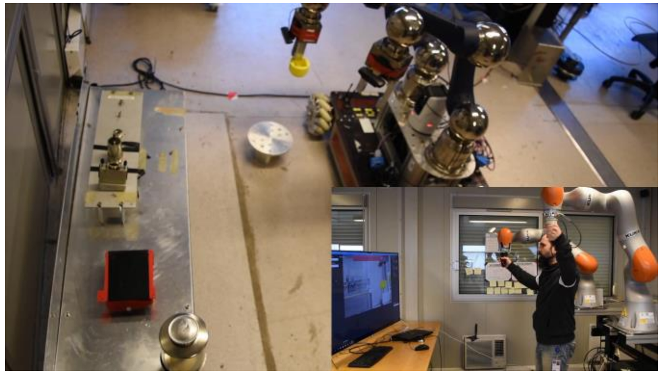


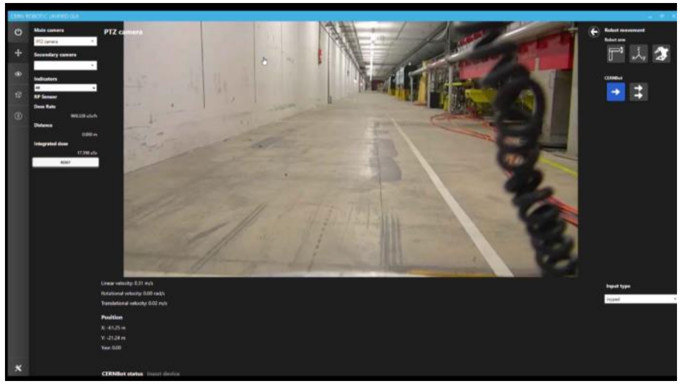
- **Machine Learning for Proprioception increase (Image super-resolution) and autonomous navigation**





- **Operator stress studies and Human-robot interface for user friendly teleoperations**





Impact

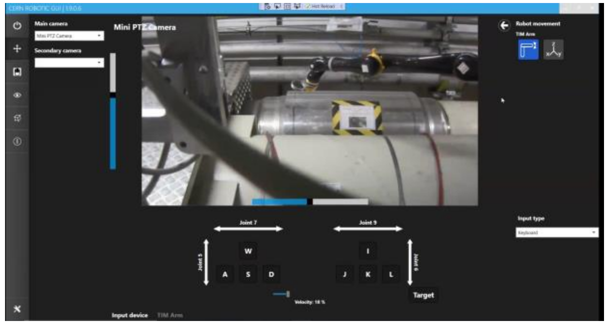
Industry

- Problems to solve (a “solution deficit”)
- Technology and experience
- A need for qualified staff
- Limited budgets

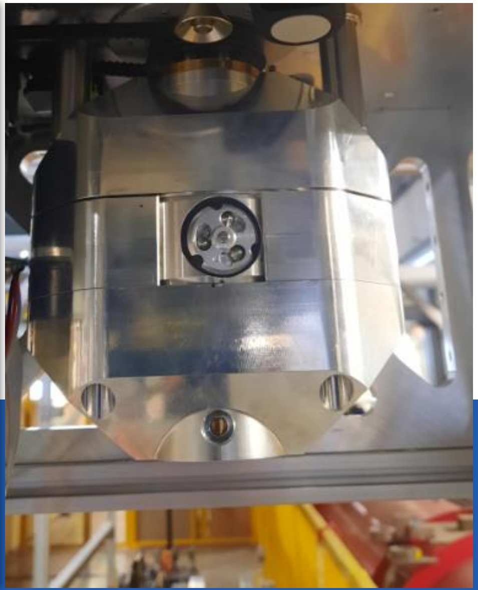
Universities

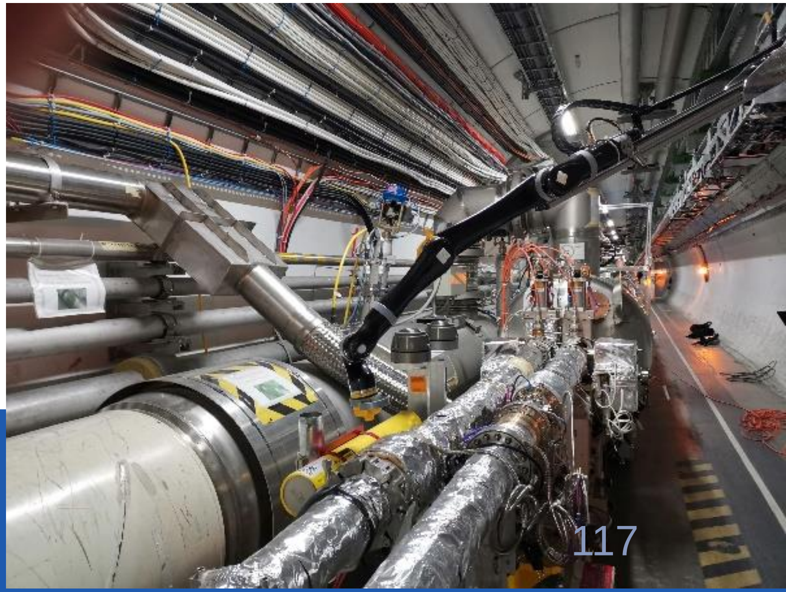
- A “problem deficit”
- Research expertise
- Training skills
- Well-qualified students looking for jobs

Automated Remote LHC BLMs/PMIL Validation

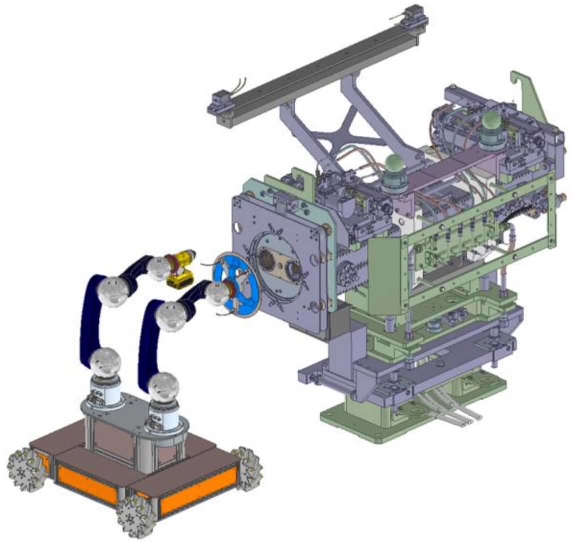


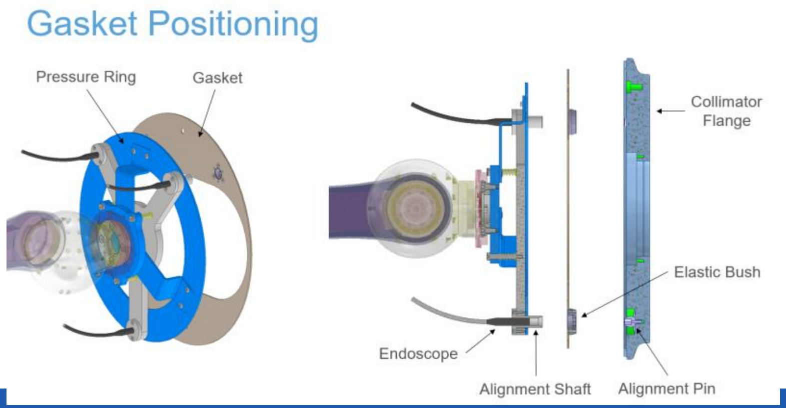
- System design and procedures based on the code of practice
- New wagon for the TIM: 11 degrees-of-freedom arm & sensor suite to measure BLM & PMIL sensors
- Integrated shielding for the radioactive source for device validation
- Automatic extraction and safe return of the source to the shielding
- Automatic recognition and pose of BLM/PMIL sensors, working towards autonomous measurements
- **Increase of machine availability and efficiency**



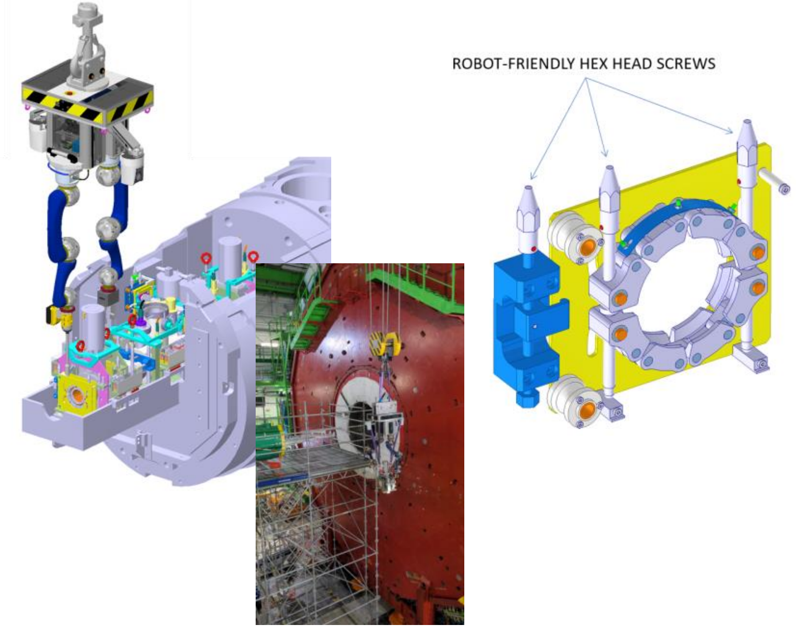


Example of Robot-Friendly New Equipment Design

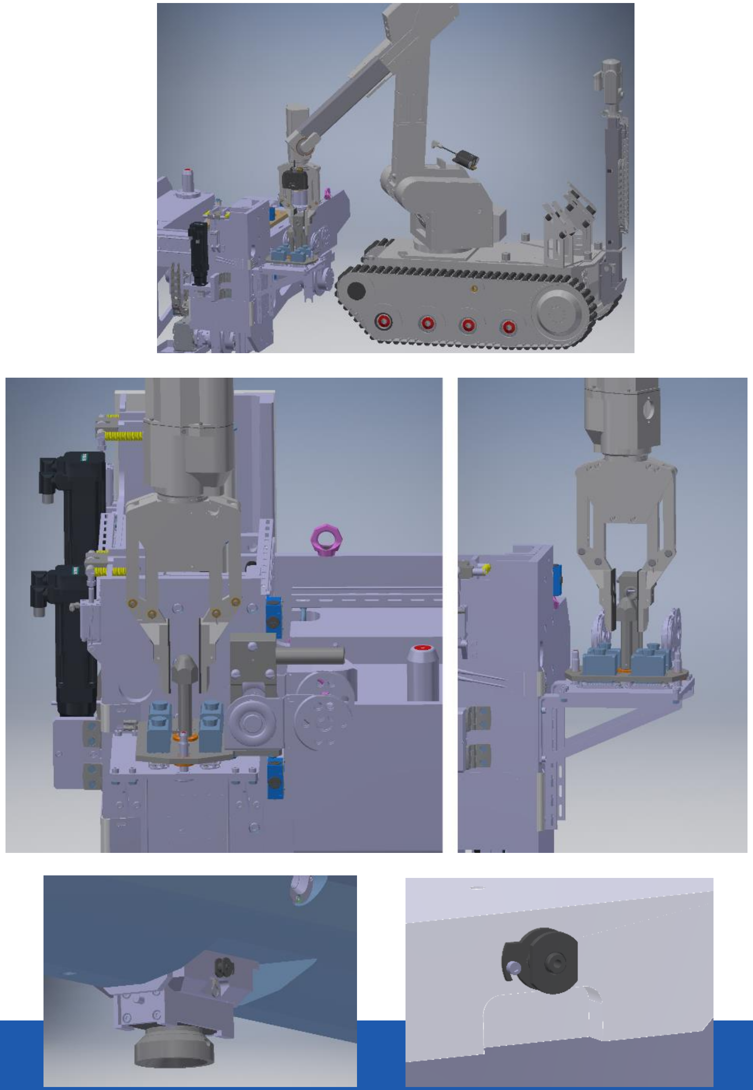




HL-LHC Collimators gaskets manipulation (Collaboration with TE-VSC, SY-STI and EN-MME)

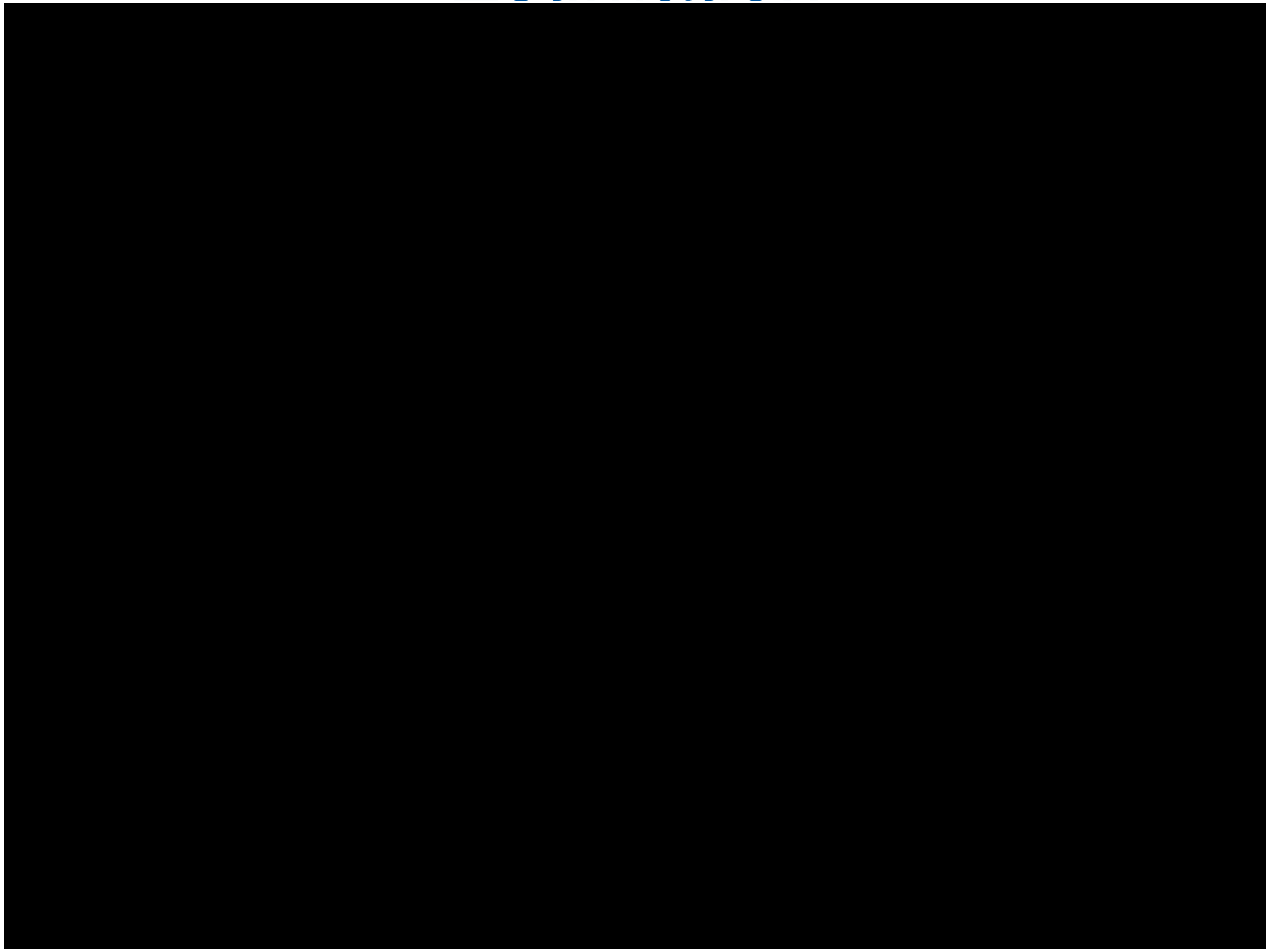


HL-LHC VAX robotic-friendly interfaces (Collaboration with TE-VSC, BE-EA)



AD target/horn trolley and TIDVG#5 feet blocking pins (Collaboration with SY-STI)

Vision Based Object Tracking System + Depth Estimation

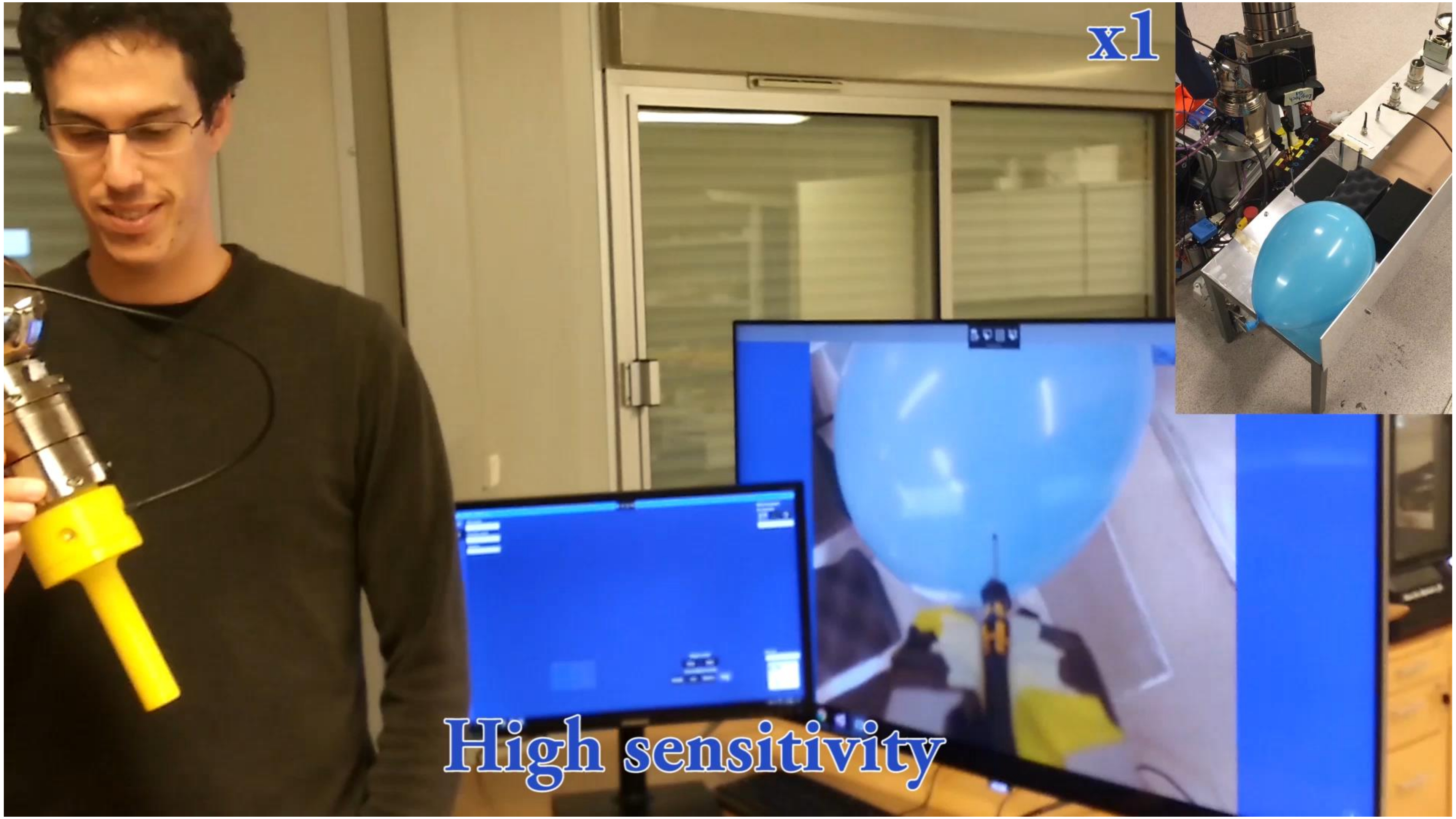


Video of the depth estimation algorithm

Vision Based Object Tracking System + Depth Estimation

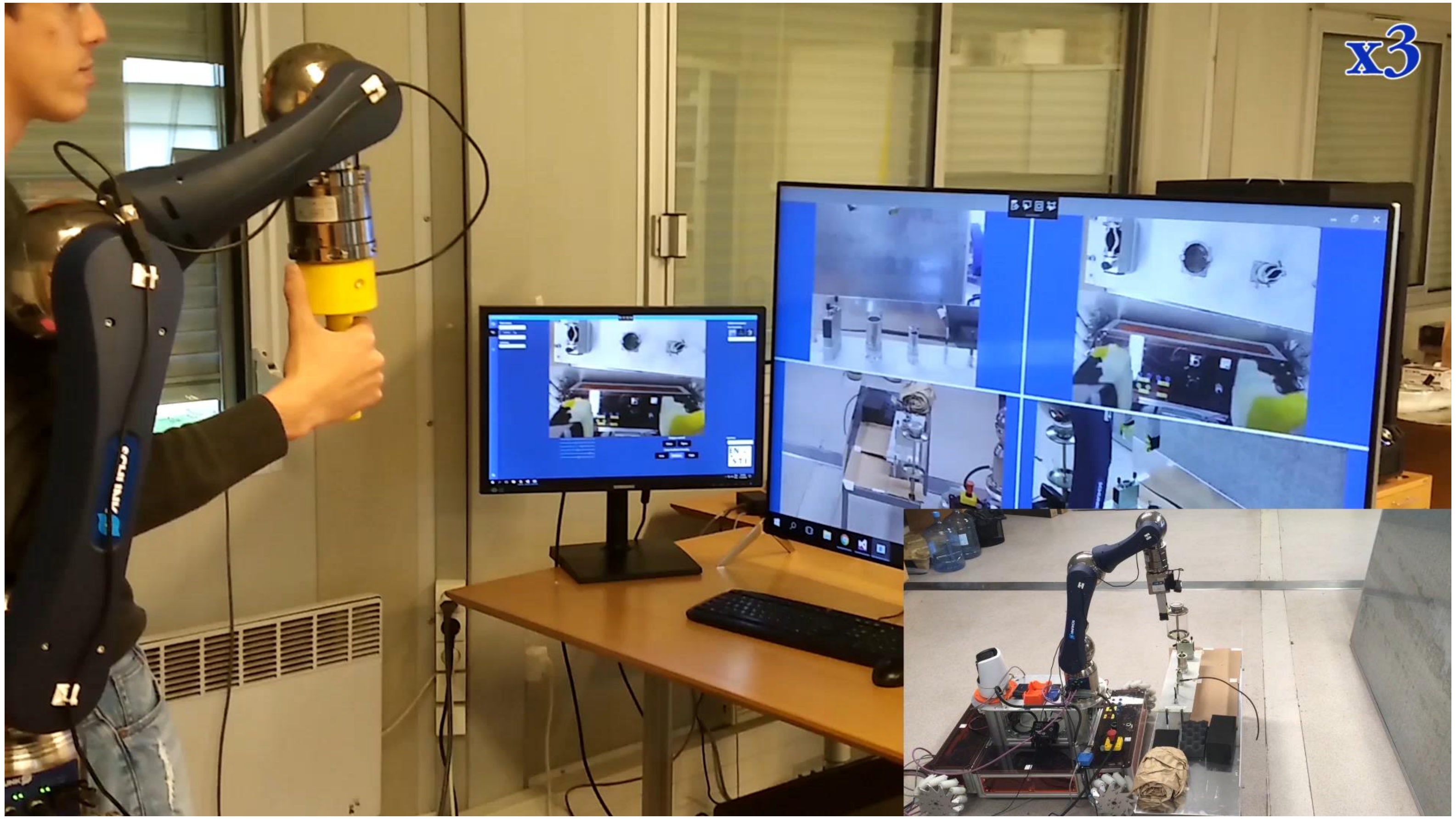
Video of the depth estimation algorithm

Teleoperation Factors: Type of Controls

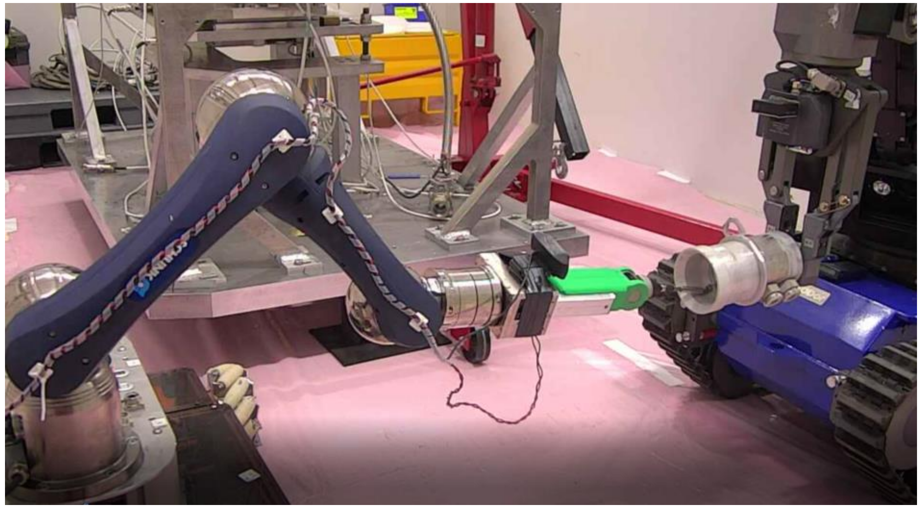


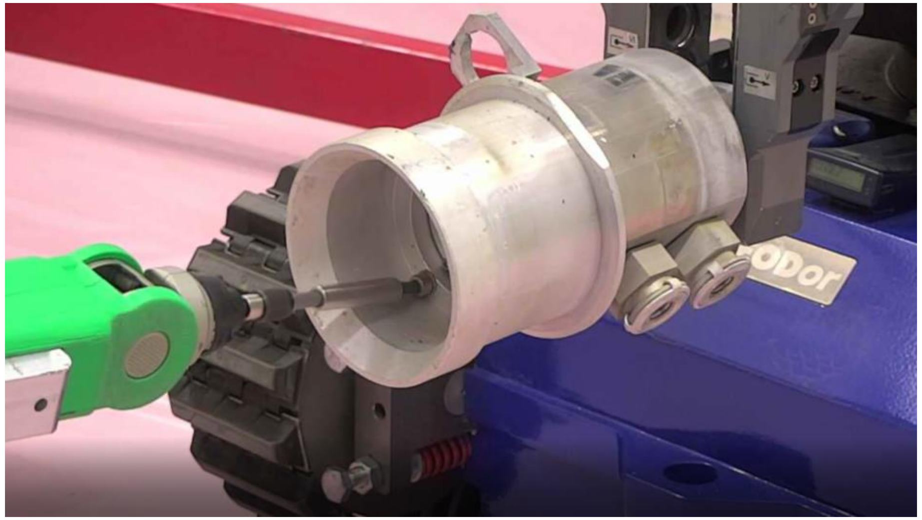
CERNTAURO Validation in Lab

- **User friendly** and portable telemanipulation system to allow equipment owners and/or expert technicians to use robot in a “transparent way”
  - ✓ **No need of expert robotic operators**

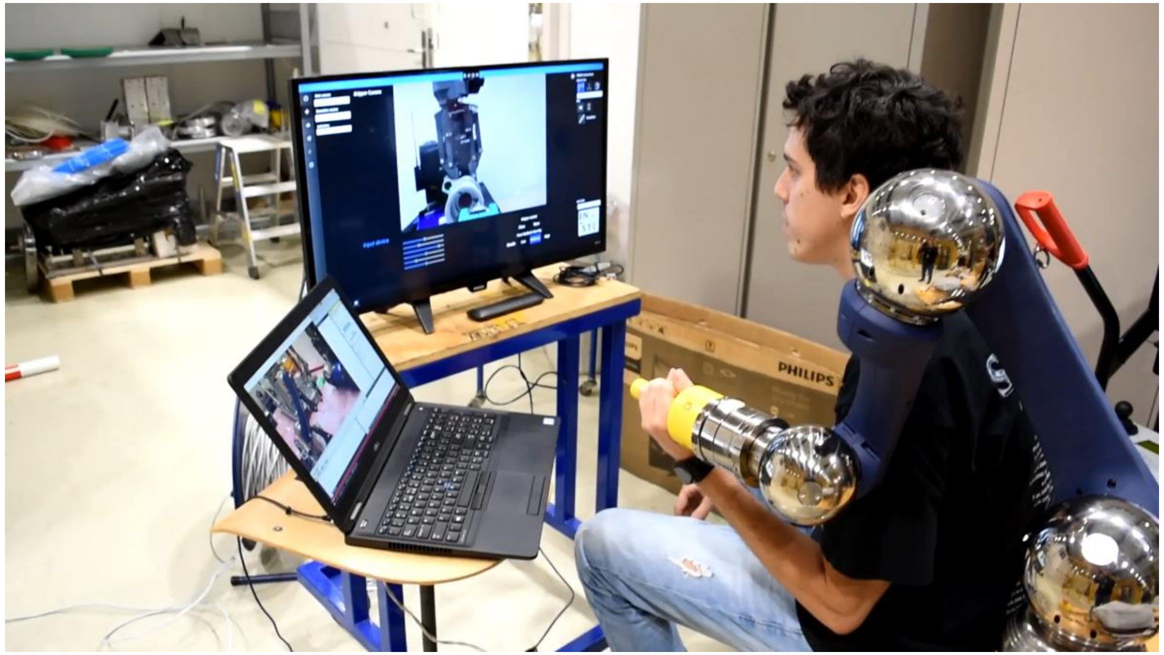


Operator Interface Performance



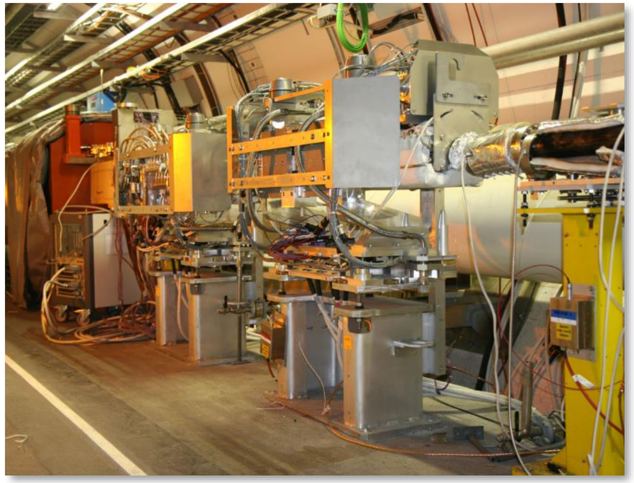


- Manipulation of radioactive targets
  - ✓ CERNTAURO intervention preparation, procedure, tooling and recovery scenarios
  - ✓ Force-feedback based bilateral control

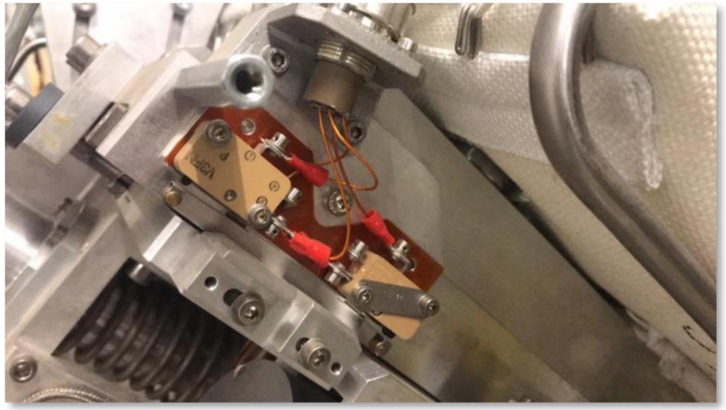


Environmental Perception: a use case

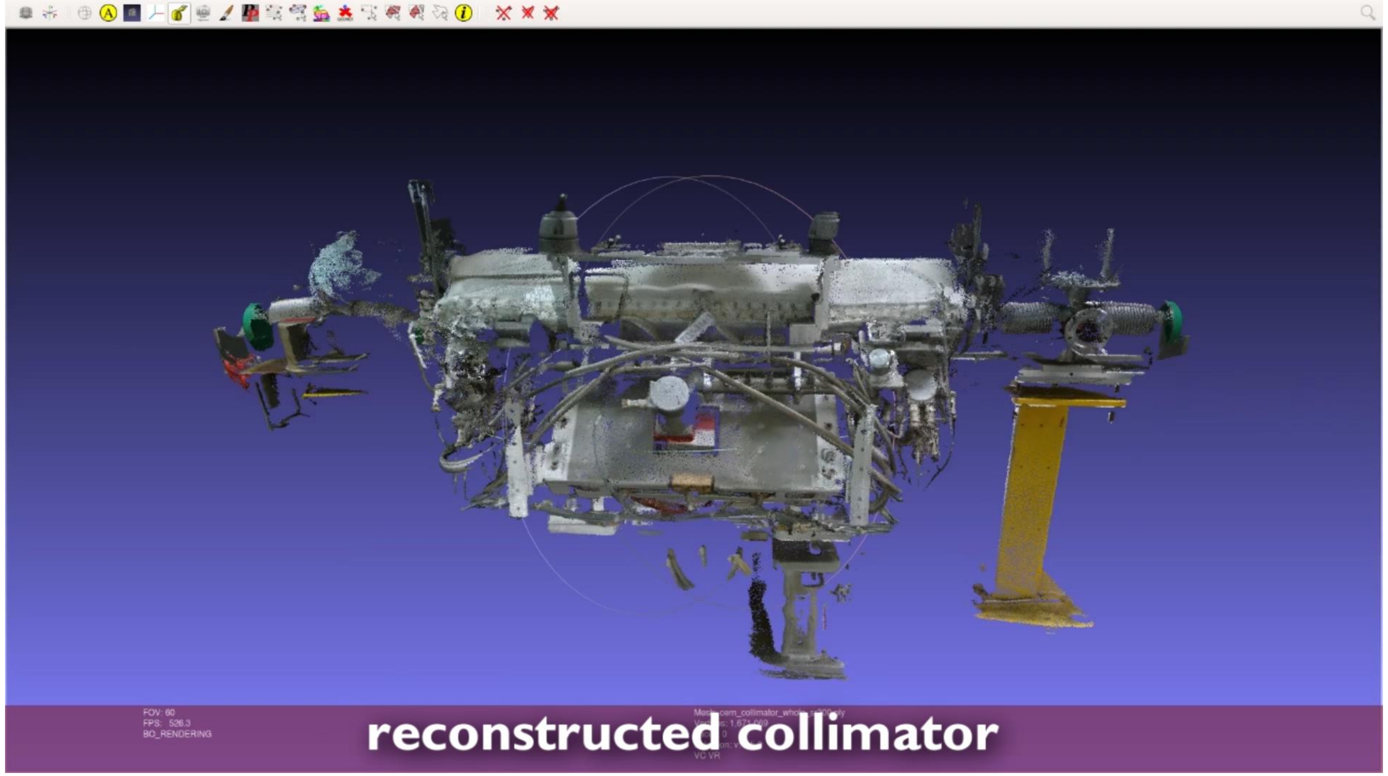
➢ Automatic recognition of collimator position switches and their actuation



LHC Collimators



Close view of the LHC Collimators position switches



Di Castro Mario, Jorge Camarero Vera, Alessandro Masi, and Manuel Ferre. "Object Detection and 6D Pose Estimation for Precise Robotic Manipulation in Unstructured Environments." Volume 495 of the Lecture Notes in Electrical Engineering series, Springer, 2019, DOI 978-3-030-11292-9_20, c 2020.

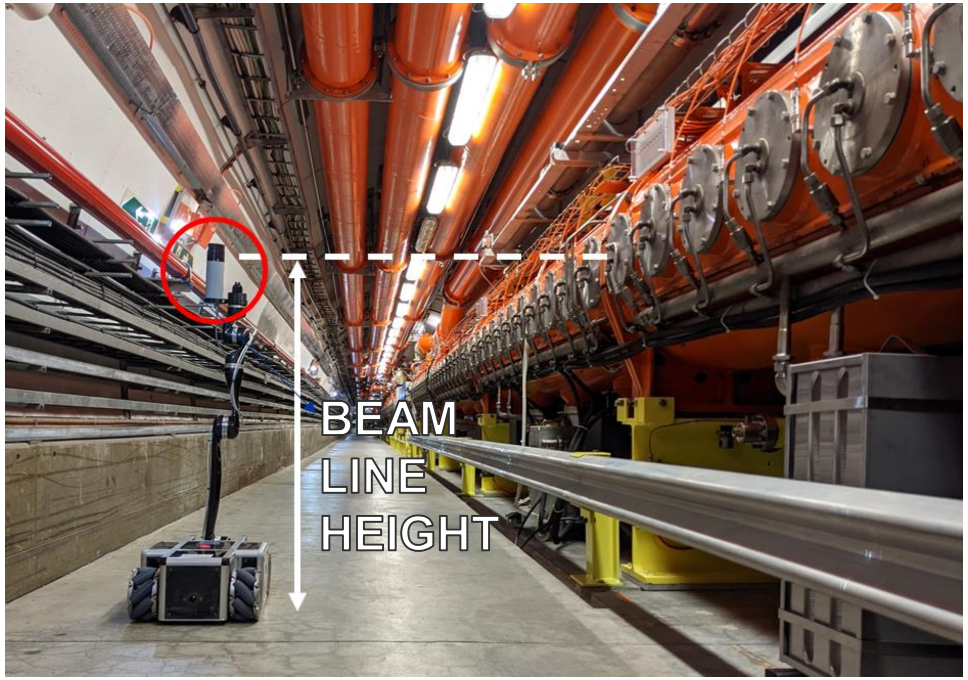
MIRA: Project Requirements

Platform size compliant with
SPS sectors doors dimensions

MIRA: Project Requirements

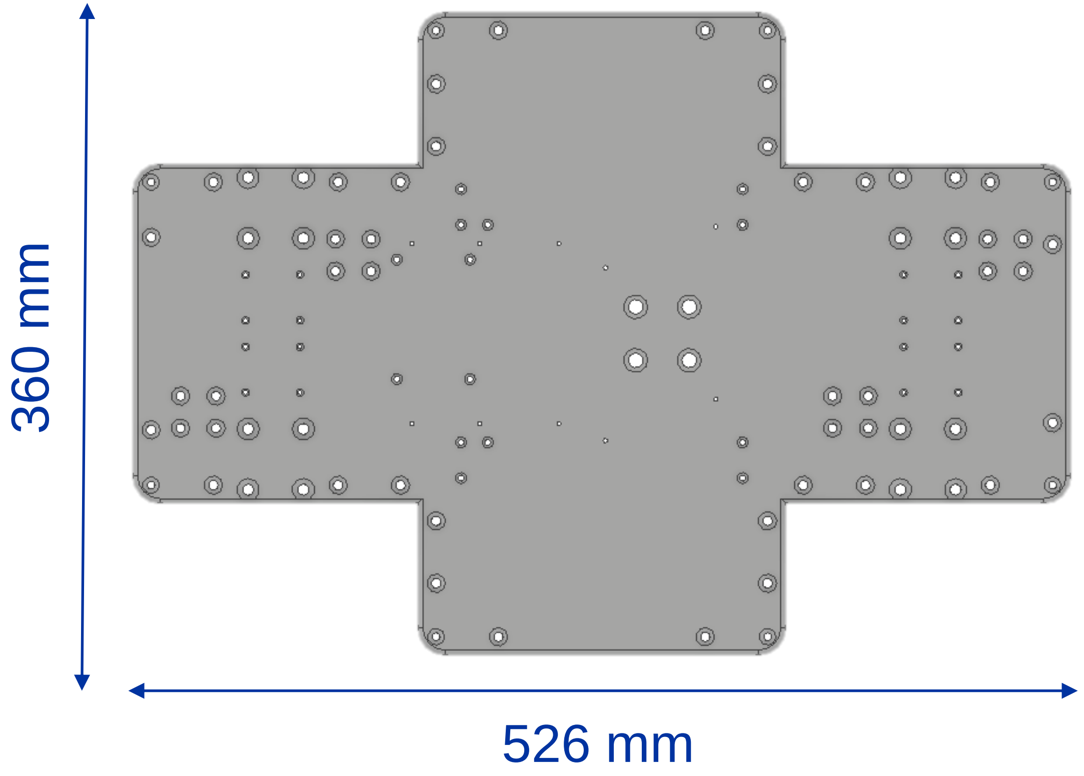
Fixed charging station for remote control and safety monitoring

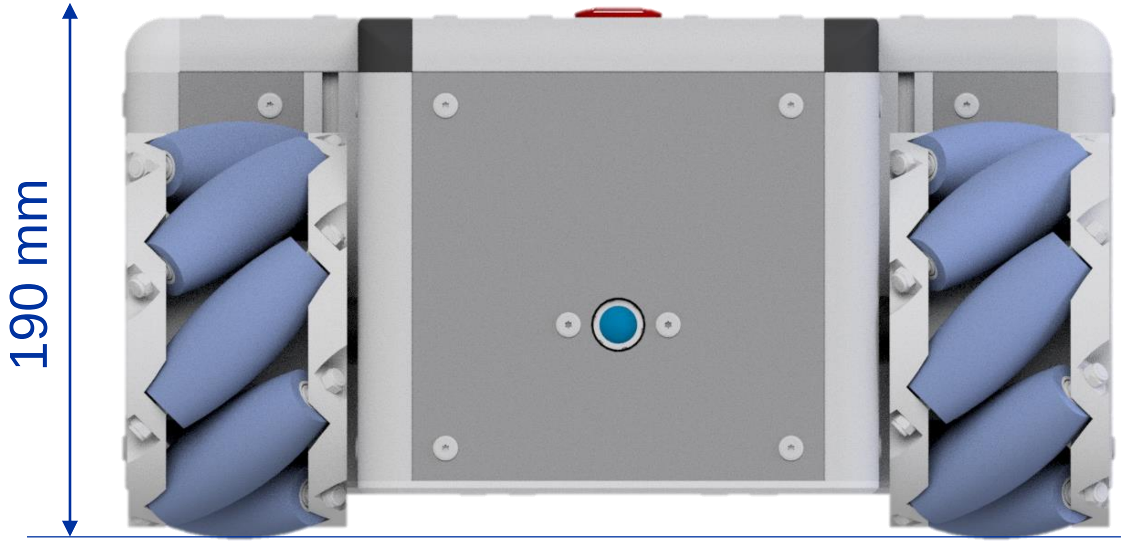
Measurement of **radiation level**



MIRA Robot: Design

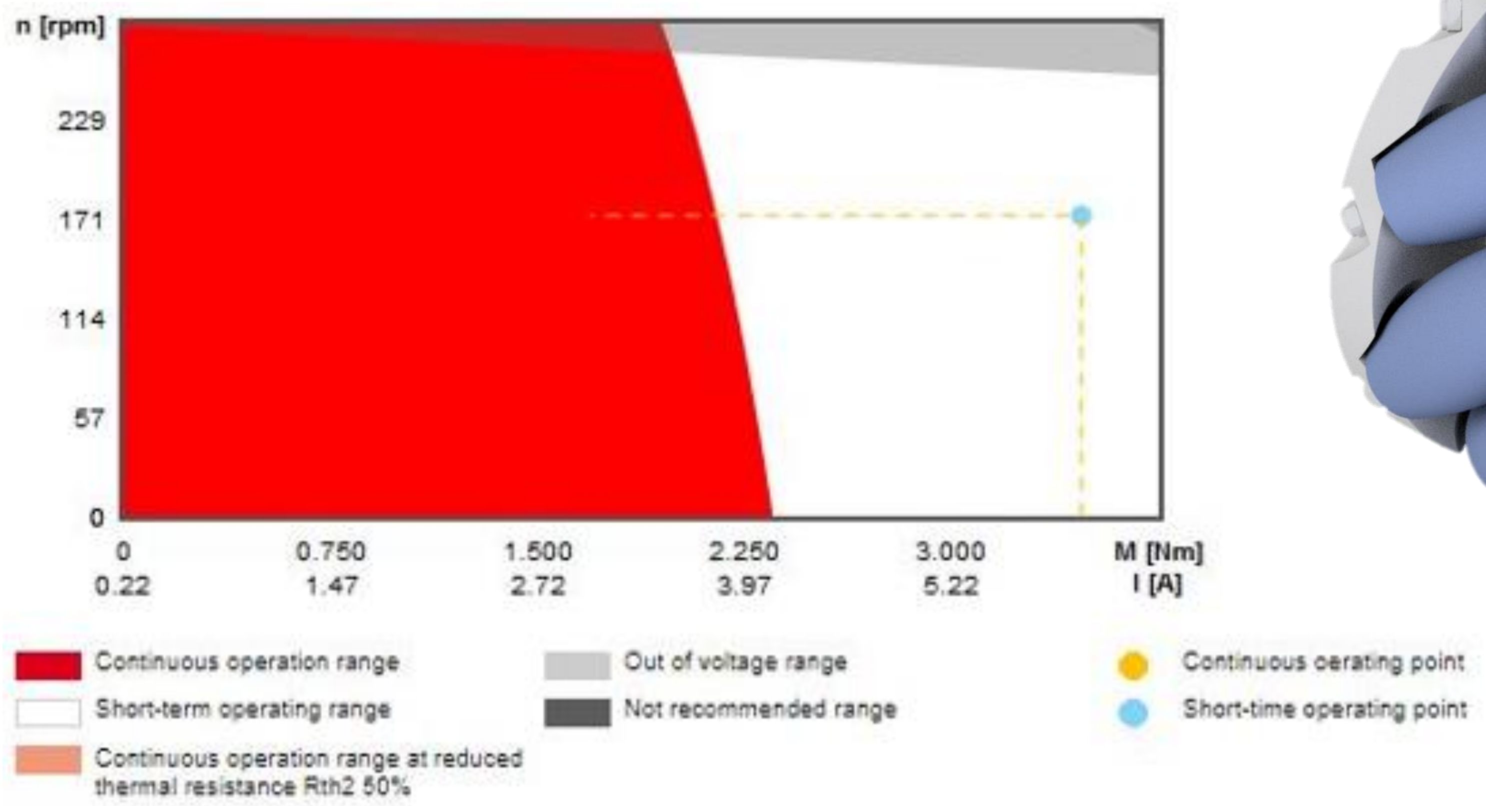
Frame size based on doors dimensions

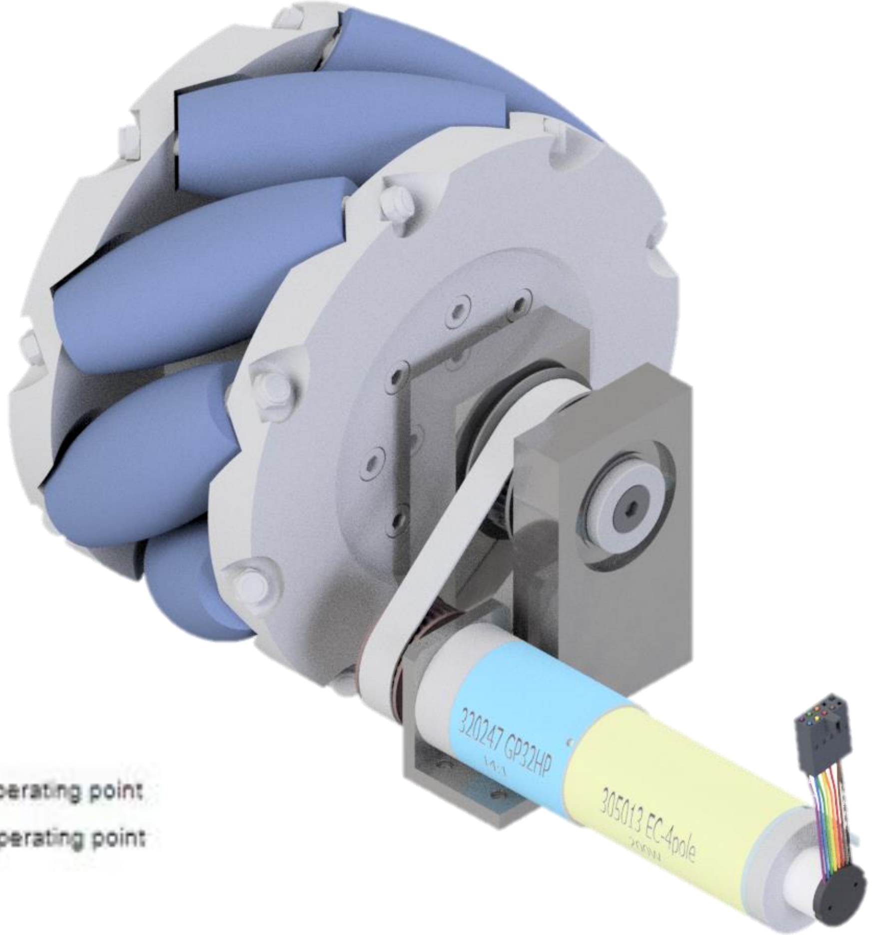




MIRA Robot: Design

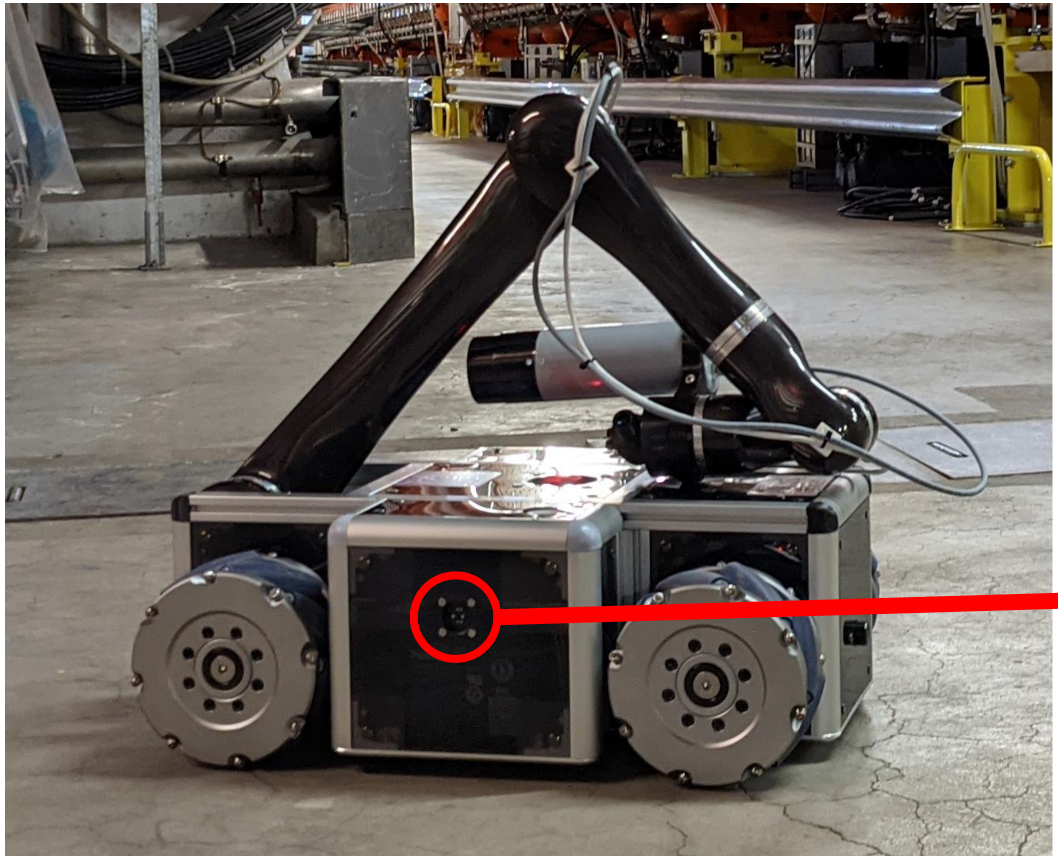
Dimensioning of the **motor** and **gearhead**

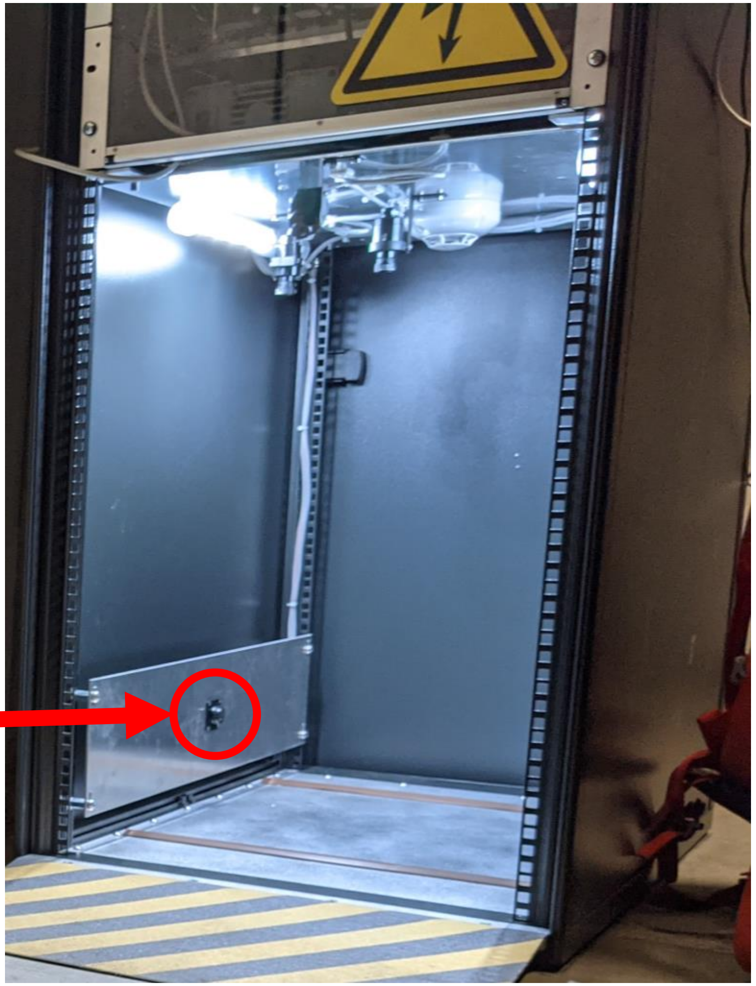




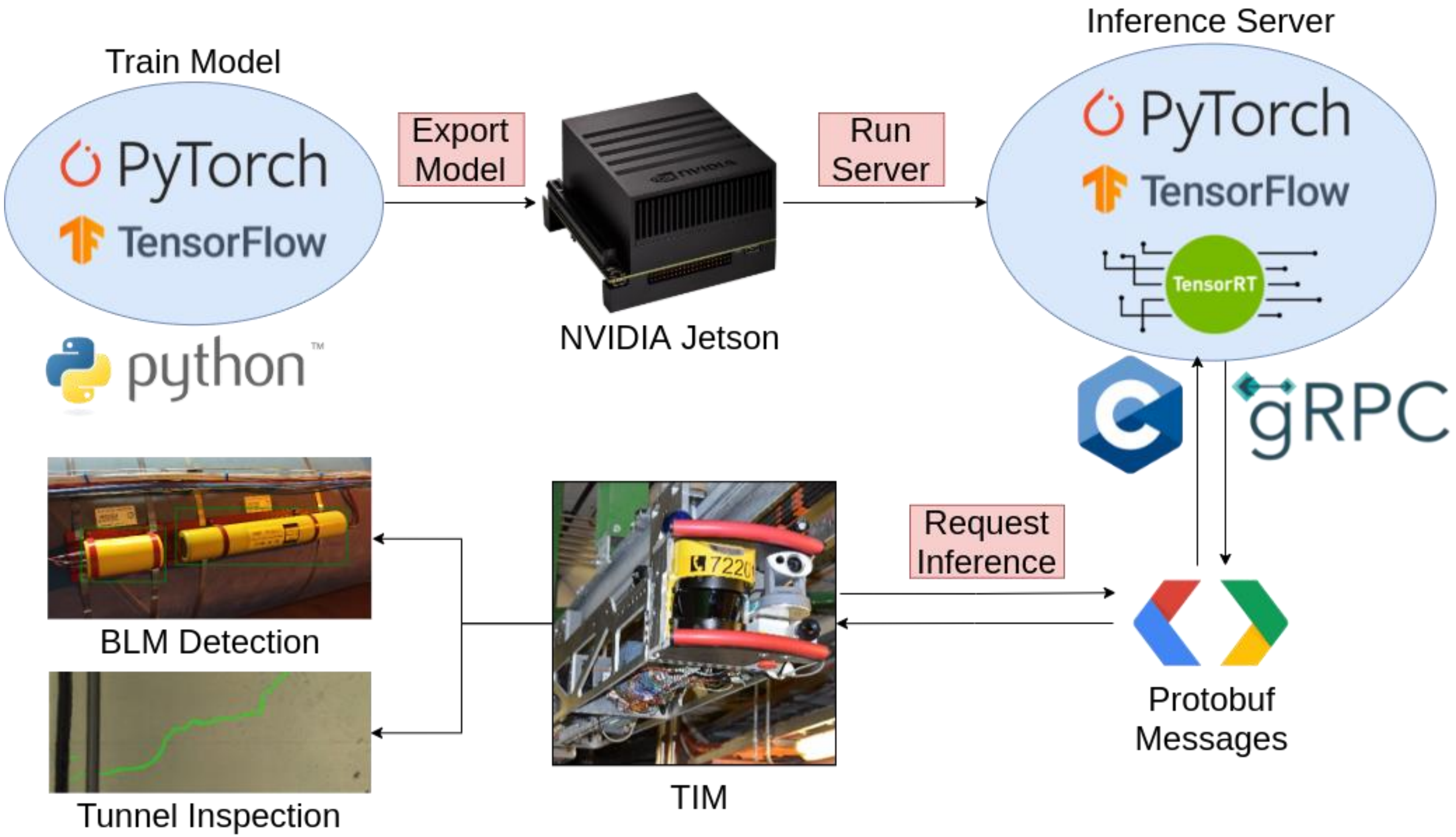
MIRA Robot: Charging Station

Once the robot enters the charging station, it approaches the power supply socket. The connection is guaranteed by a magnetic connector.



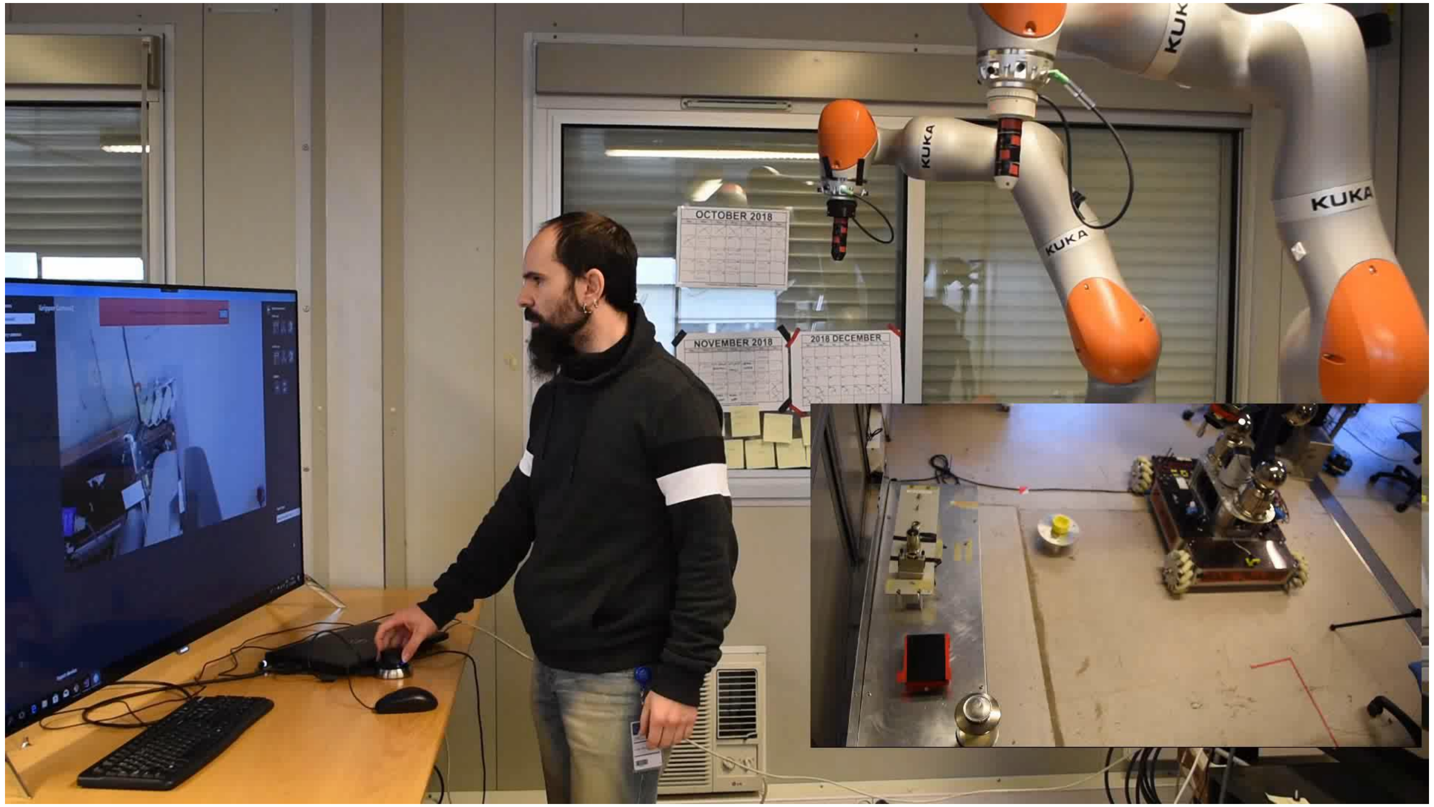


Workflow Example



Master-Slave Haptic-Based Teleoperations

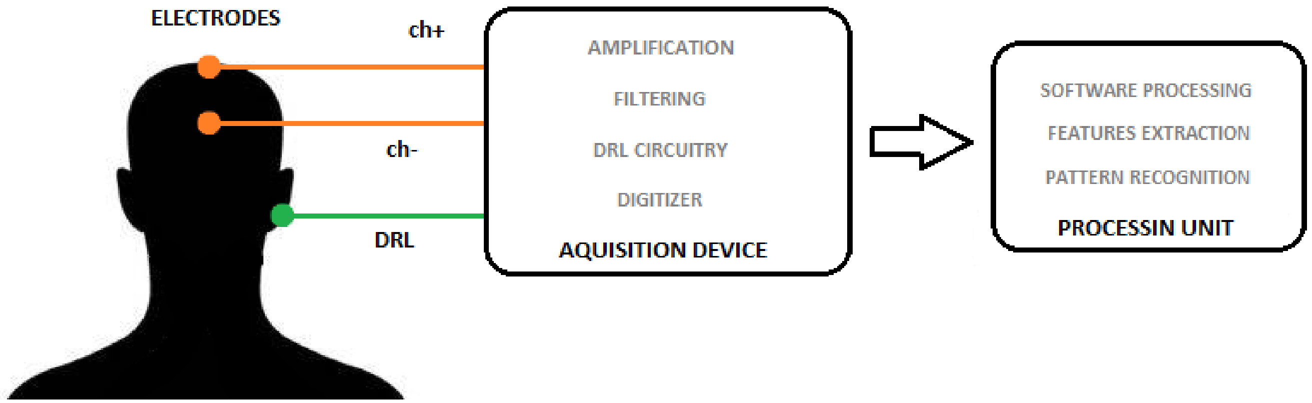
- In house **user friendly** and portable telemanipulation system to allow equipment owners and/or expert technicians to use robot in a “transparent way”
  - ✓ **No need of expert robotic operators**

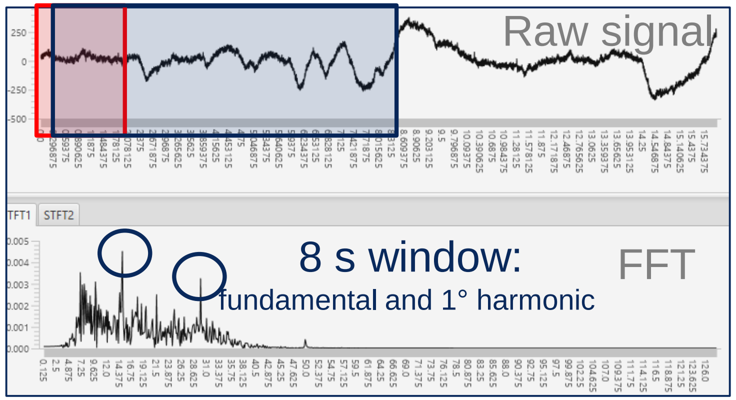


Brain-Robot Interface for robot arm control

- Online analysis of brain signal
- Augmented reality glasses used for commands display
- Eyes focus point detected by CNN processing Steady State Visual Evoked Potentials (SSVEP [15]) which are synchronous responses produced in the visual cortex area when observing flickering stimuli

Hardware used for the brain monitoring





Example of brain activity monitoring

Brain-Robot Interface for robot arm control