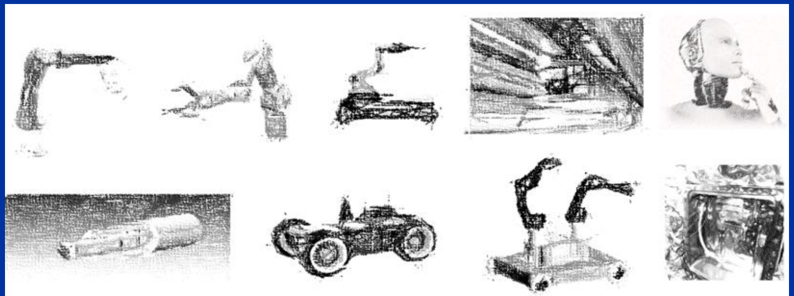
Controls
Electronics &
Mechatronics

BEAMS

CERN

Robotic Solutions for Remote Maintenance and Quality Assurance



Mario DI CASTRO

BE-CEM

TE-MSC Seminar , 03.02.2022

Acknowledgments

Many thanks to several colleagues for their support

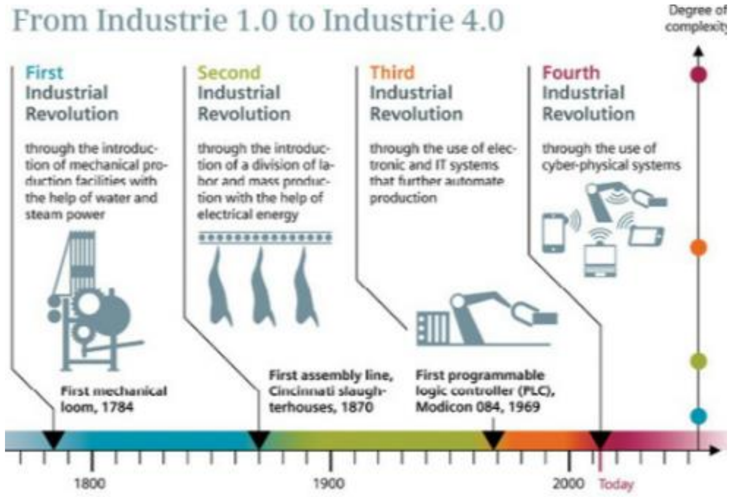
MRO section members, STI group, HE group, RP group, A. Masi, R. Losito, S. Gilardoni, M. Calviani, J.-L. Grenard, M. Modena, S. Roesler, M. Nas, J. Osborne, Y. Pira and many others

Content

- Introduction to robotics
- Needs and challenges for robotics at CERN
- The robotic service in BE-CEM
- Some challenging robotic missions
- Future objectives
- Conclusions

Current industrial revolution

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



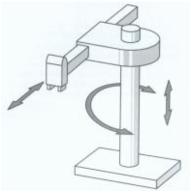
- **Human-robot cooperation**
  - ✓ ISO 2011
  - ✓ Robots can assist humans
  - ✓ Robot learning by demonstration

Robotics: main type of robots

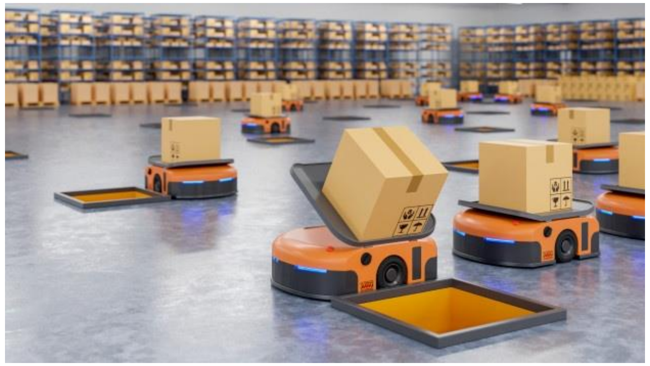

Robotic arm


Scara

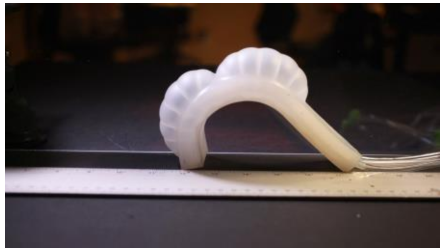

Cartesian


Cylindrical

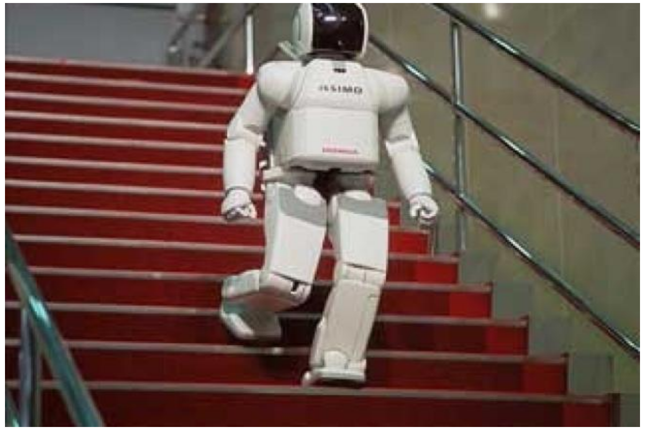
Articulated robots


Automated guided vehicles (AGVs)


Flying robots


Soft robots

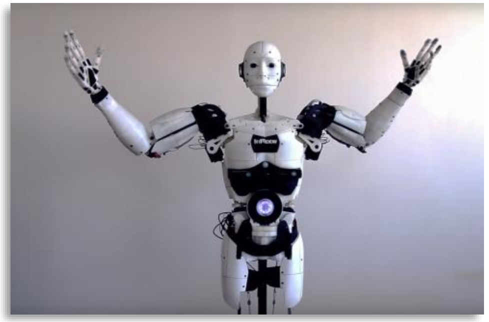

Hyper-redundant/ snakes


Humanoids

Quadrupeds

Robotics: type of robots (based on application)

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



Human-robot Interface

- **The interface devices are the ones that links the robot to the operators**
- **They have mainly a double functionality**
  - ✓ Report the status of the robot
  - ✓ Generate commands based on operator actuations
- **Classified by their functionality**
  - ✓ Actuation device: GUI etc.
  - ✓ Re-alimentation device: video, graphs etc.
  - ✓ Bilateral devices: haptic interfaces

Artificial Intelligence

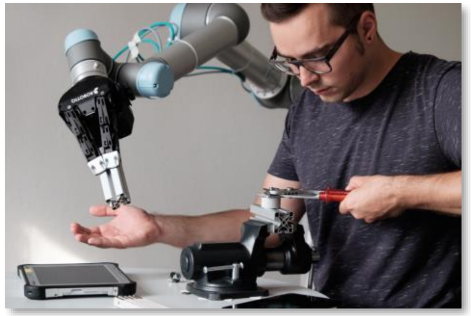
- **Intelligence exhibited by machines [1] [2]**
  - ✓ Localization
  - ✓ Knowledge
  - ✓ Learning
  - ✓ Planning
  - ✓ Decision making
  - ✓ Perception/Sensing

Machine learning in robotics #1

- Great advances in robot vision thanks to supervised deep learning techniques
  - Accuracy in object tracking (Fast-RCNN, Mask-RCNN)
  - Object grasping points calculation
- Control of closed chains kinematic robots
  - Still an open issue, Long short-term memory (LSTM) networks for system dynamic learning
- Advances in situation awareness for autonomous behaviors
  - Possibility of learning to predict external changes in the environment
- Human-Robot collaboration
  - Advances in speech recognition, gesture recognition, human action prediction

Grasping points for everyday objects [2]


Saliency detection (center of attention) in self-driving cars for situational awareness [3]

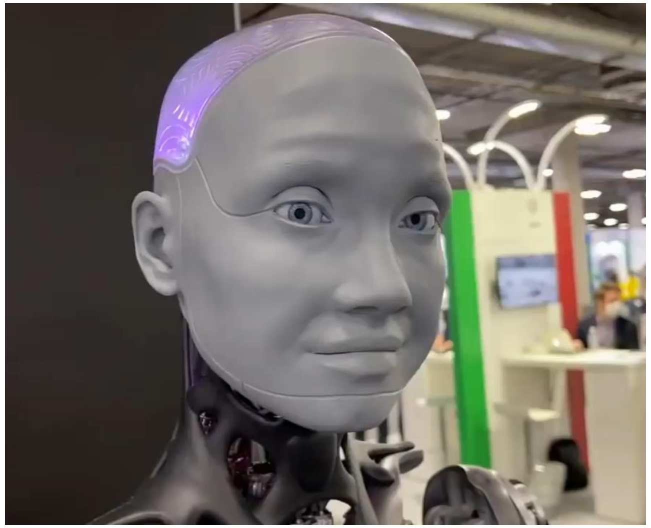

Human Robot collaboration for mechanical assembly

Machine learning in Robotics #2

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

Jia Jia

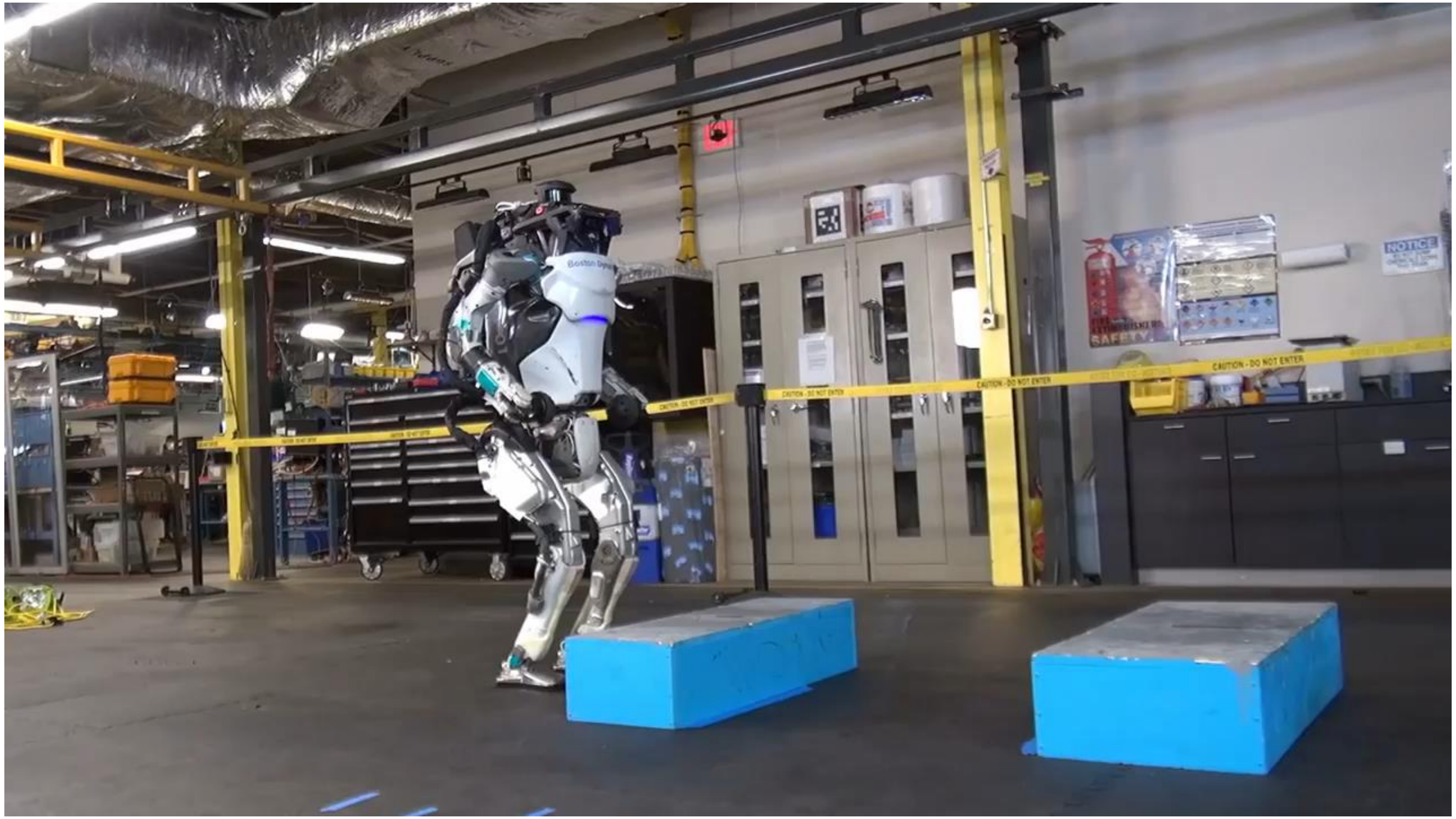
Sofia



Ameka

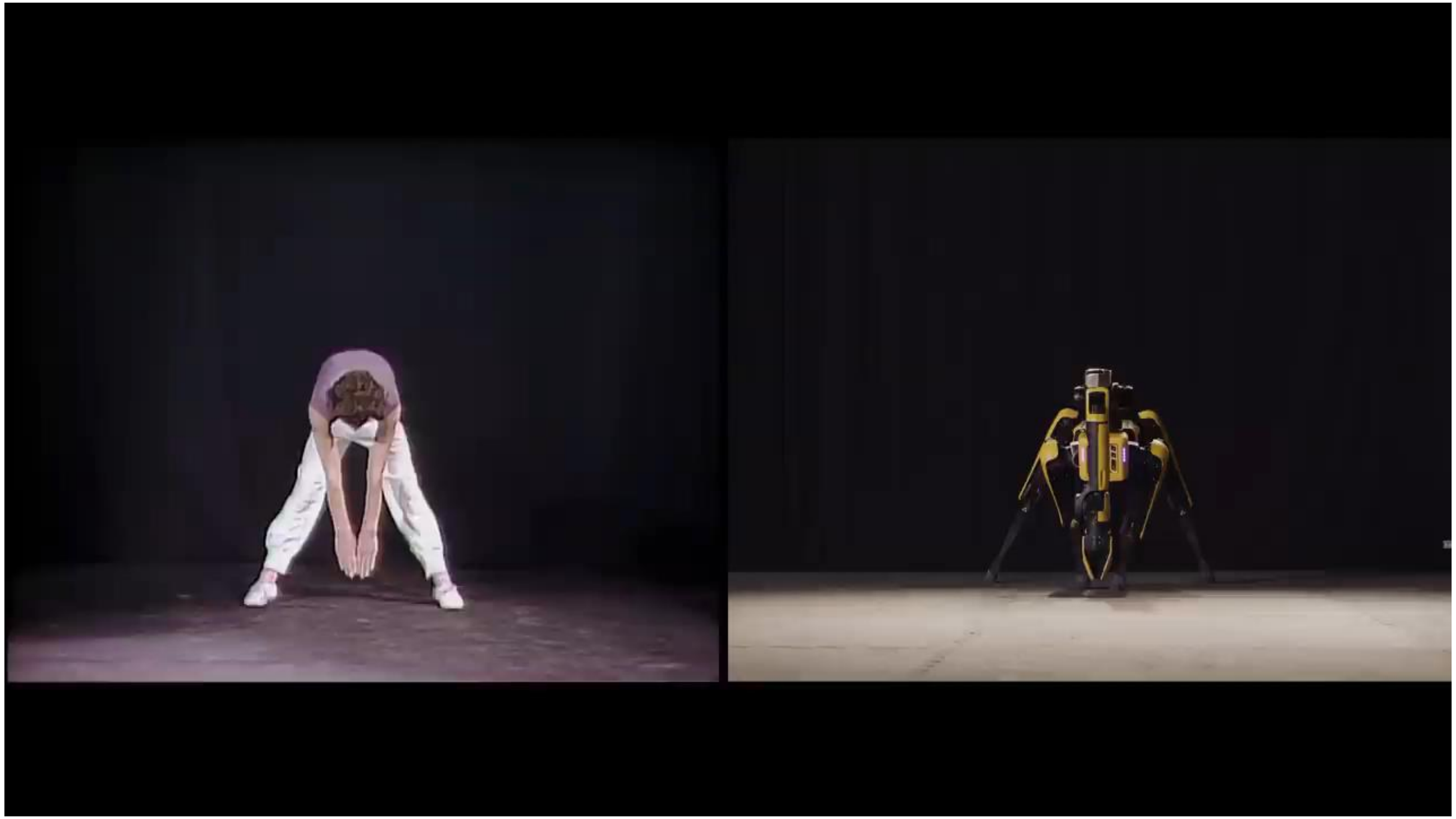
Robots made by *Boston Dynamics*

ATLAS: A mystery for the robotic community

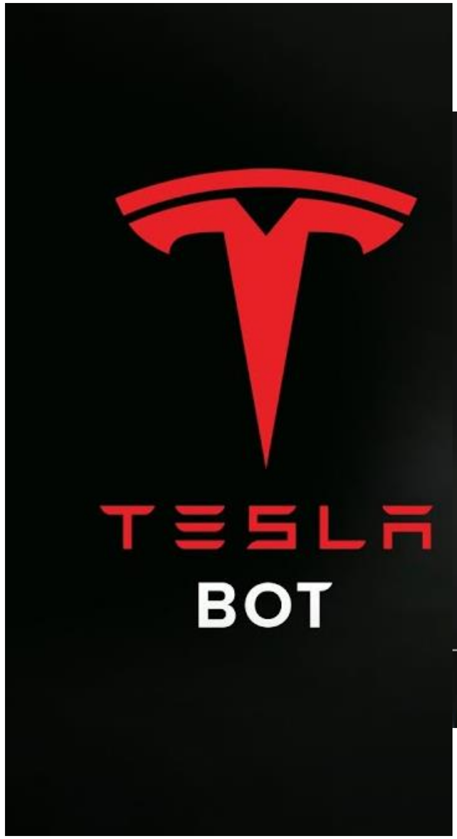


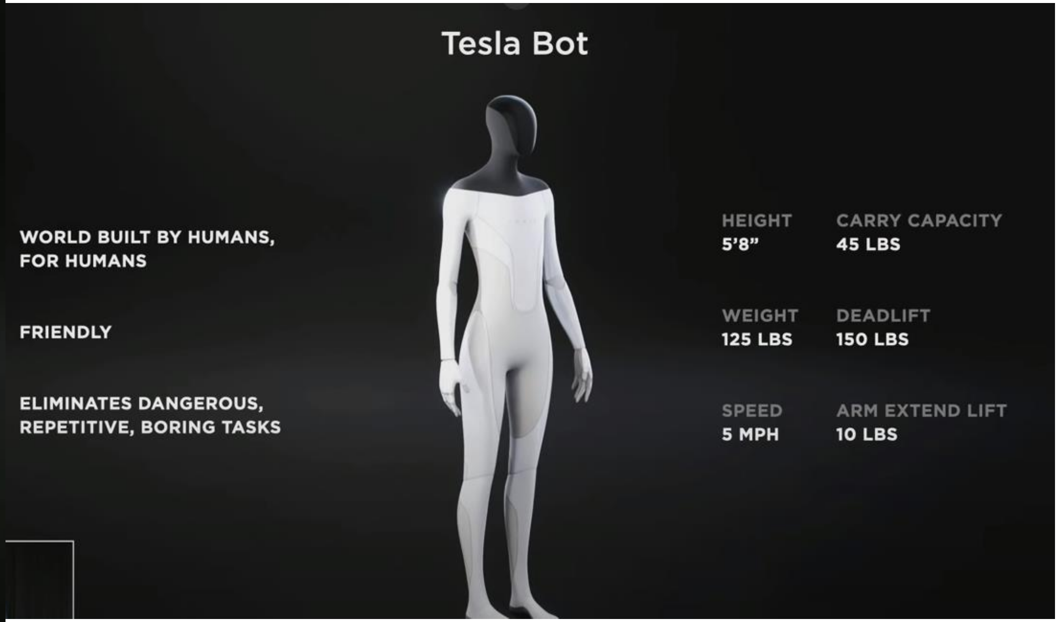
Robots made by *Boston Dynamics*

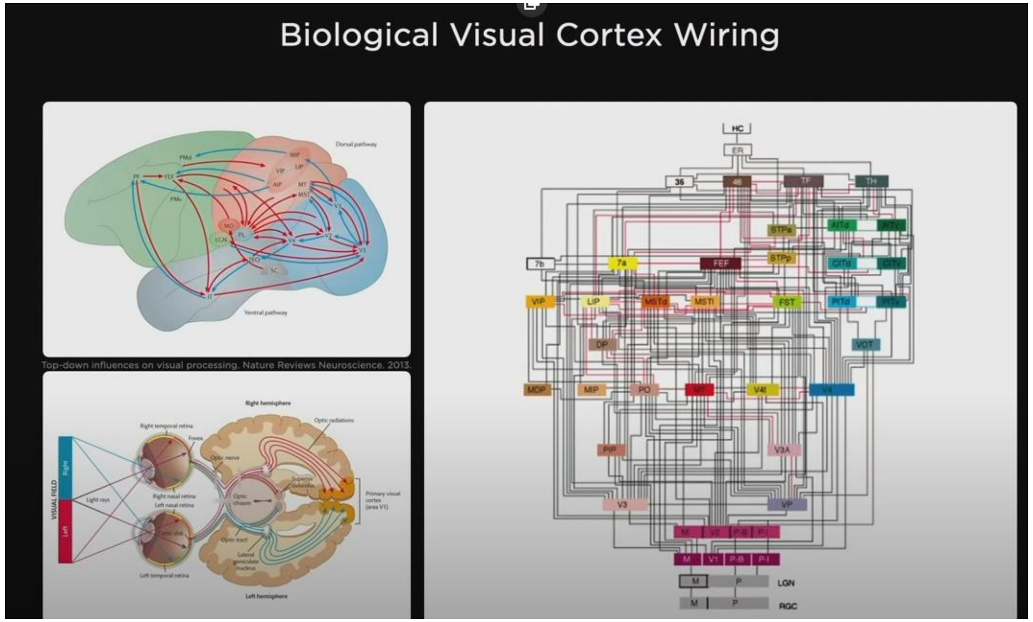
Spot: A mystery for the robotic community



Recently announced a new robot: TESLA bot





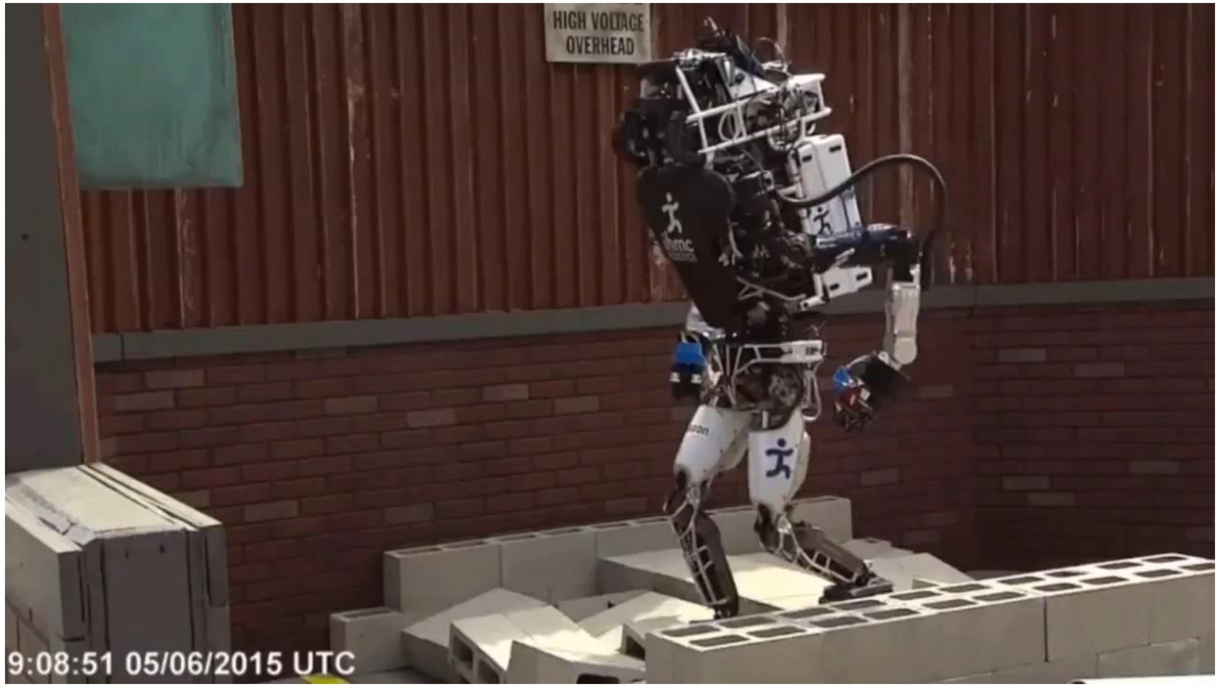


Our dream: Robots made in Hollywood

iRobot, movie of 2004 anticipating what we'll have in 2035

Robots trying to solve "real" tasks

DARPA Robotics Challenge [5]



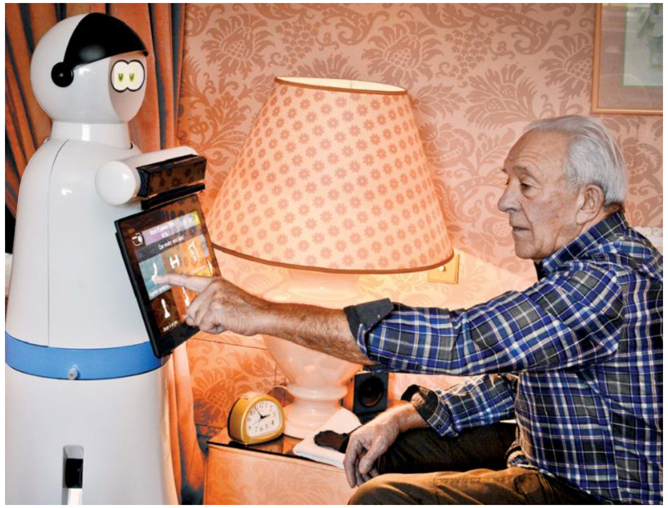
Current state of collaborative robots

- **Robot still do not appear fast enough**
  - Slow in decision making
  - Difficult to adapt to real world scenarios

Robot still don’t appear fast enough [4]

Where R&D in Robotics Worldwide is Mainly Going?

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



Teleoperation: a step of 80 years

Primary-secondary robot controls with visual feedbacks, unilateral fully mechanic tele-manipulators (during the 40’s, nuclear applications)

Courtesy of Argonne National Labs

Primary-secondary robot controls with haptic feedbacks, bilateral tele-manipulators (today, used for space applications)

Courtesy of DLR

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.)

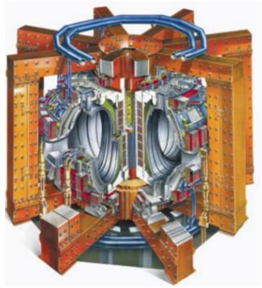
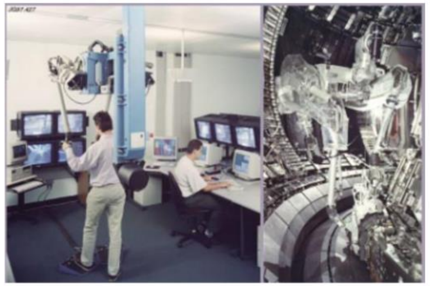
Intuitive Surgical: https://www.youtube.com/watch?v=TGjnb86HndU

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

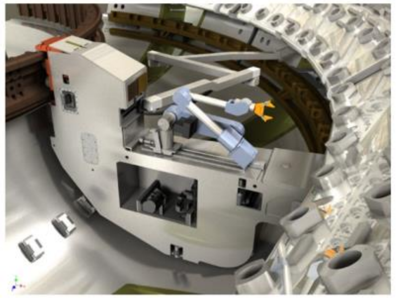
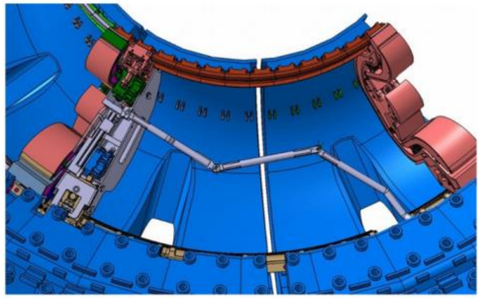
- Mainly test and prototypes devices
- Not necessary designed to be robust
- Industrialization of concepts in most of the cases not easy

Teleoperation in Structured Big Science Facilities

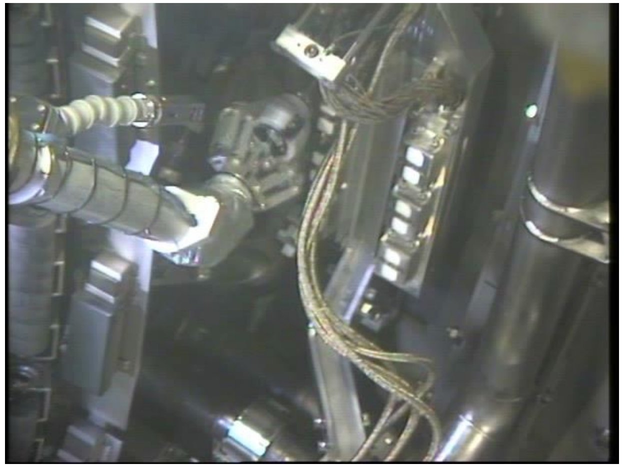
- Joint European Torus (JET)
- Spallation Neutrino Source (SNS)
- International Thermonuclear Experimental Reactor (ITER)

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

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

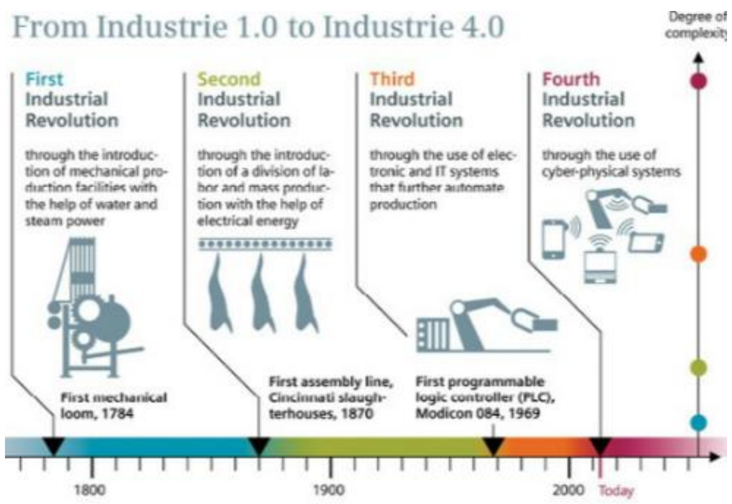


JET Torus (left) and remote handling approach using the MASCOT system

- 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

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

Robotics and Ethical aspects

- **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?


INTERNATIONAL NEW YORK TIMES

FRIDAY, MAY 27, 2016 | 17

TECHNOLOGY COMPANIES BUSINESS

State of mind is issue in the Redstone battle

Determining competence uses geriatric medicine, psychiatry and the law

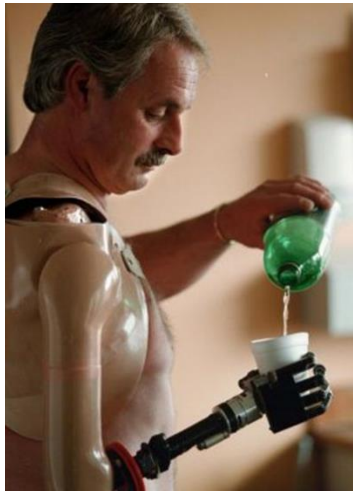
Not human, but cause to worry

SEATTLE

Experts at conference explore questions about artificial intelligence

Robotics for us

- 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

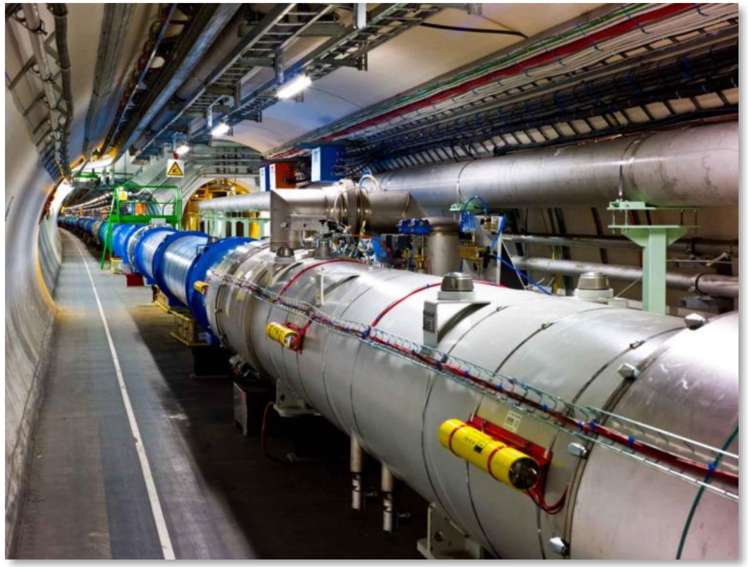



Robots must improve the quality of work by taking over dangerous, tedious and dirty jobs that are not possible or safe for humans to perform.
ALARA principle followed for each intervention

Content

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

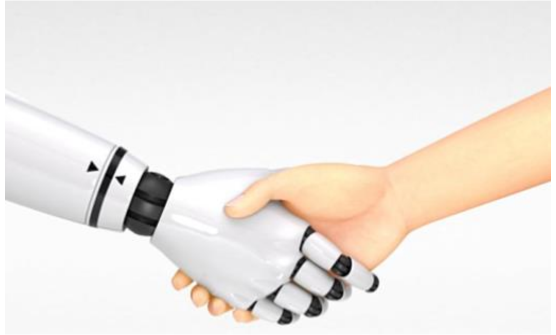
North Area experimental zone

Radioactive sample handled by a robot

Availability of Particle Accelerators

Reliability	Maintainability	Availability
Constant	Decreases	Decreases
Constant	Increases	Increases

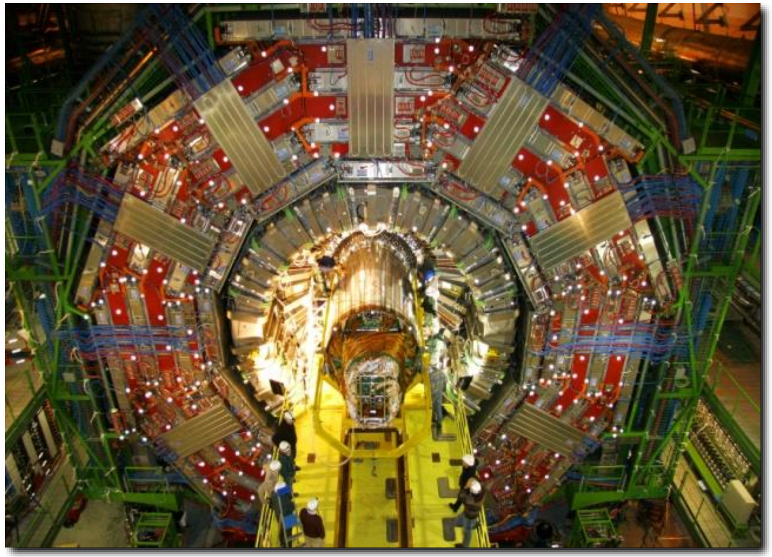
But before deploying robots, their reliability must be verified to be really high and recovery scenarios must be foreseen



Main difficulties for robotics at CERN

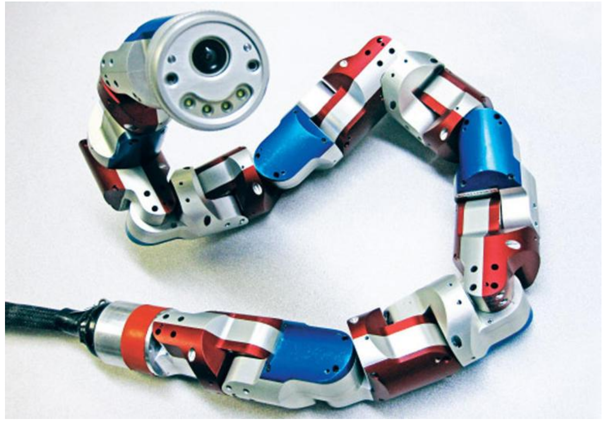
- Need for maintenance intervention and inspection in harsh and semi-structured environments
- **Radiation, magnetic disturbances**, delicate equipment not designed for robots, big distances, communication, time for the intervention, highly skilled technicians required (non robotic operators), etc.



Suitable robots for 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**



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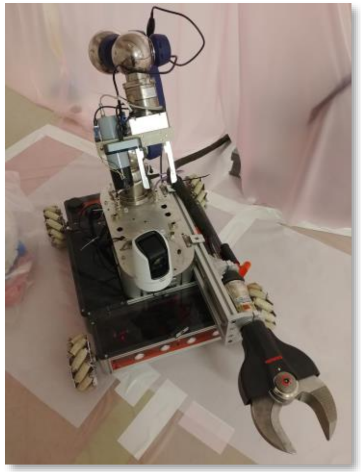
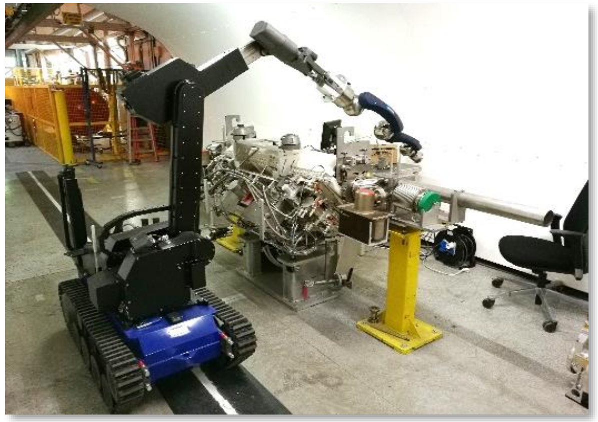
Robotic Support for CERN: Type of Robots Overview

Telemax robot

Train Inspection Monorail [10] (CERN made)

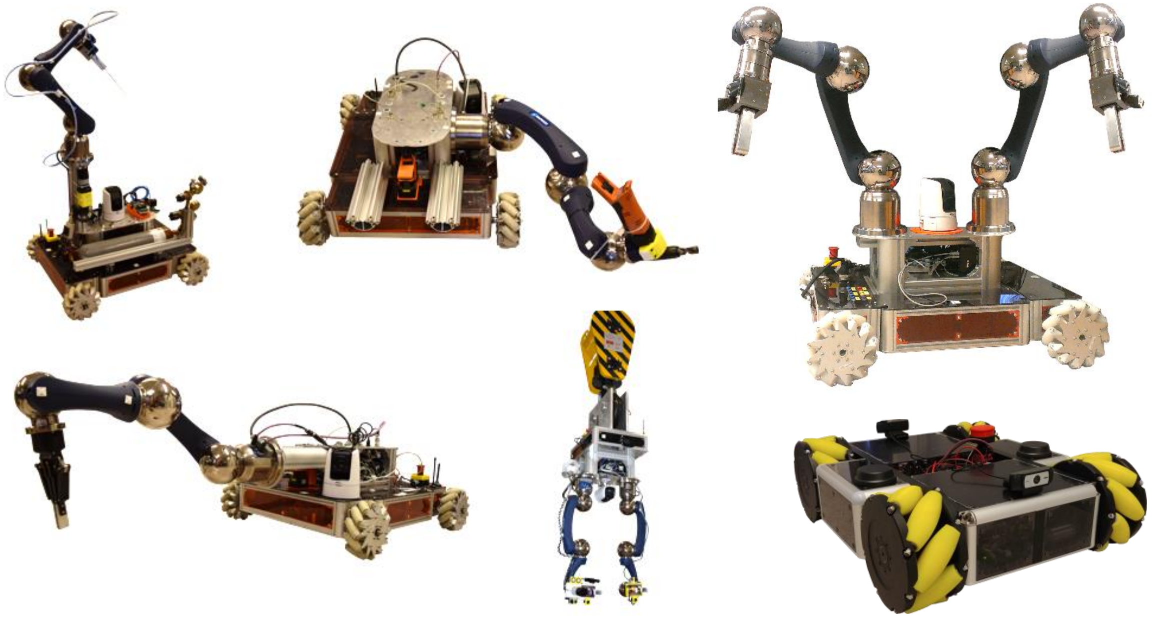




Teodor robot

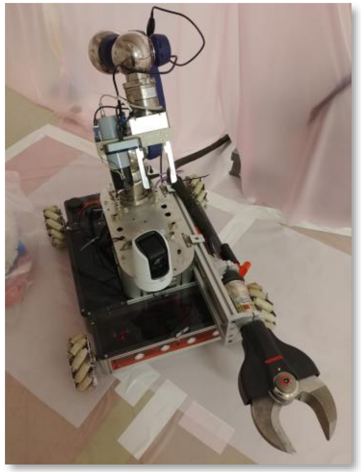
EXTRM robot (CERN controls)

Drone for tele-operation support

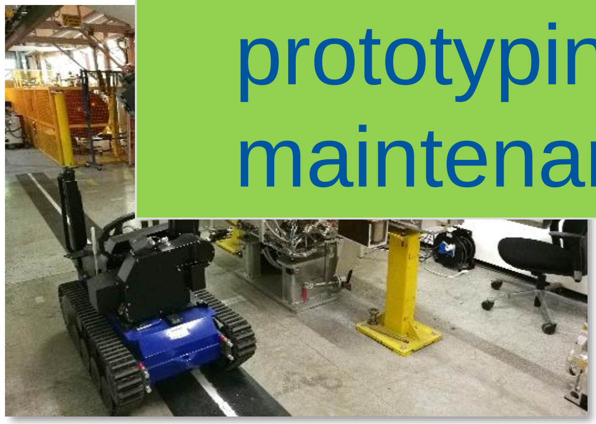


CERNBot [11-17] in different configurations (CERN made)

Robotic Support for CERN: Type of Robots Overview

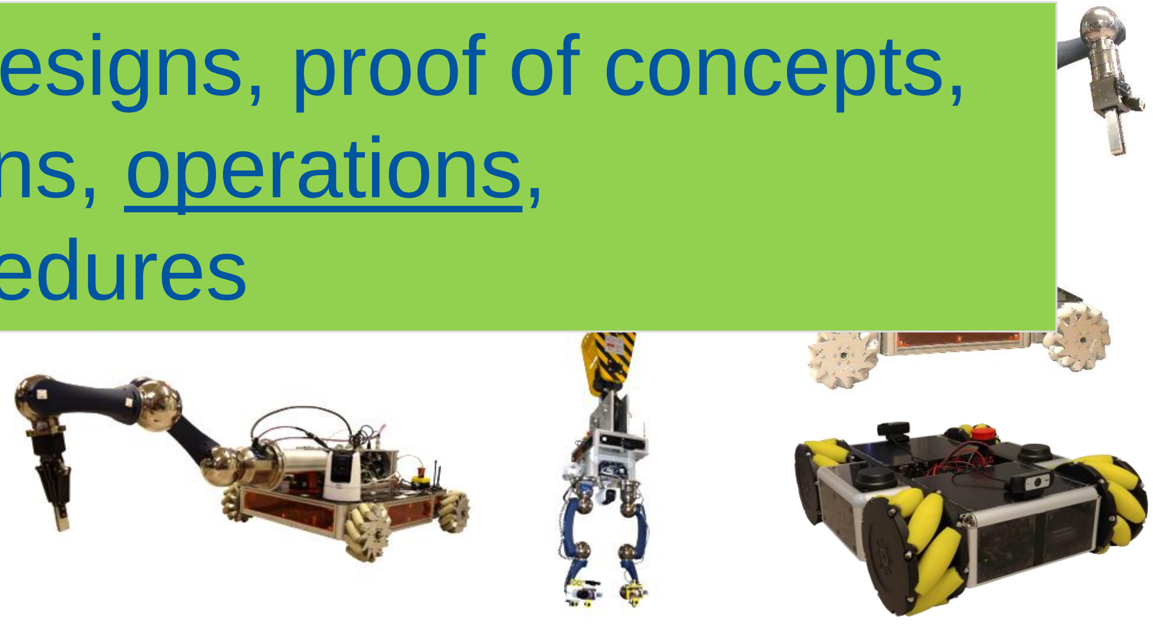


- Mechatronics conceptions, designs, proof of concepts, prototyping, series productions, operations, maintenance, tools and procedures



Teodor robot

EXTRM robot (CERN controls)



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

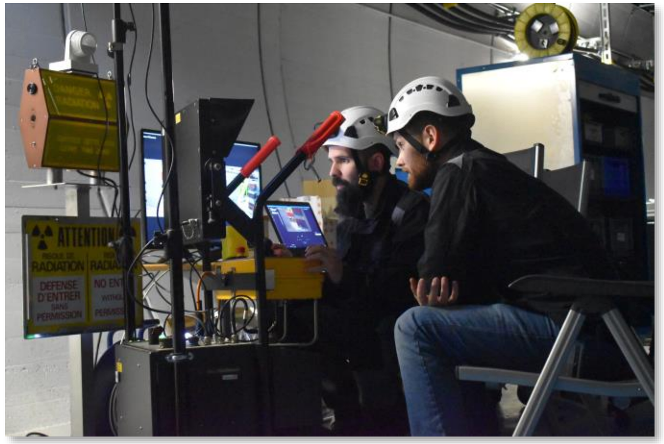
Drone for tele-operation support

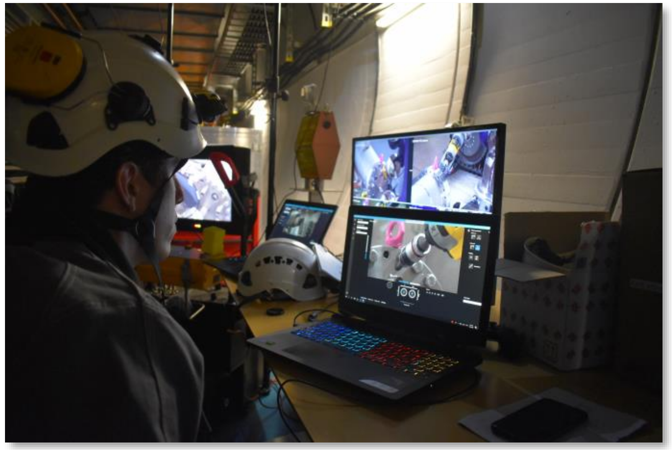
Robotics technologies are mainly used for:

- 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…

Robotic service for remote maintenance

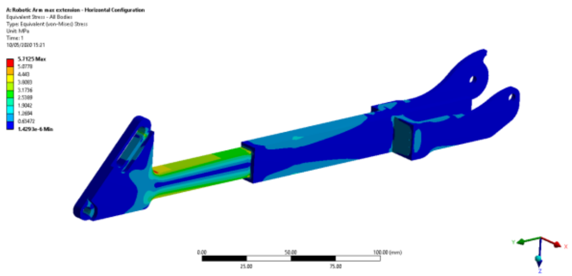
- ➢ Remote inspection and teleoperation
  - ✓ Robotic controls (kinematics + feedbacks) and operation

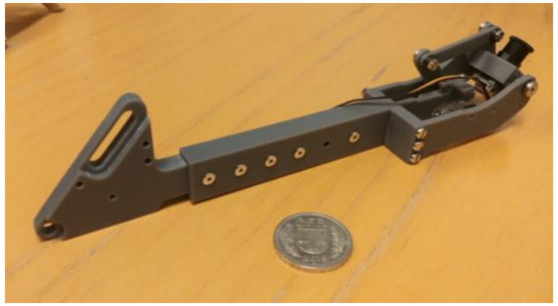




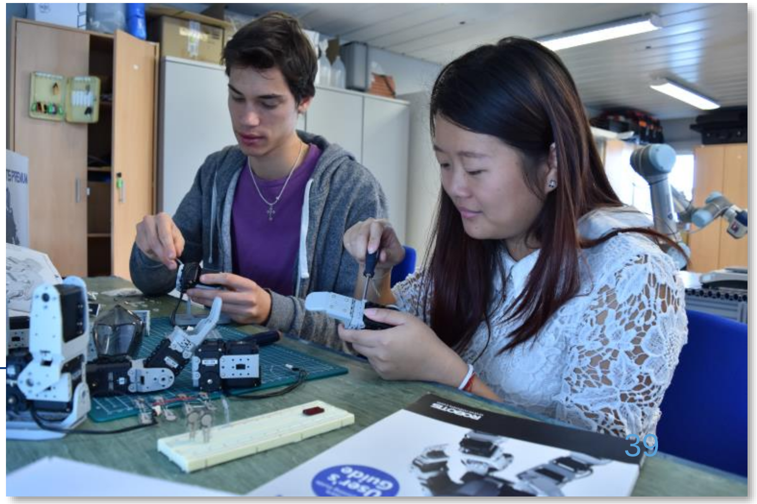
Robotic Lab #1, building 937

- 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 [42]



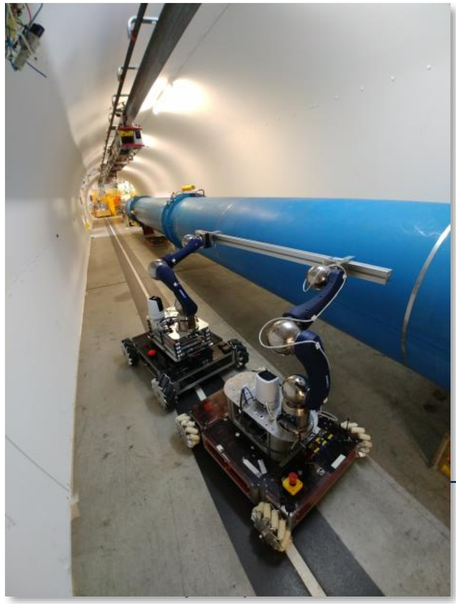


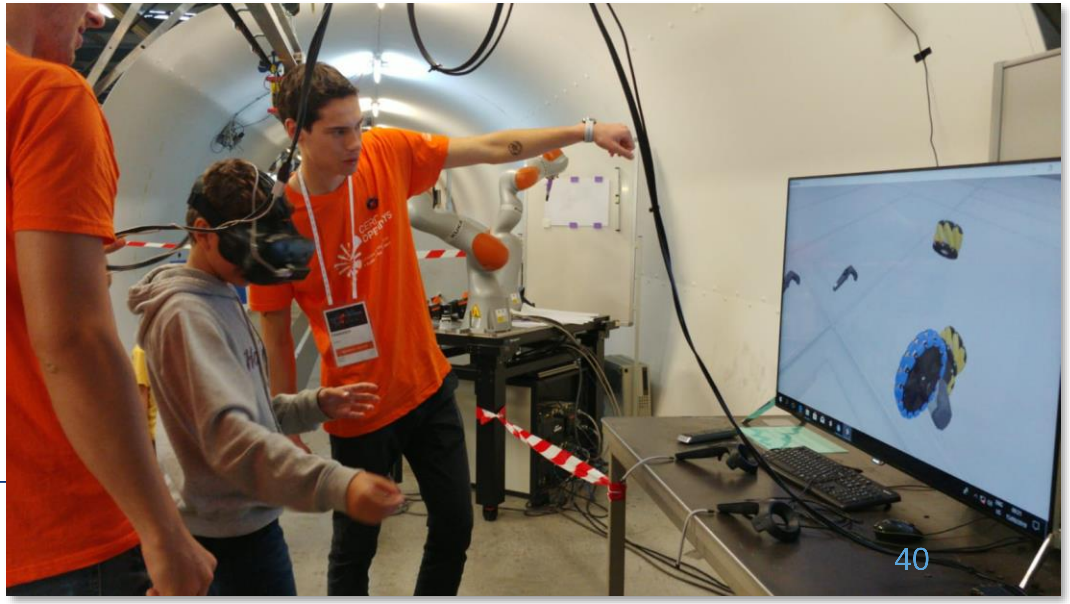
Desig and 3D printing prototype for the RF cavity inspection robot



Robotic Lab #2, building 927

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





Main Motivations for Custom Robotic Development #1

- CERN accelerator complex is vast with different type of machines
- 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** semi-structured and harsh environments

Main Motivations for Custom Robotic Development #2

- Industrial robot have **<u>very complicated human-robot interfaces demanding intense operators training</u>,** controls are not open to be integrated in our control system, communication channel is often via radio signal, not built to reduce contamination risks etc.

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

CERNTAURO framework [7]

CERN Telemanipulation semi-**A**utonomous **U**nit for **R**obot **O**perations

Mechatronic System

Perception

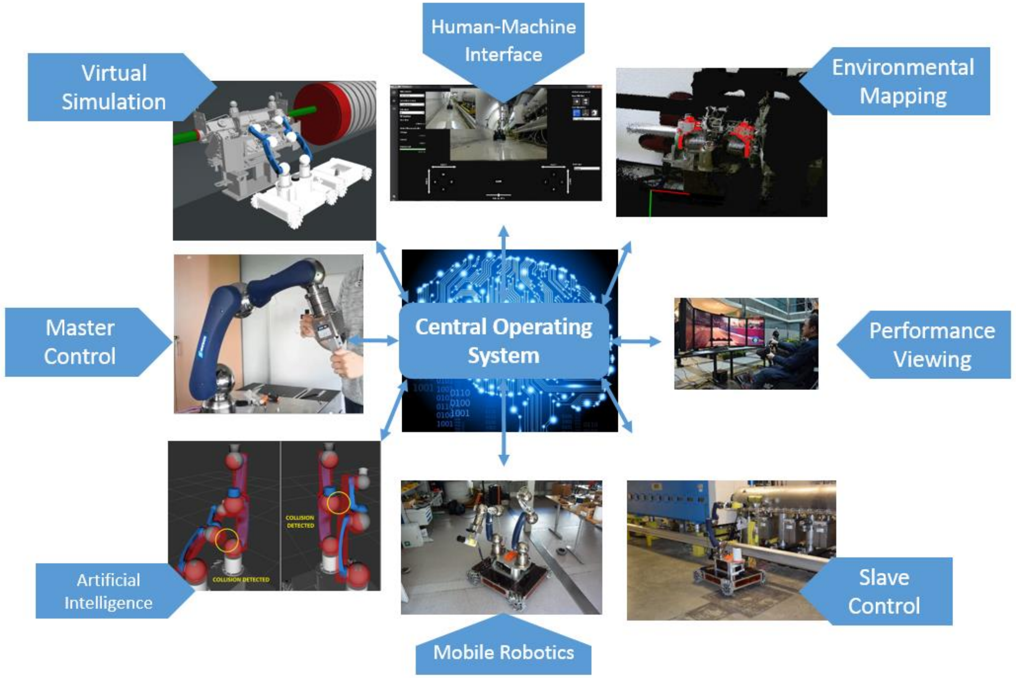
Actuation

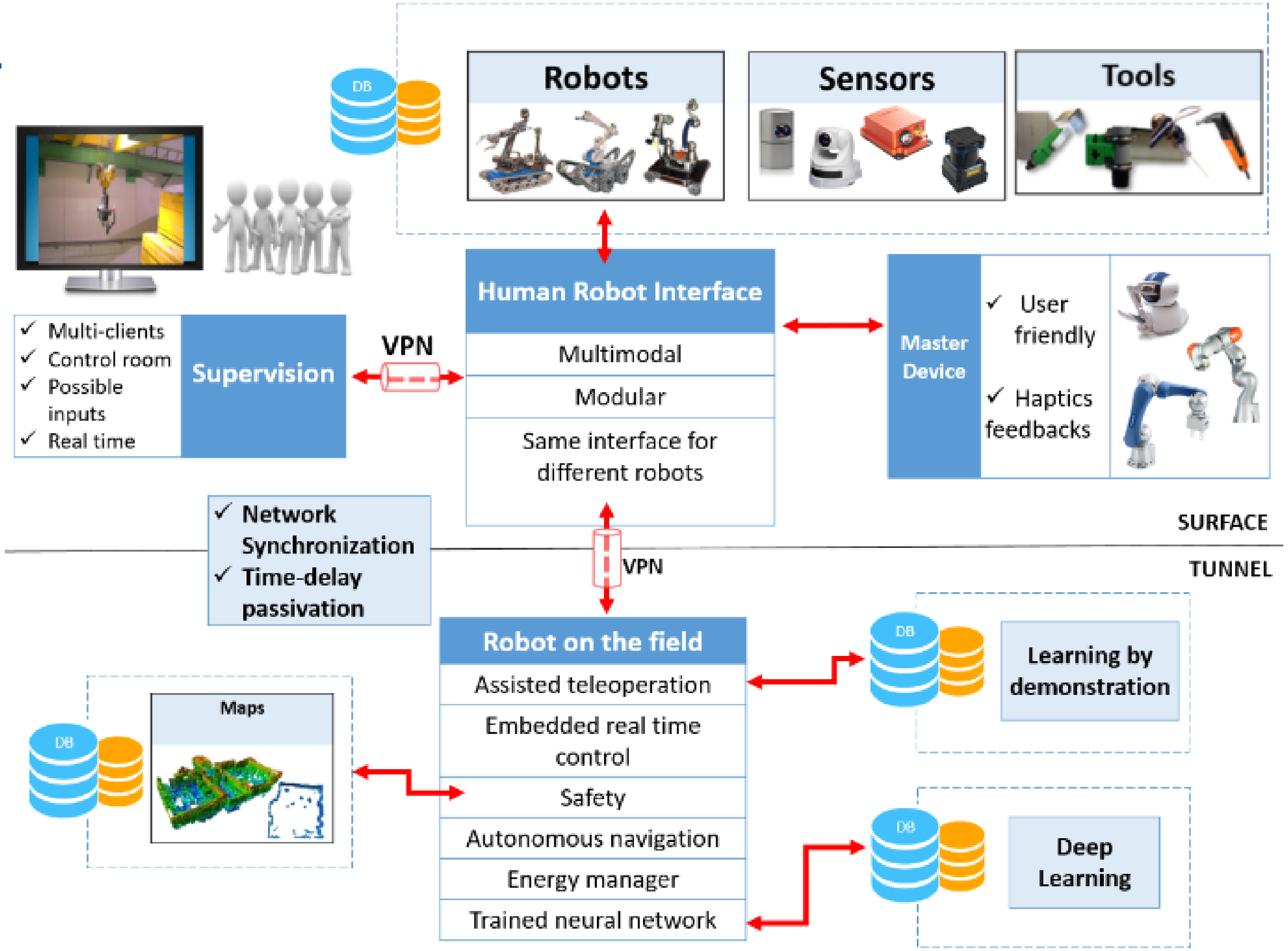
Motion

- **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

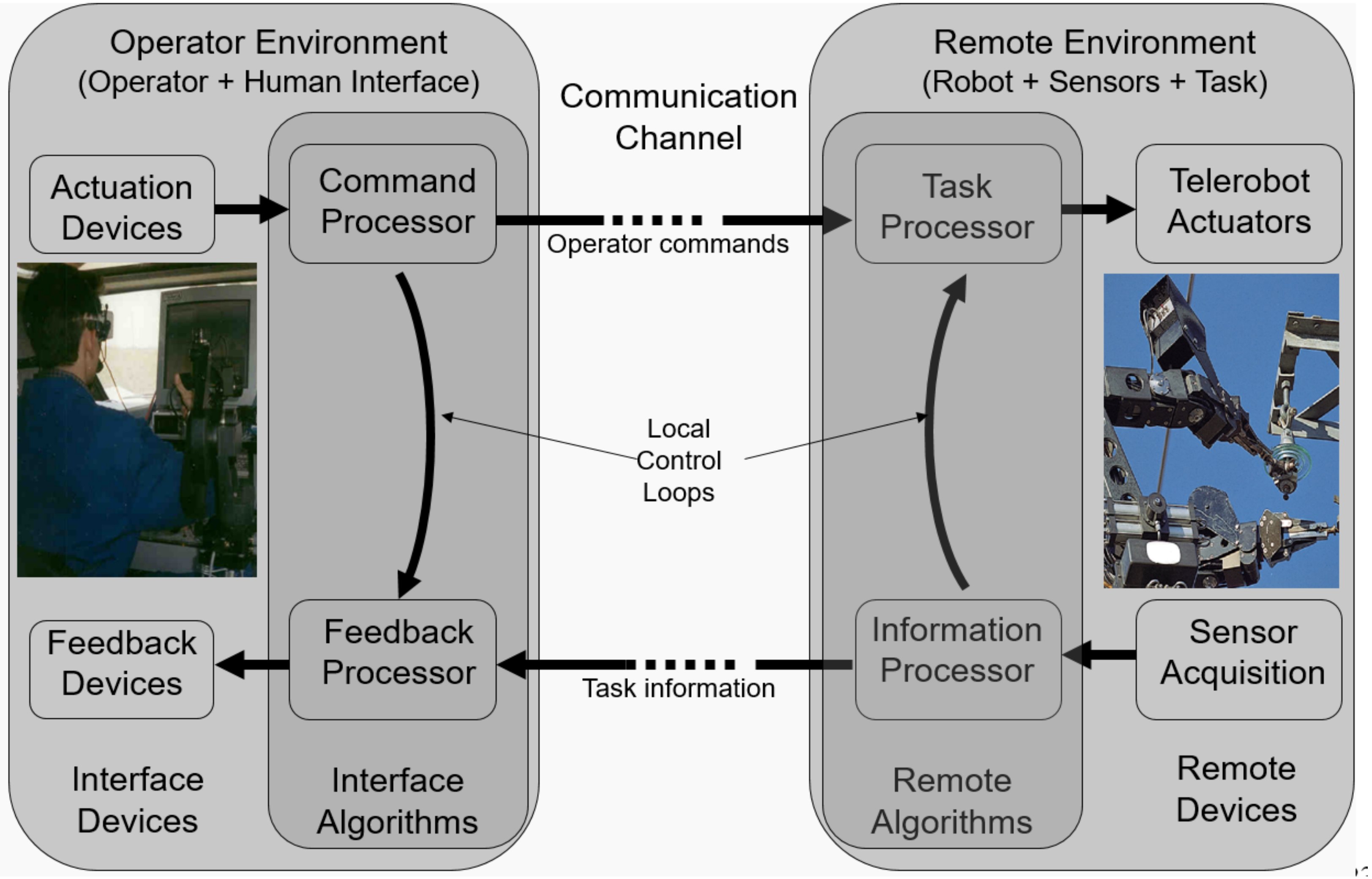
CERNTAURO framework

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

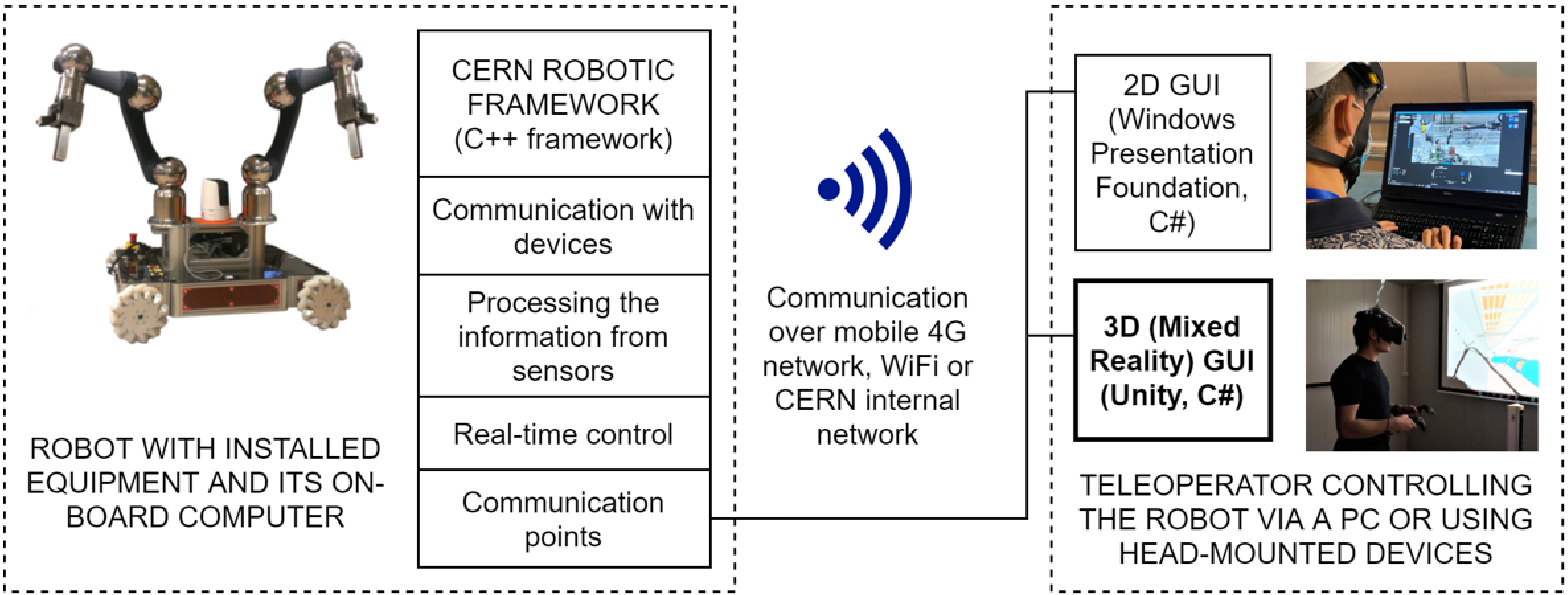




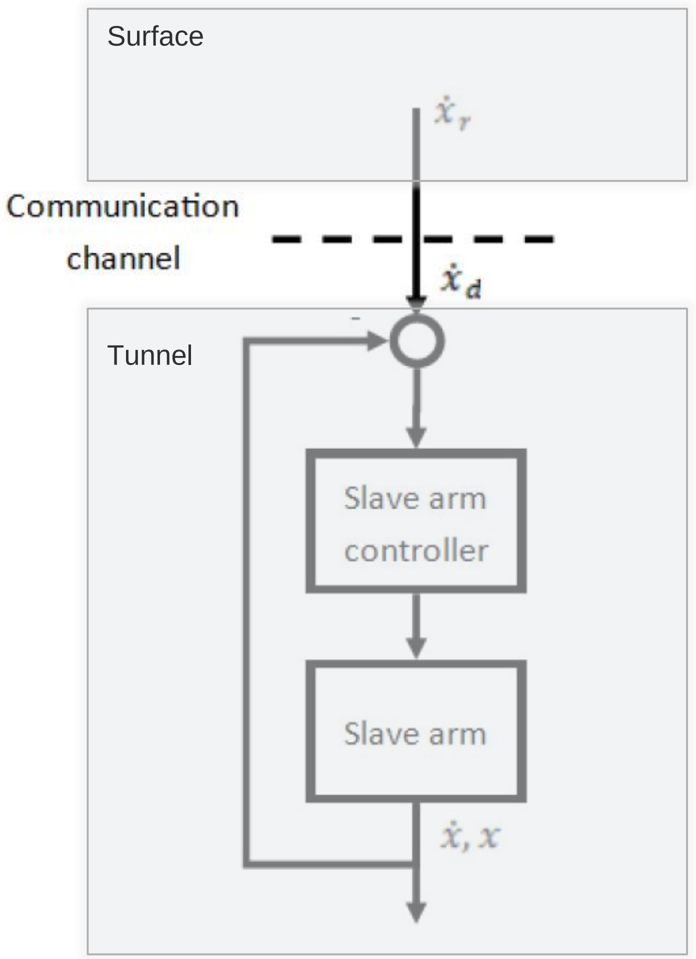
General Scheme of a Teleoperated System



How the robots are controlled

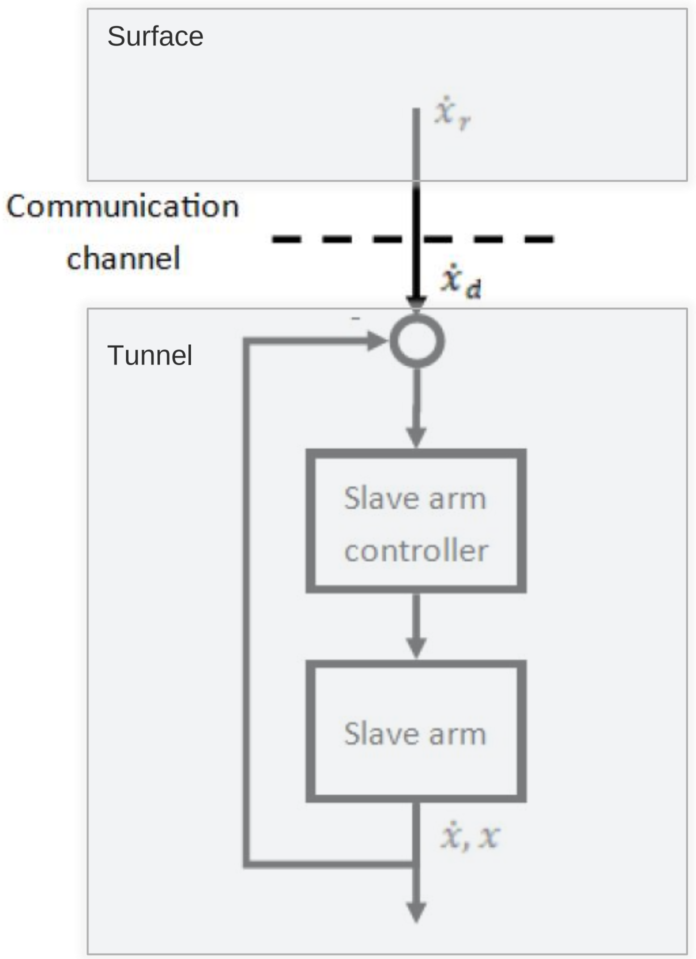


Unilateral vs Bilateral Controls



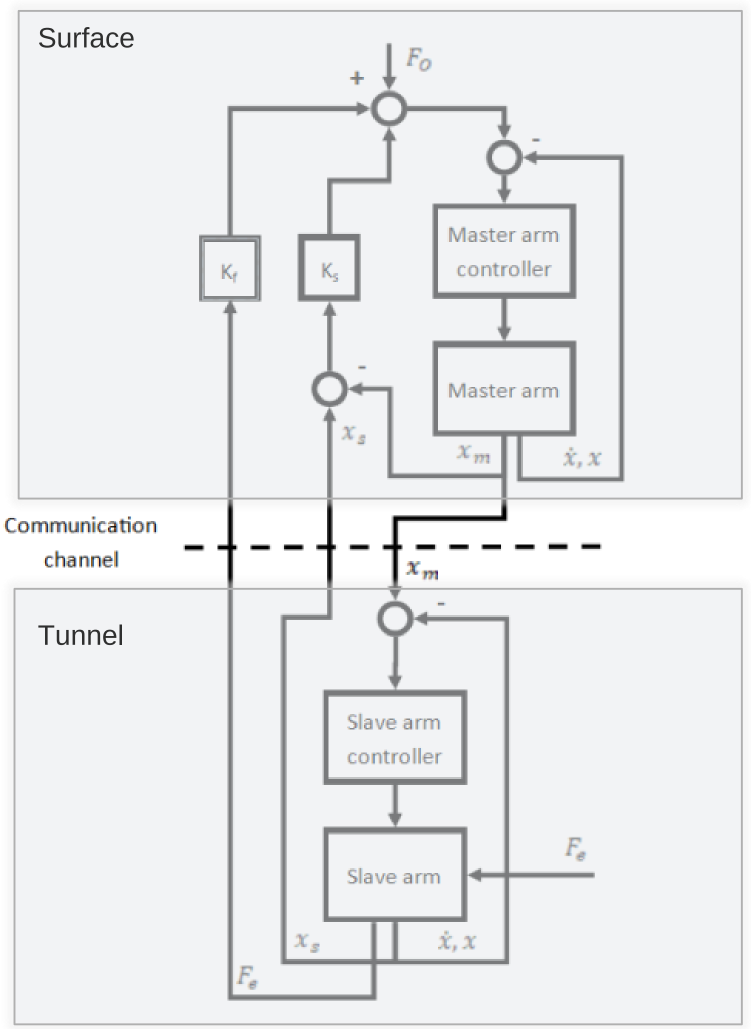
Unilateral control scheme of CERNTAURO

Unilateral vs Bilateral Controls



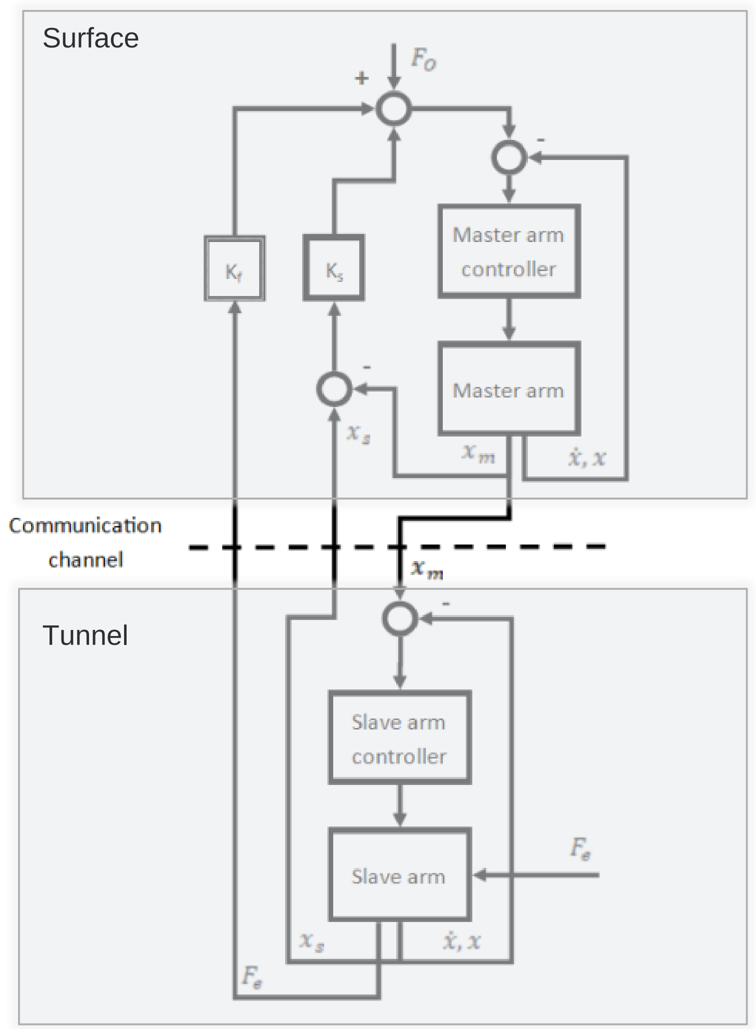
Unilateral control scheme of CERNTAURO

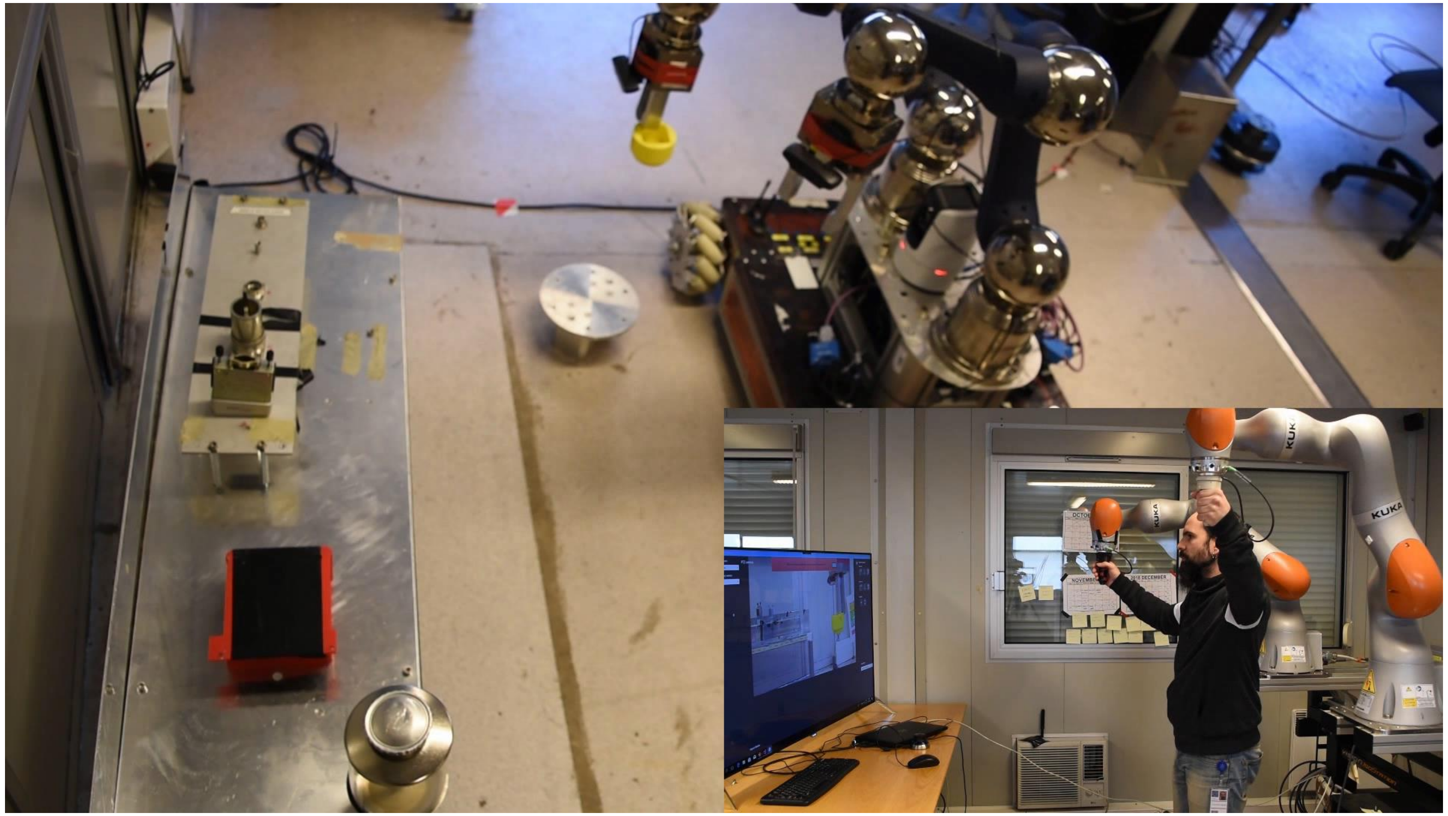
Unilateral vs Bilateral Controls



Bilateral control scheme of CERNTAURO. Experience of imitation

Unilateral vs Bilateral Controls





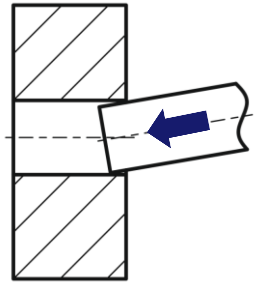
Bilateral control scheme of CERNTAURO. Experience of imitation

Dynamics

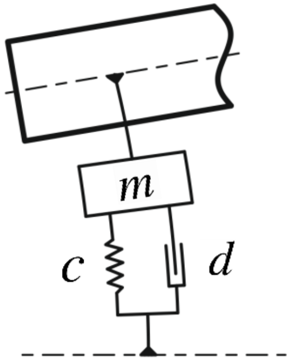
Example: Compliant Control

TIM Handling Radioactive Source for BLM Tests

Problem:



Solution:



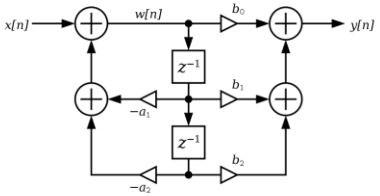
1. Mass spring damper system

$$\mathbf{M}\ddot{\mathbf{x}} = \mathbf{h} - \mathbf{C}\mathbf{x} - \mathbf{D}\dot{\mathbf{x}}$$

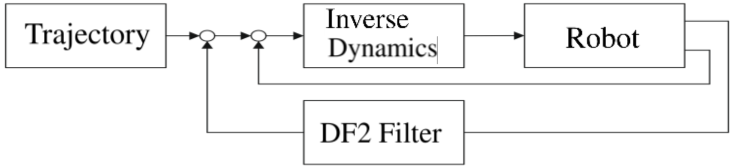
2. Discrete Frequency domain

$$\mathbf{G}(z) = \frac{\mathbf{b}_0}{1 + \mathbf{a}_1 z^{-1} + \mathbf{a}_2 z^{-2}}$$

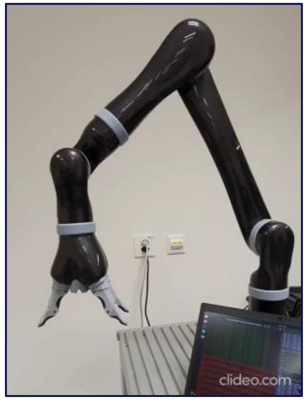
3. Implementation in C++ Framework in Direct Form II



4. Controller



Low Damping:



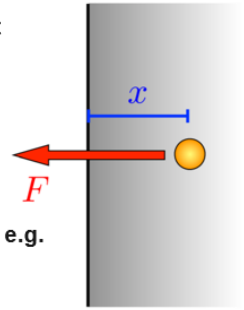
High Damping:

Haptics

How strong is the robot arm?
How fast can it move?
Haptics lets you understand the way the robot moves

Virtual Wall – often as a linear spring, k is the stiffness coefficient

$$F(x) = \begin{cases} -kx, & if\ x > 0 \\ 0, & otherwise \end{cases}$$



Simple shapes – often as a potential well (repulsive or attractive), e.g. sphere

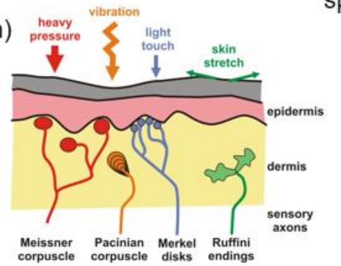
$$F(x,y,z) = \begin{cases} -k(x^2+y^2+z^2-r^2), & if\ x^2+y^2+z^2 < r^2 \\ 0, & otherwise \end{cases}$$

Tactile Sensors – lighter contact, up to 10kHz bandwidth

Thermoreceptors (temperature)

Mechanoreceptors (see below)

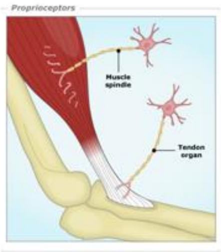
Nocioreceptors (pain)



Kinesthetic/Proprioceptive Sensors – heavier contact, ~0.1-100Hz bandwidth

Force sensors (Golgi tendon organs)

Position and motion sensors (muscle spindles)



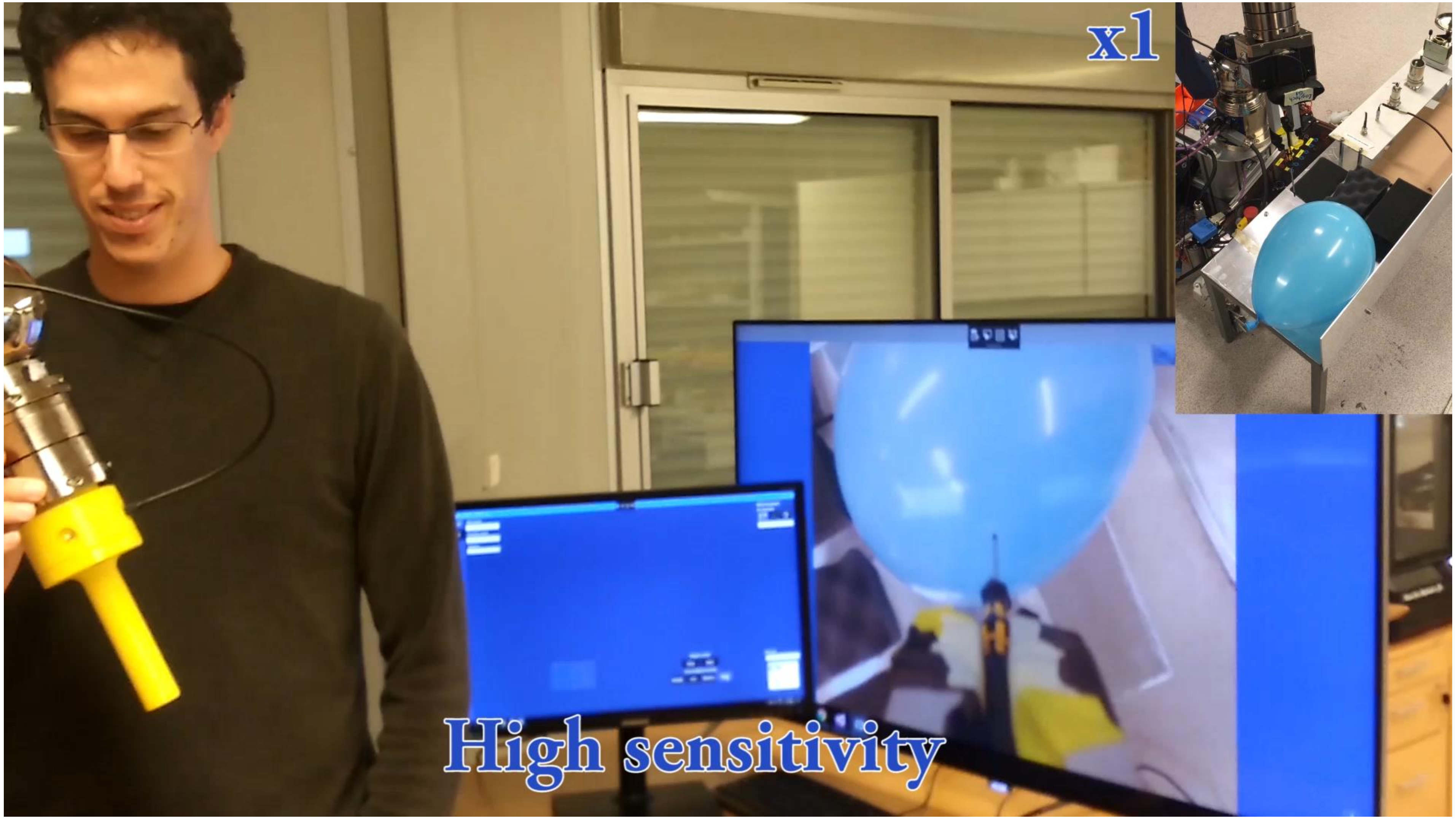
Be strong

Stay gentle

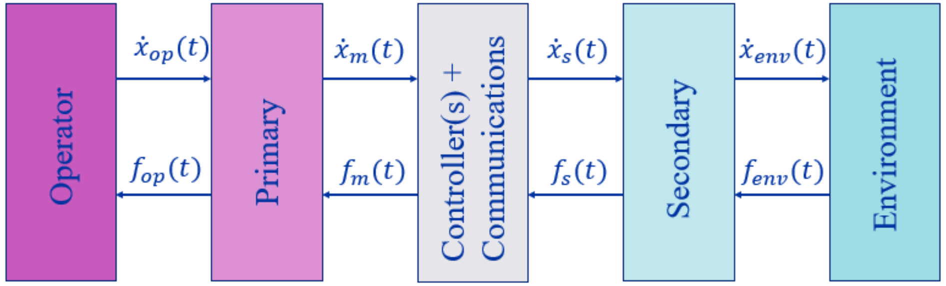
Unknown and unstructured environment:
How much does it weigh?
What happens if I touch it?
Does it break easily?
Haptics lets you understand your effect on the environment

More on E. Matheson Academic lecture
https://indico.cern.ch/event/1055745/

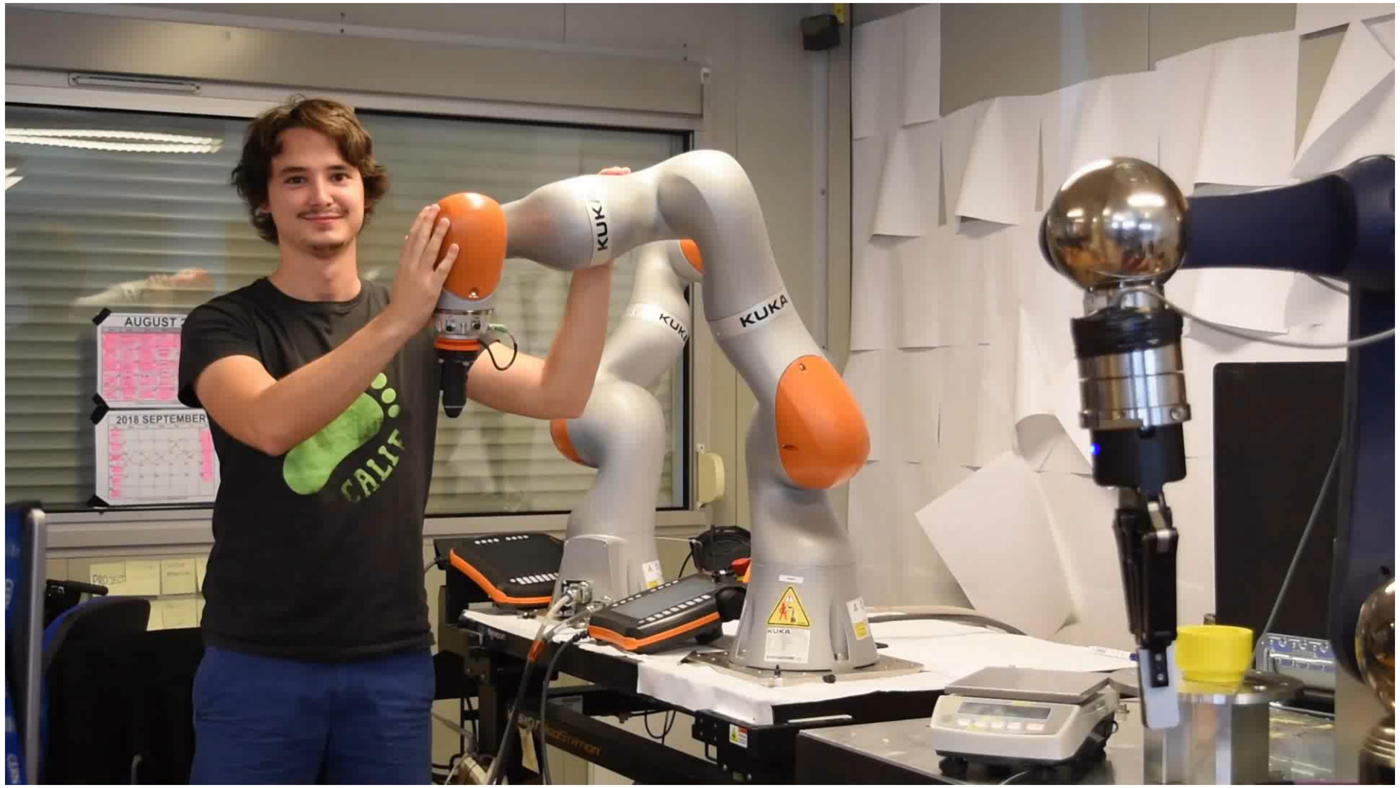
Bilateral Controls and Haptics



Impedance-Mode Control

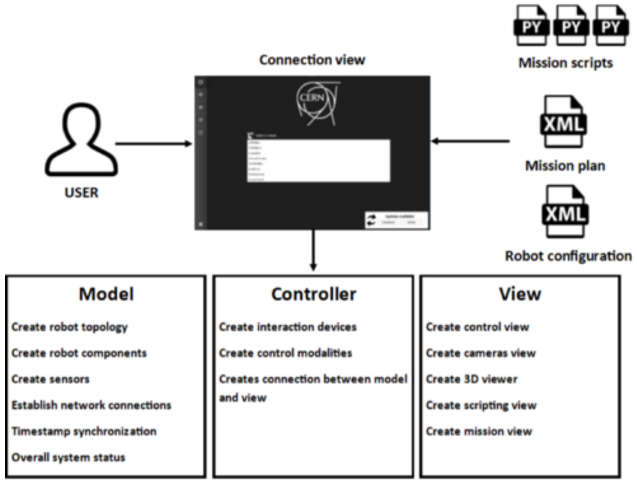


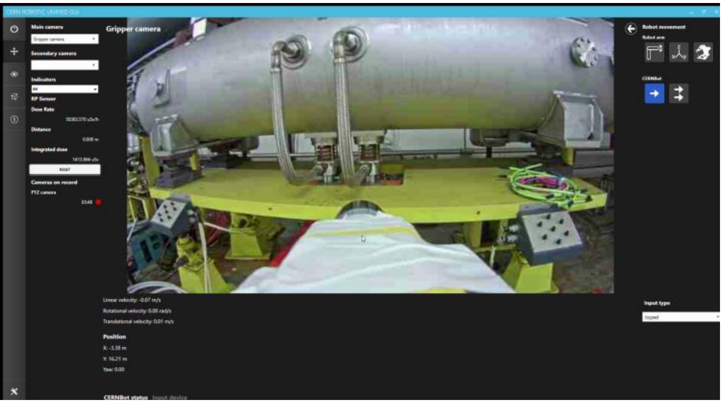
$F_{op} = Z_{op}(\dot{x}_{op})$, *where* Z_{op} *in the operator impedance*
$F_{env} = Z_{env}(\dot{x}_{evn})$, *where* Z_{evn} *in the environment impedance*
$F_{op} = F_{env}$ *is equivalent to perfect transparency*

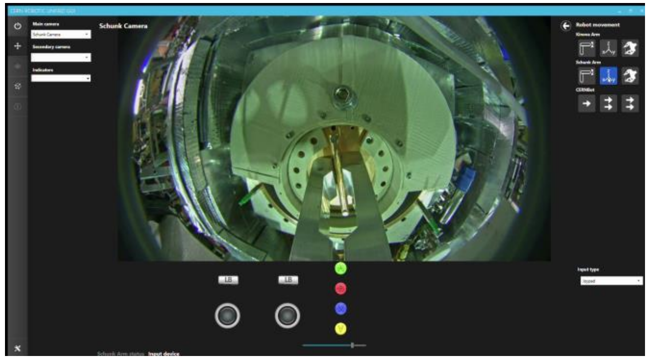


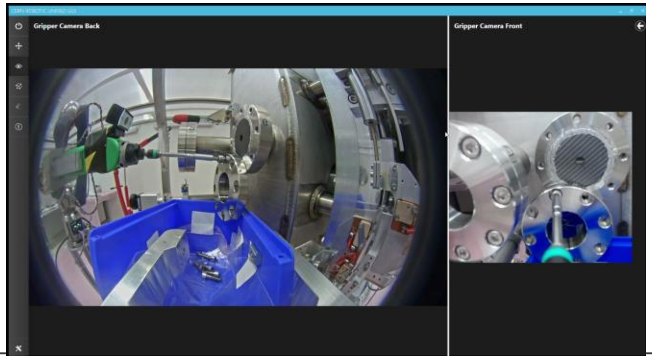
Human-Robot-Interface

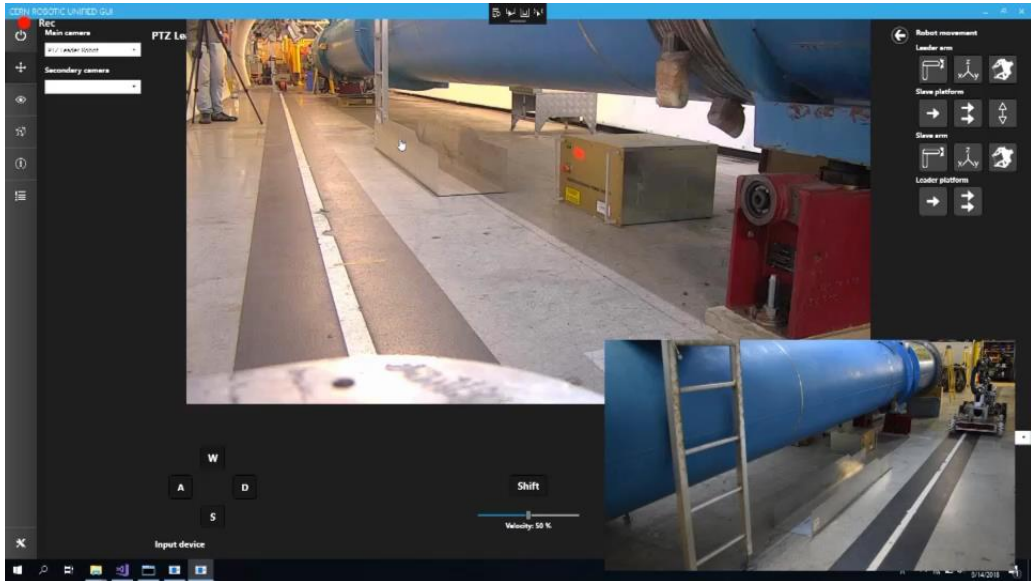
- ➢Controls all the BE-CEM robots
- ➢Includes enhanced reality modules
- ➢Different inputs device (keyboards, joystick, master arm etc.)
- ➢Operators training options
- ➢Multi screens capability
- ➢Time-delay passivation



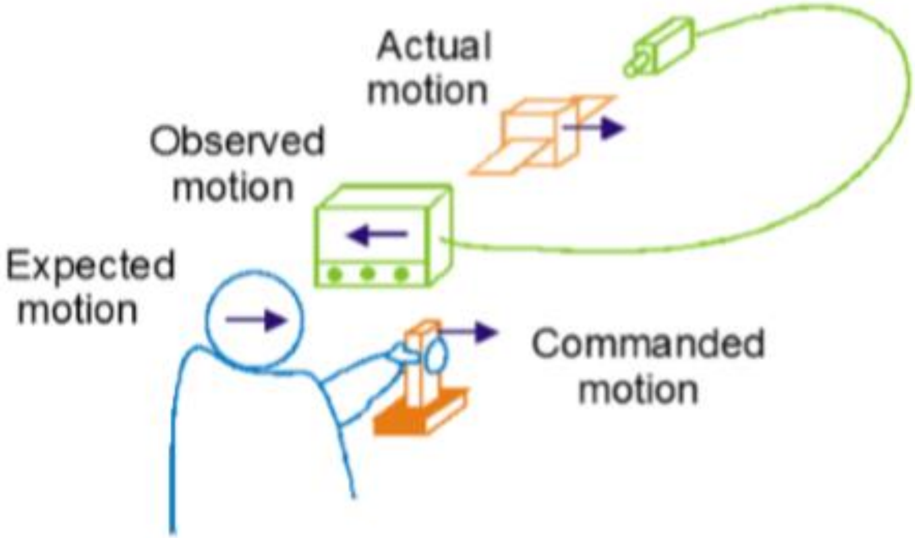




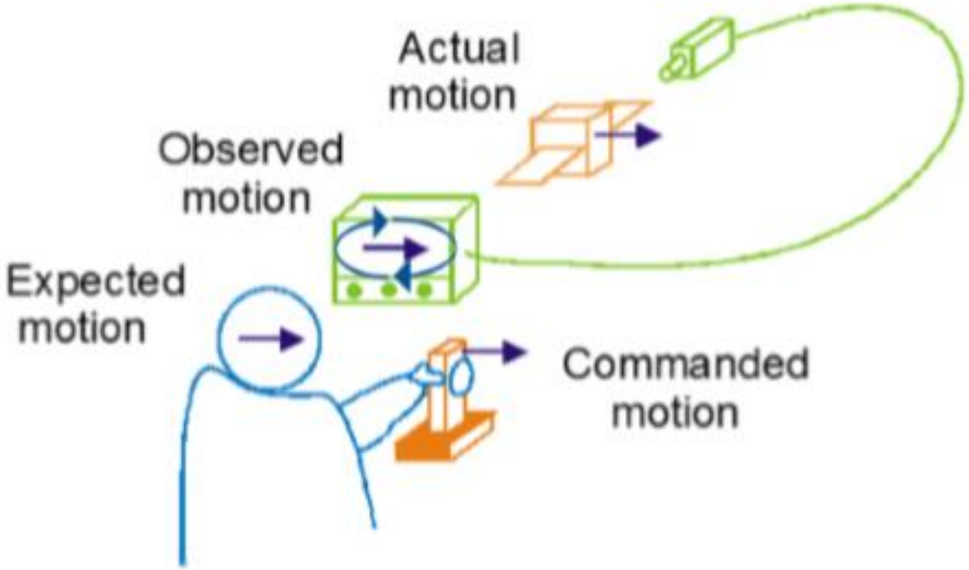




Tele-proprioception



Observational misalignment

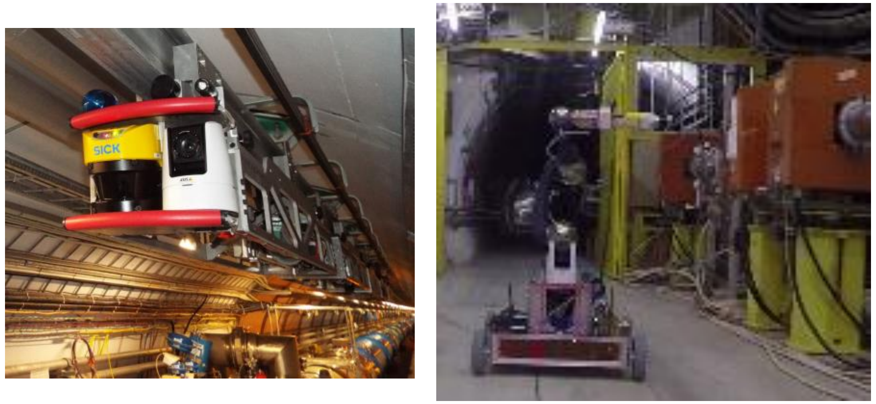


Correct proprioception

- CERNTAURO image processing module for the operator could automatically adjust the picture orientation/rotation given to the operator to increase the tele proprioception and to increase the transparency of the teleoperation system

Robotic preventive maintenance and inspection

SPS MKP oilers refill

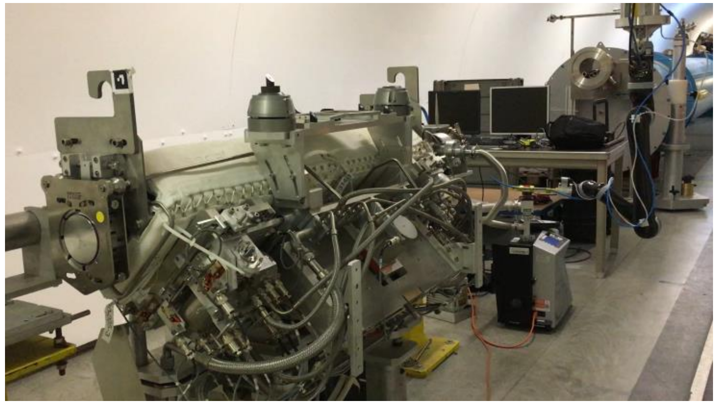


Remote radioprotection surveys

Cabling status inspection

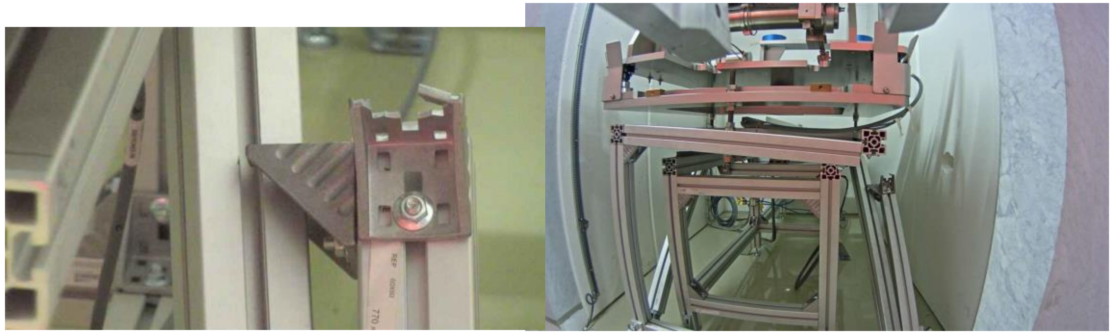
Temperature sensor installation on AD target

Tunnel structure monitoring



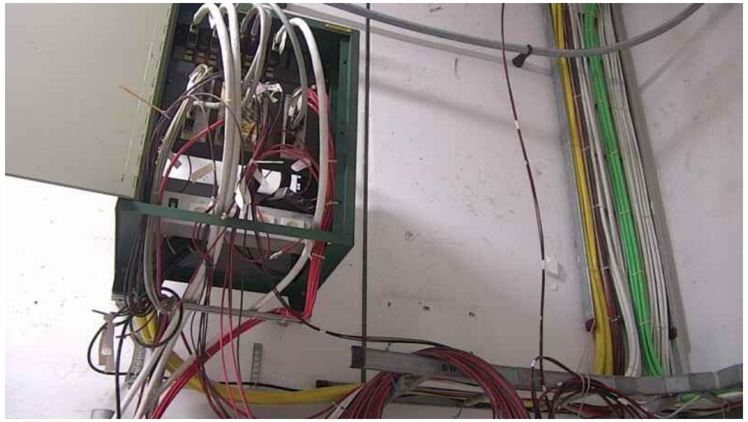
Remote Vacuum Leak detection

Fast reaction to equipment failures in radioactive areas

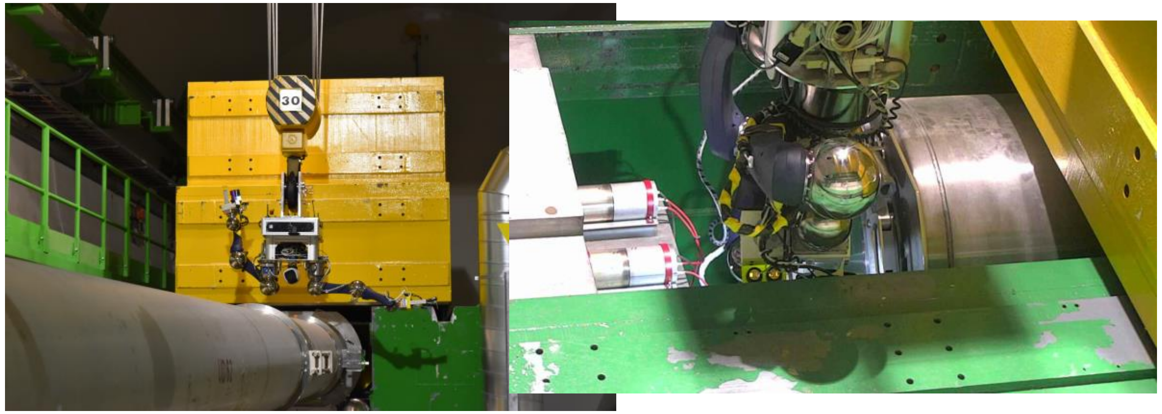


CHARM Target
In place 1 hour after the call

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

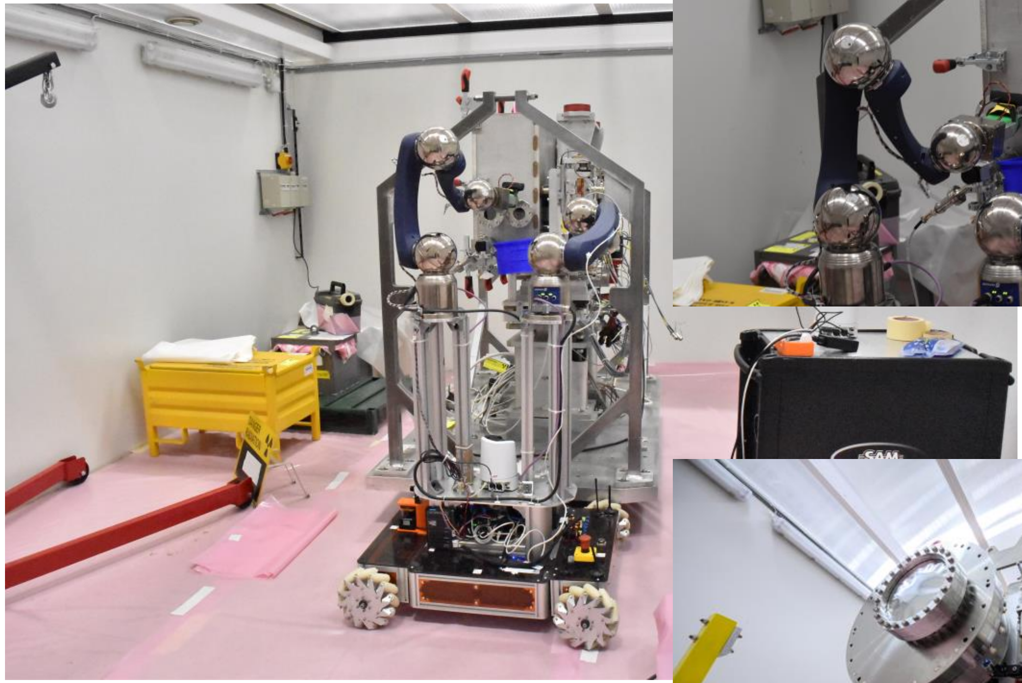


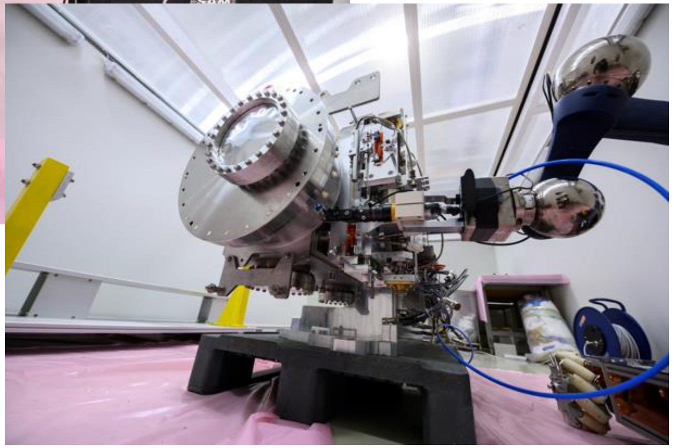
North Area BLM cables connection
In place 50 minutes after the call

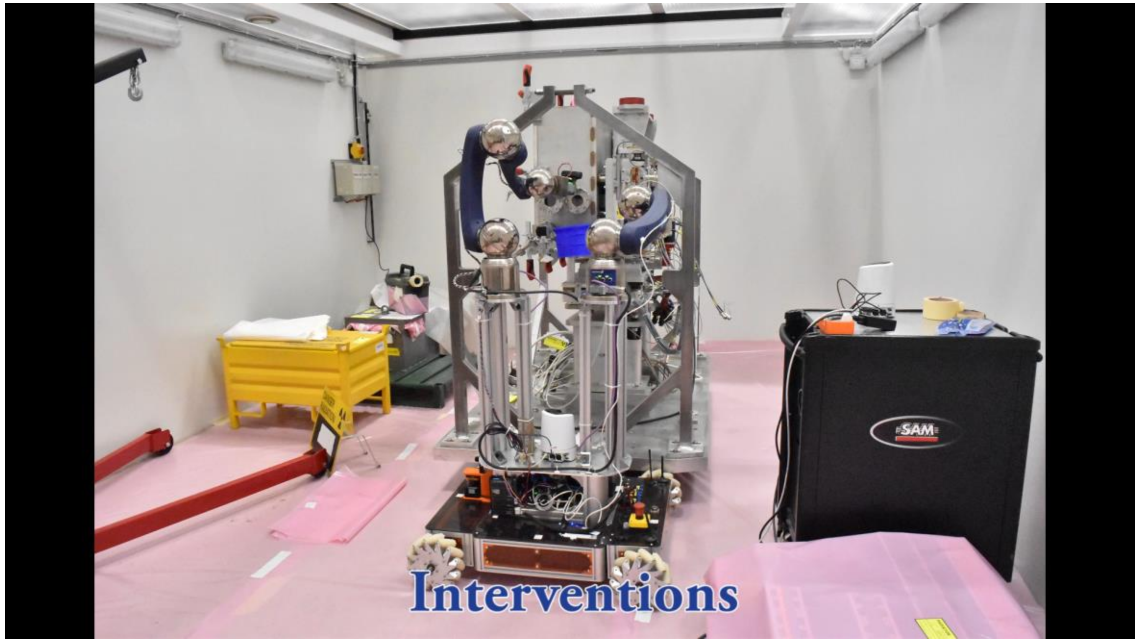


LHC TDE
New robot built in 3 days

Post-Mortem Analysis

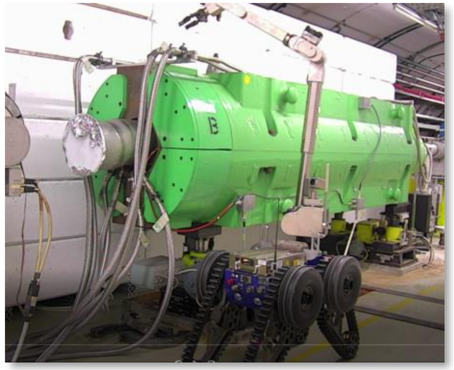


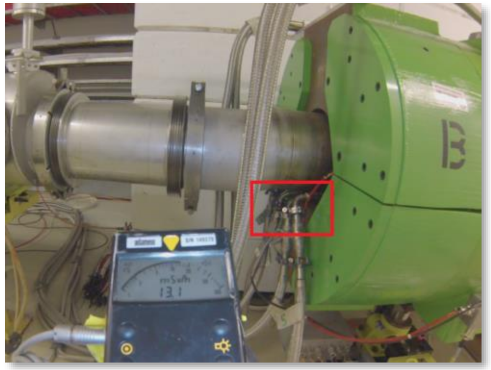


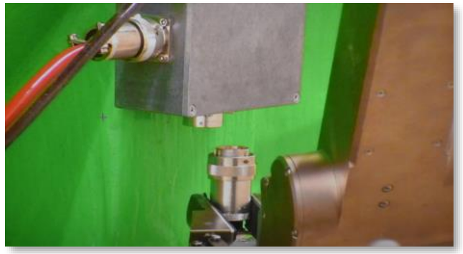


Importance of the design phase

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







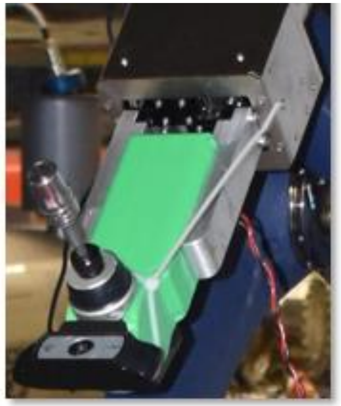
Easier remote or hands-on manipulation than chain-type connection

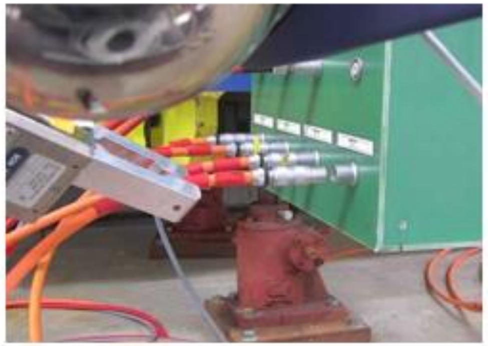
Procedures and Tools

- 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





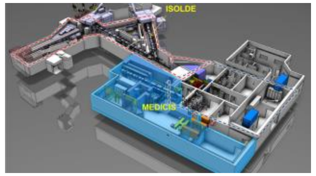



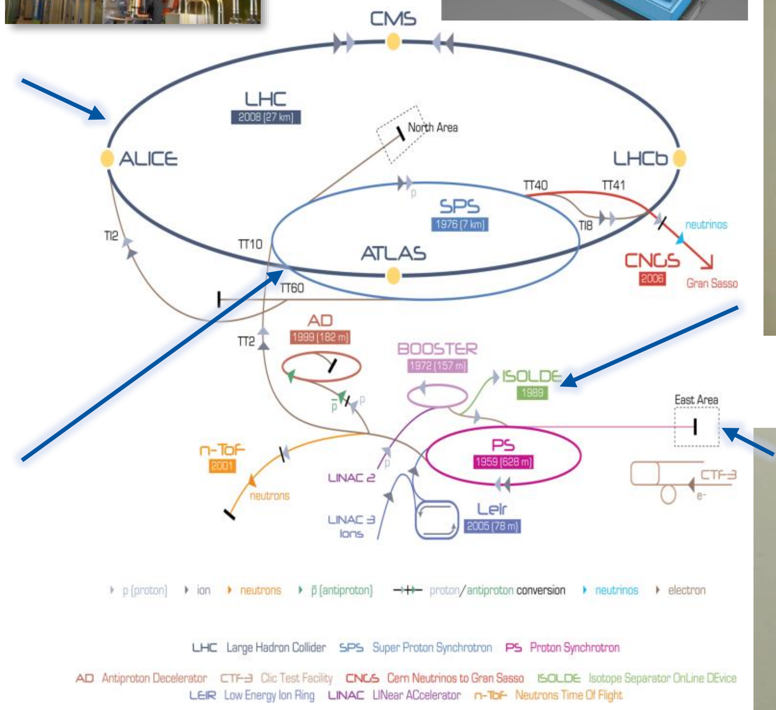


More on L. Buonocore Academic lecture, https://indico.cern.ch/event/1055745/

Main Robots integrated/controlled within facilities at CERN

TIM (x4)





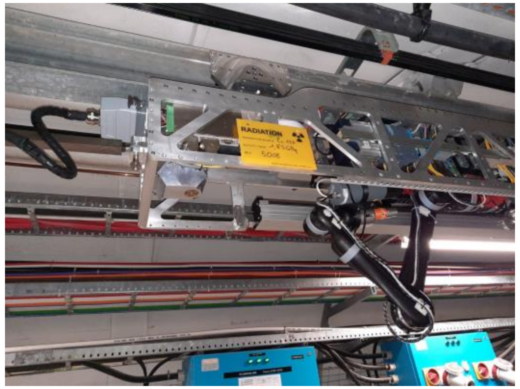
Kuka Robots (x3), Collaboration with EN-HE

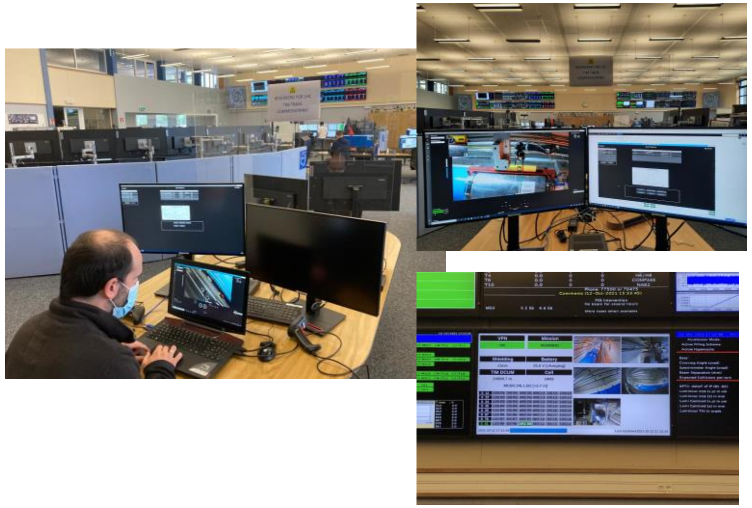
MIRA - CERNbot

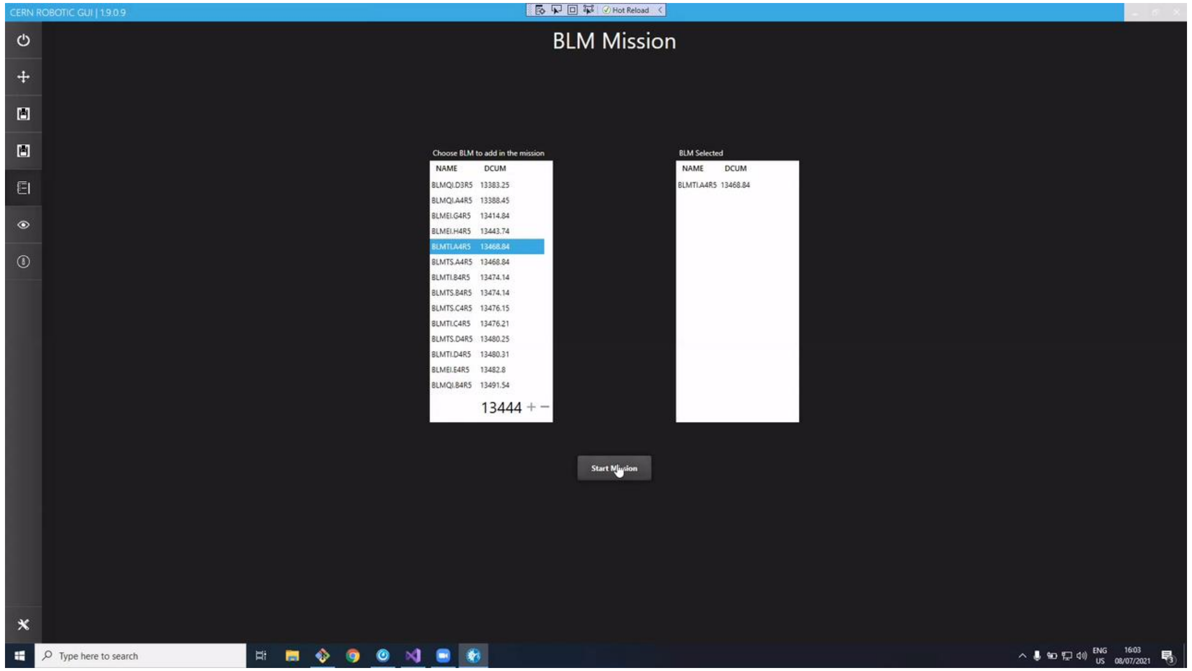
CHARMbot

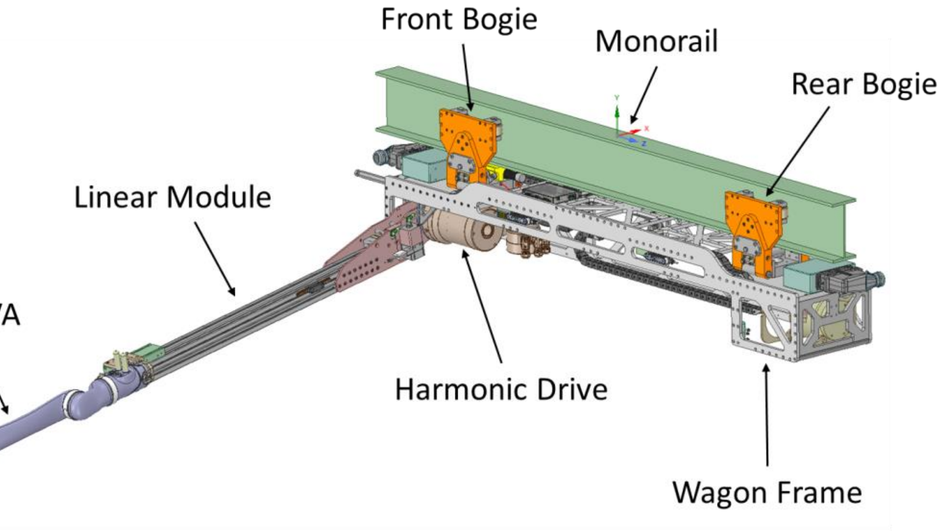
Novel TIM robotic wagon

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



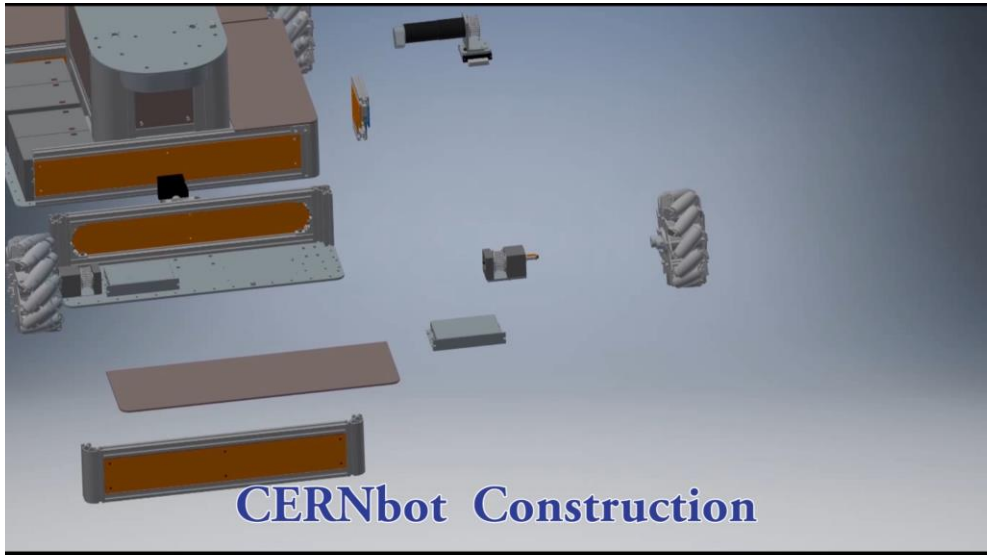


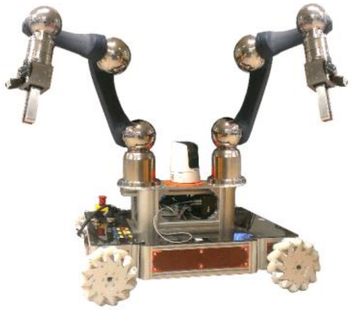


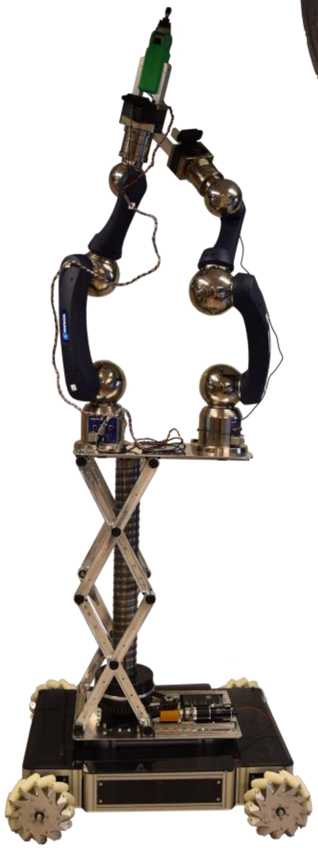


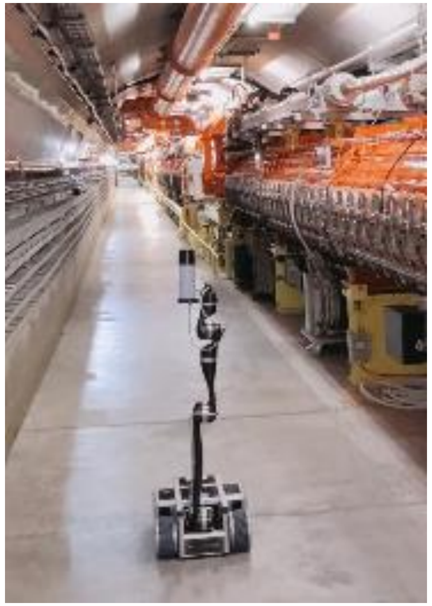
New TIM robotic wagon with extracted arm

Modular Robot/Concept (CERNbot)





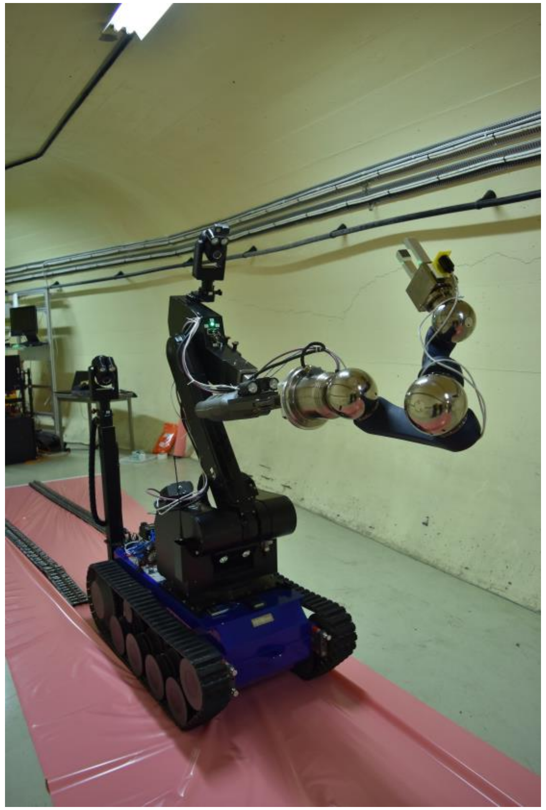


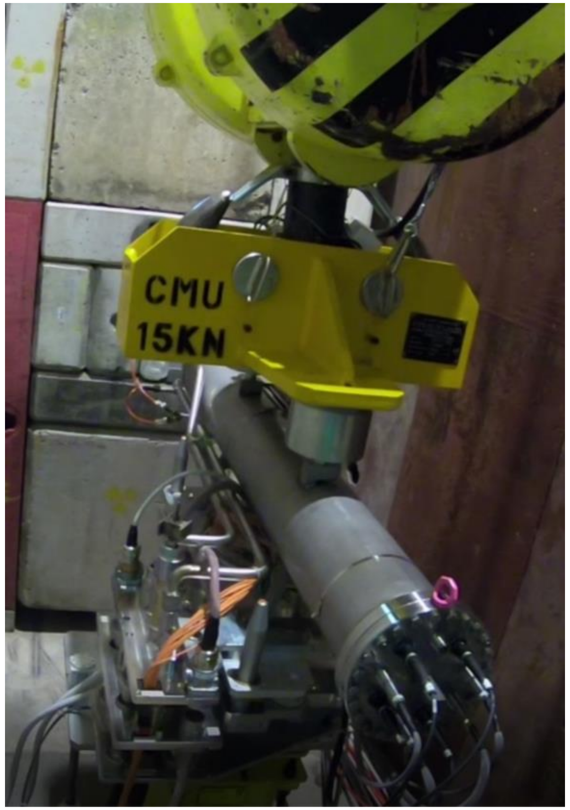


CERNbot, CERNbot2, CHARMbot, MIRA, CRANEbot

Modular Controls

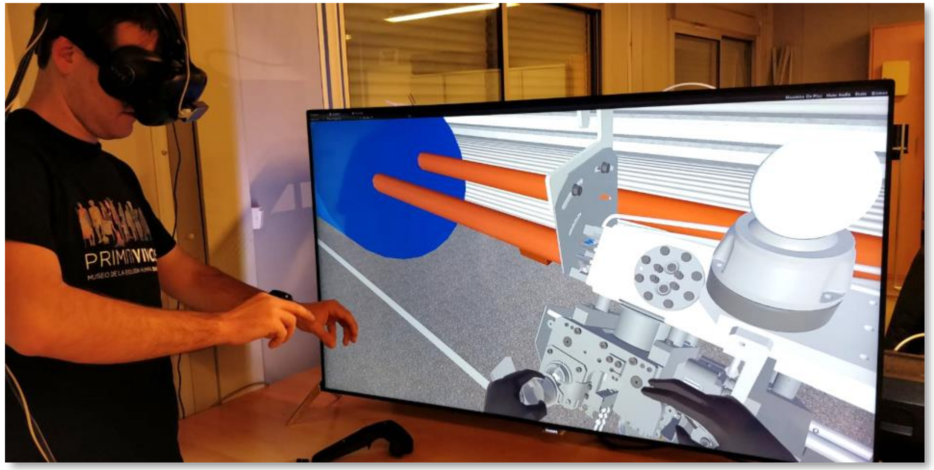
- Particle beam target maintenance, **integration of CERNTAURO on industrial robot**
  - ✓ **CERNTAURO adaptability → seamless control of multi-robots**
  - ✓ Manipulation from unstable support

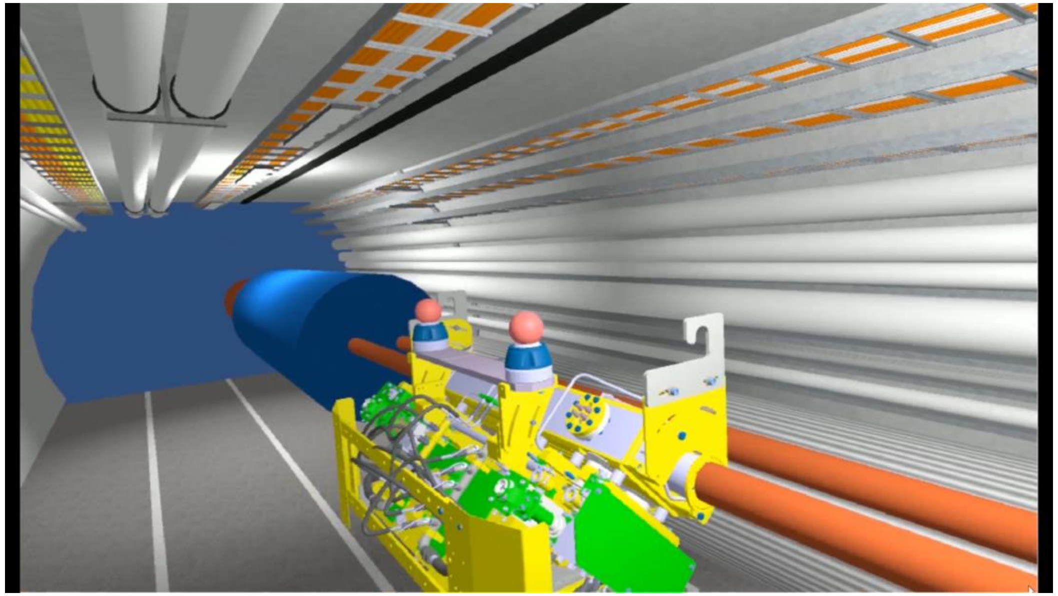




Current use of Enhanced Reality in BE-CEM

- 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

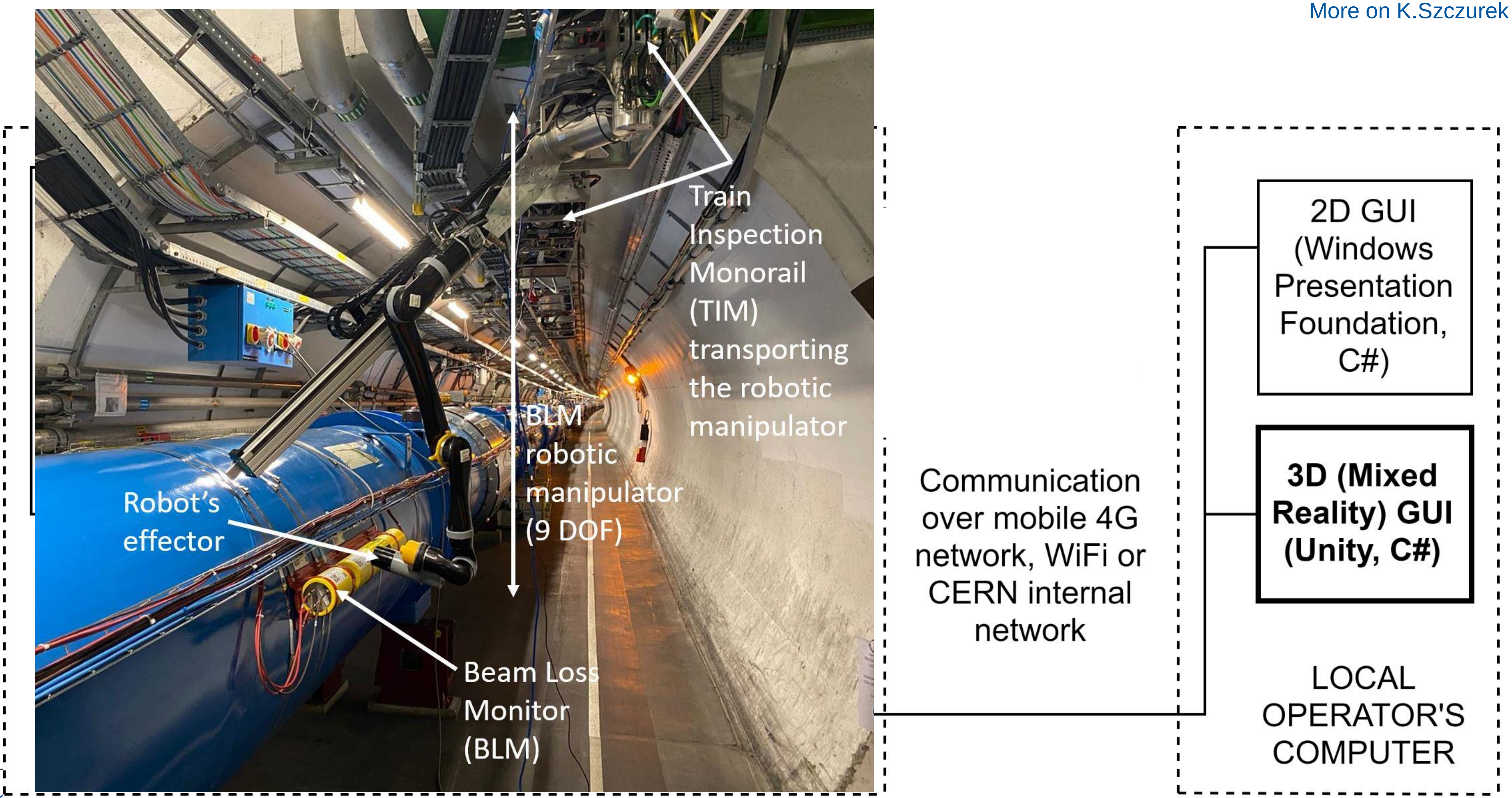




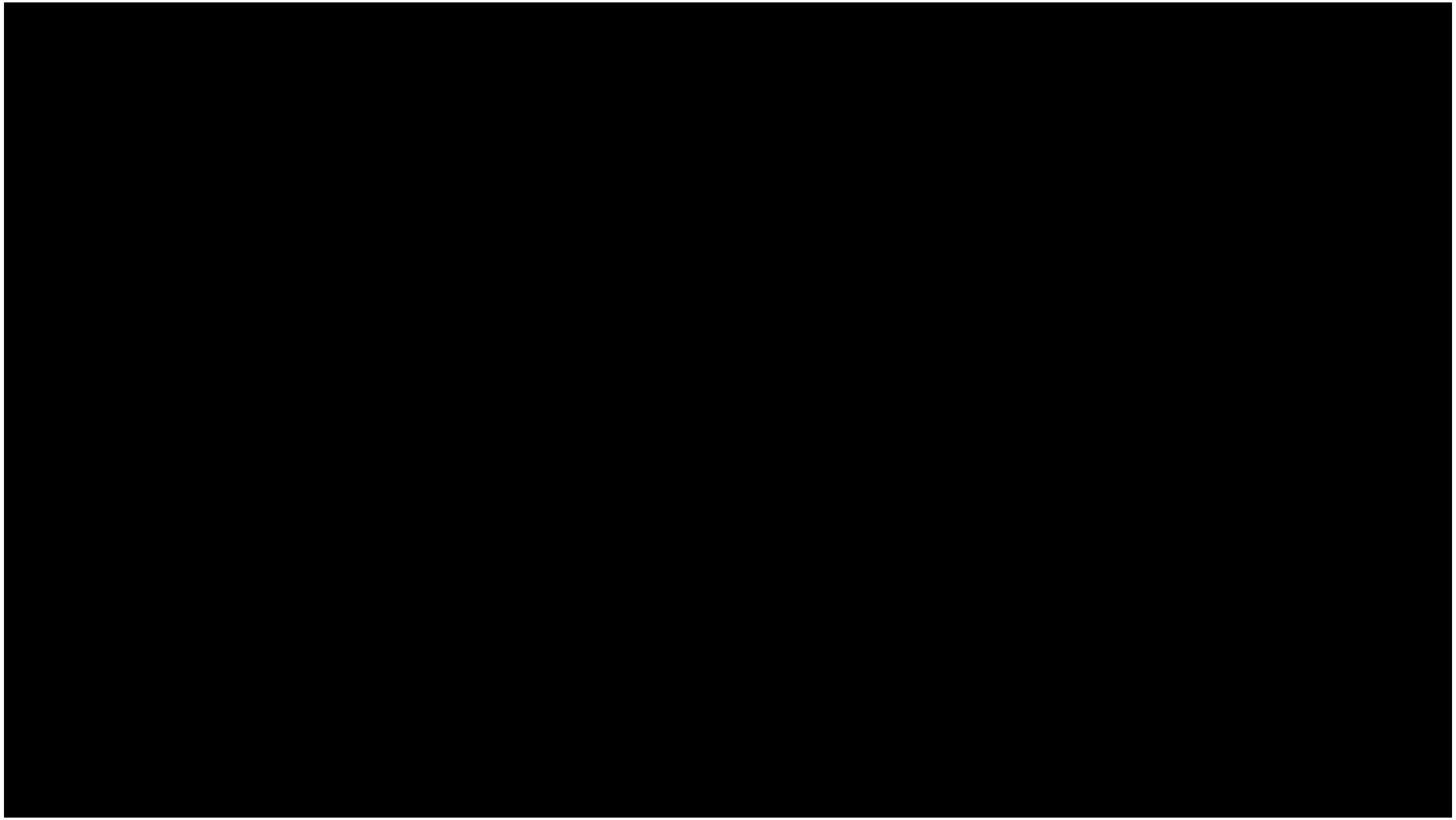
More on K. Szczurek Academic lecture https://indico.cern.ch/event/1055745/

Mixed Reality Human-Robot Interface

More on K.Szczurek lecture

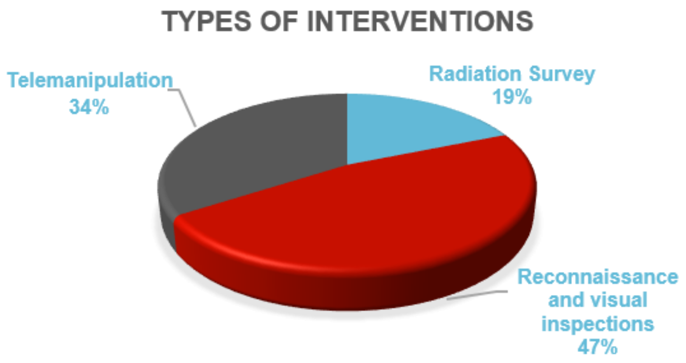


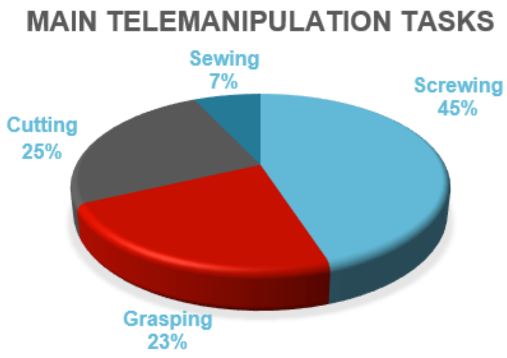
Mixed Reality Human-Robot Interface



Robotics Interventions

Nr. of Interventions since 2014	Nr. of tasks performed	Robot operation time in harsh environment [h]
150	~500	~ 500



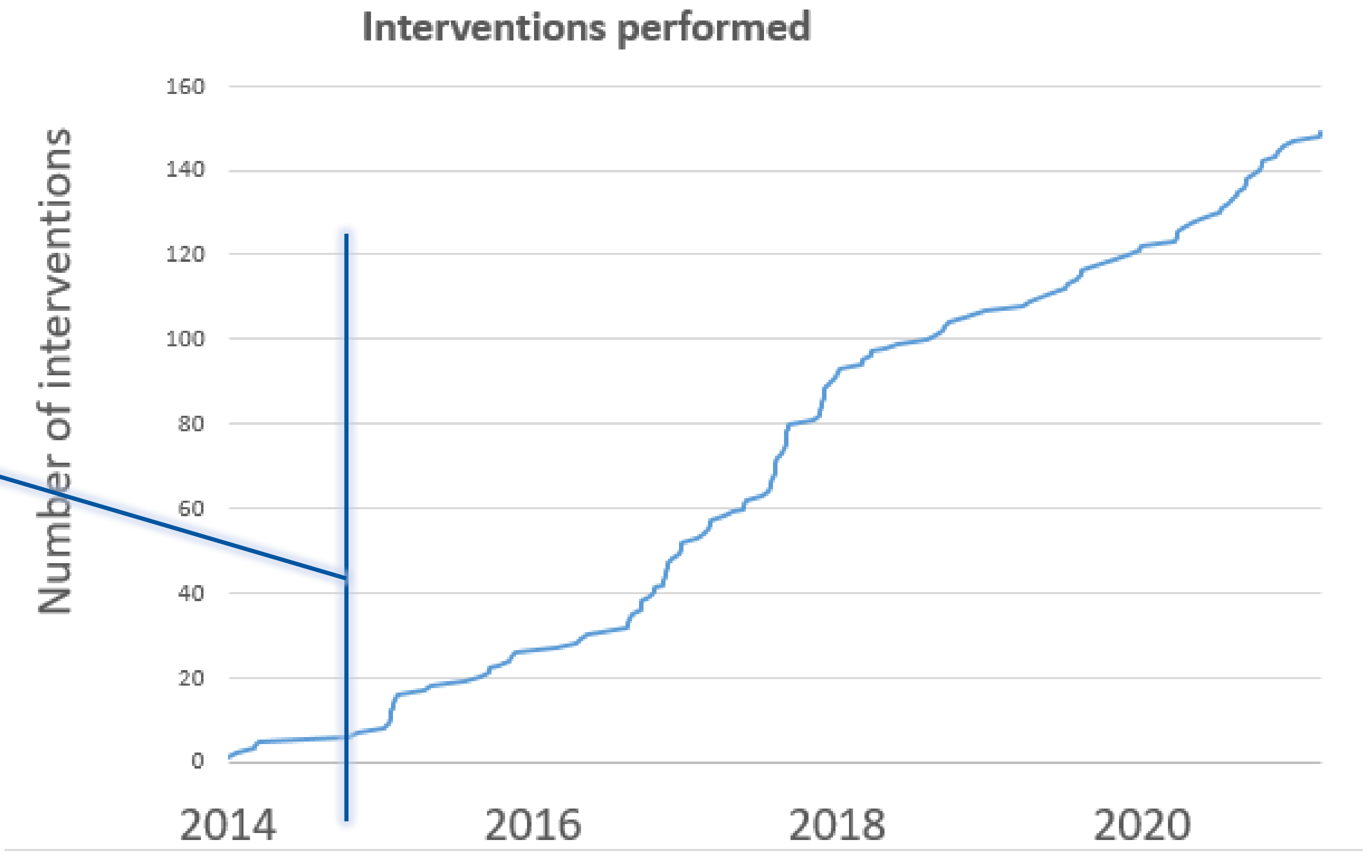


Remote maintenance test facility (b927)

Continuing developing best practice for equipment design and robotic intervention procedures and tools including recovery scenarios.
ITHACA HL-LHC WG (https://edms.cern.ch/document/2067140/1.0/**)**

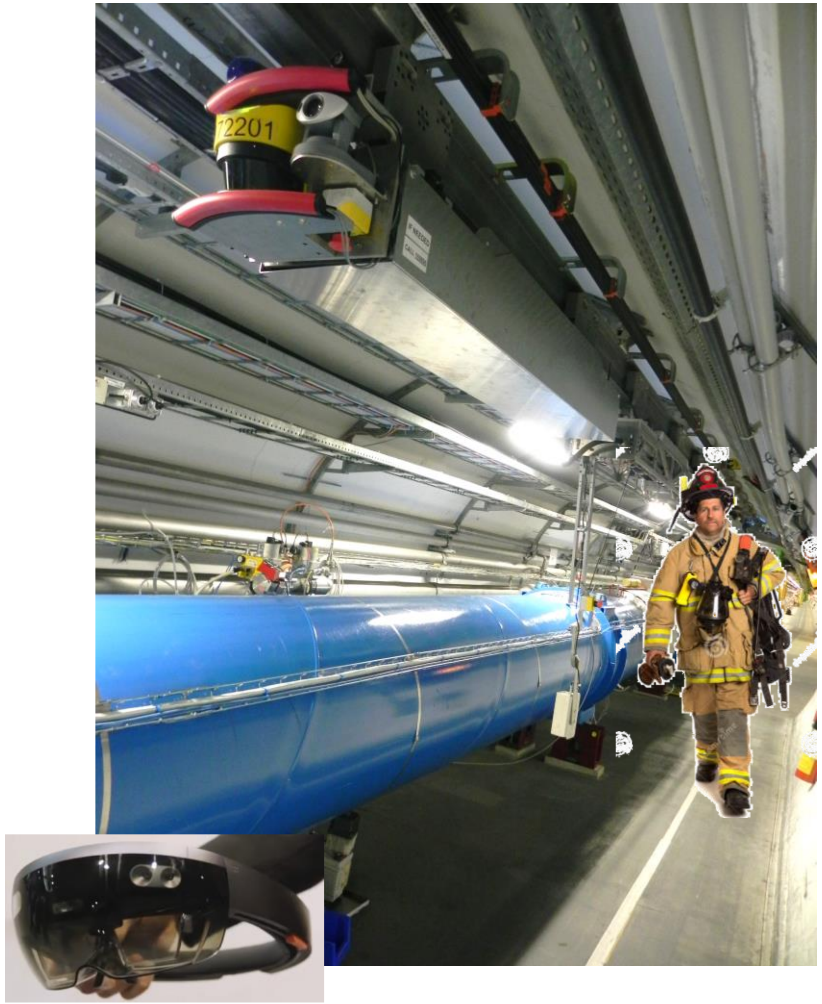
Robotic Support at CERN

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



Early intervention robots

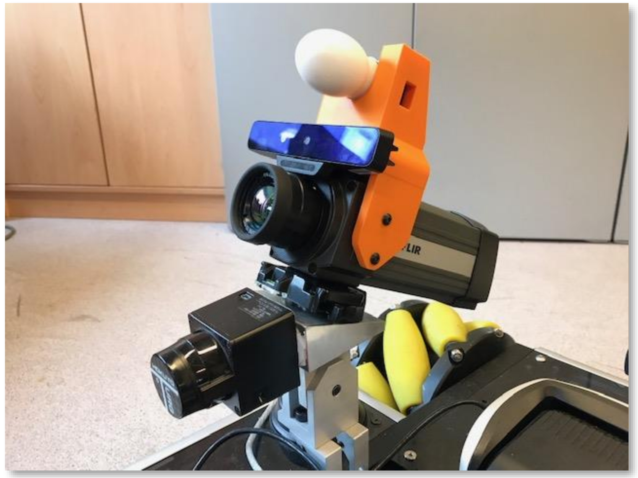
- **With such large distances, early intervention systems are necessary for example in case of accident or fire**
  - ✓ **Human fire response** (Fire Service) in accelerator facilities is judged **fundamental but not enough** due to response delay, personal risk assessment and reliability.
    - ❖ **Robotic** 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.**



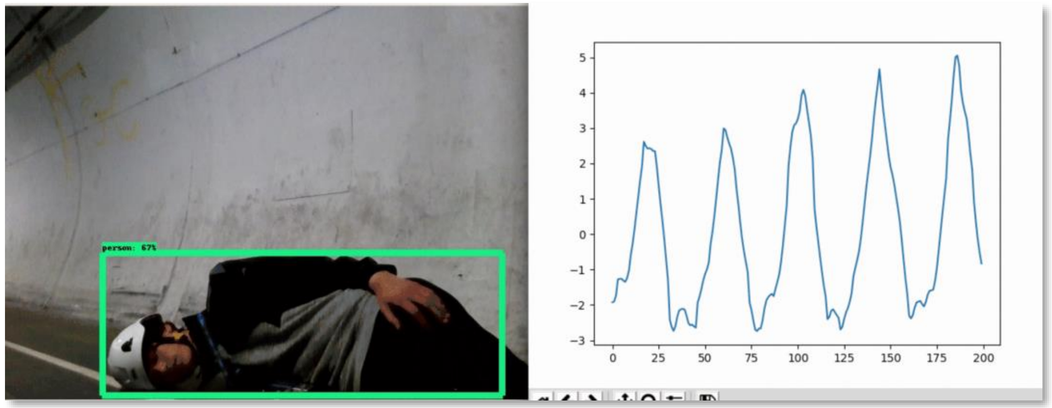
Collaboration with HSE-FRS

People recognition and vital monitoring

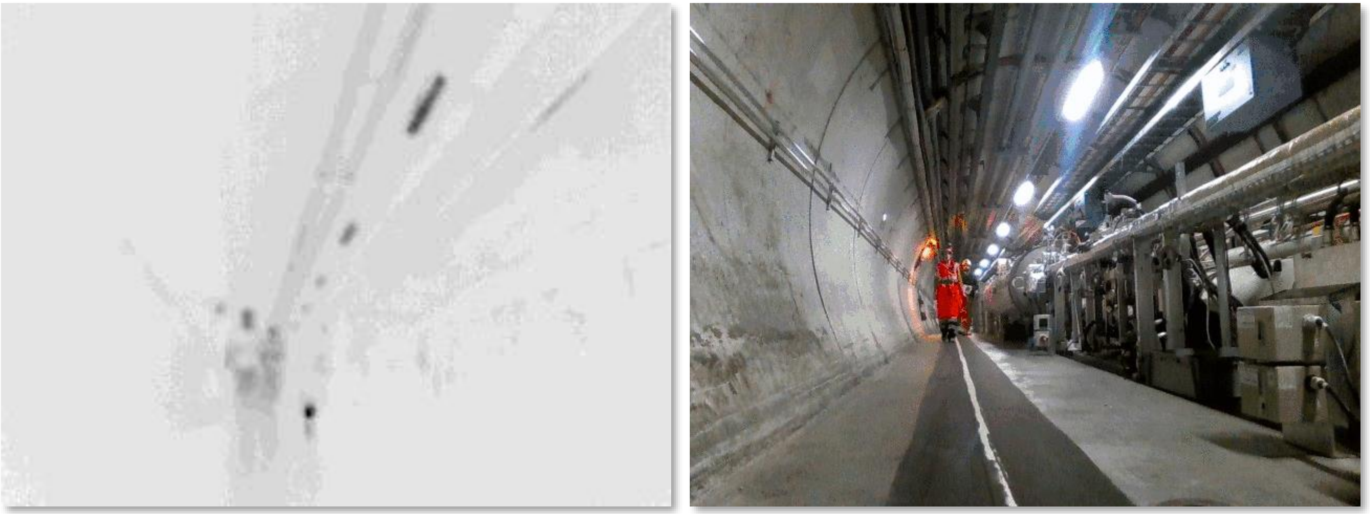
- Machine learning techniques enhance people detection and vital signals monitoring at distance
- People search and rescue is of primary interest in disaster scenarios
- People monitoring during rehabilitation



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

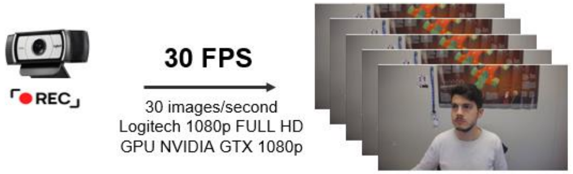


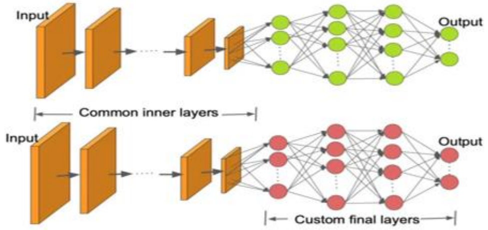
Online respiration monitoring

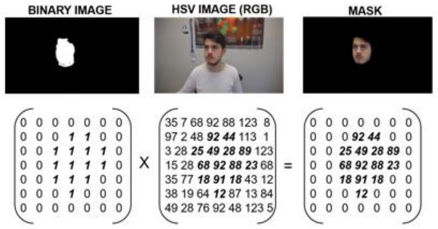


Online people recognition and tracking

MARCHESE project: Health Contactless Monitoring







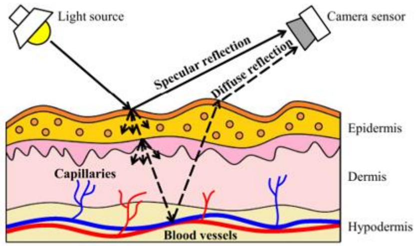
SKIN PIXELS
NO-SKIN PIXELS

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

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

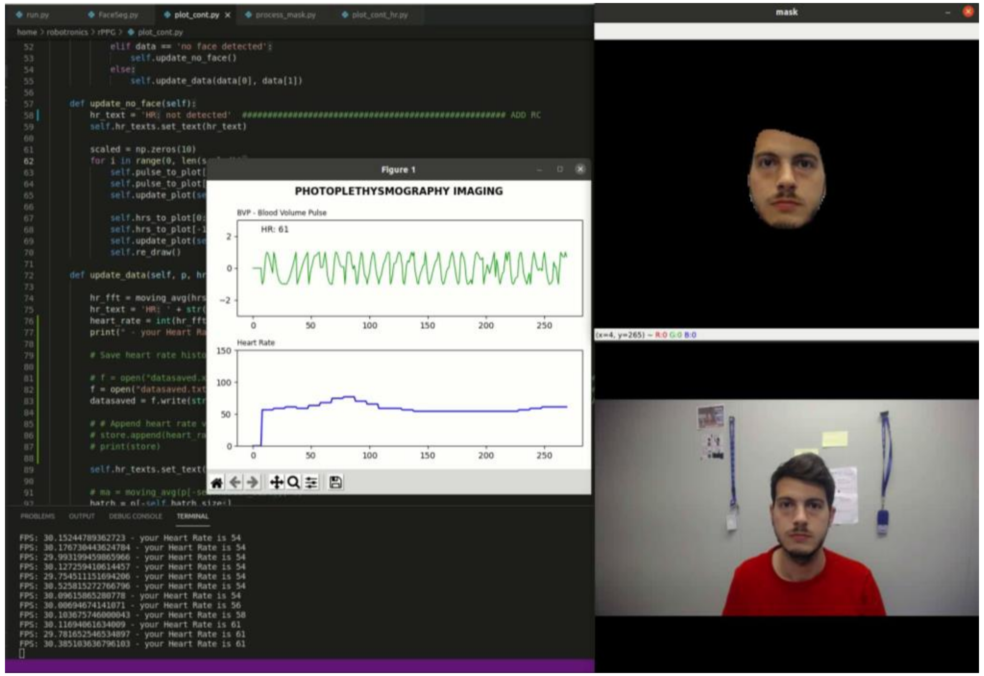
SPECULAR REFLECTION is a mirror-like light reflection from the skin surface (not contain any pulsatile information). Time dependent: body motion influence.

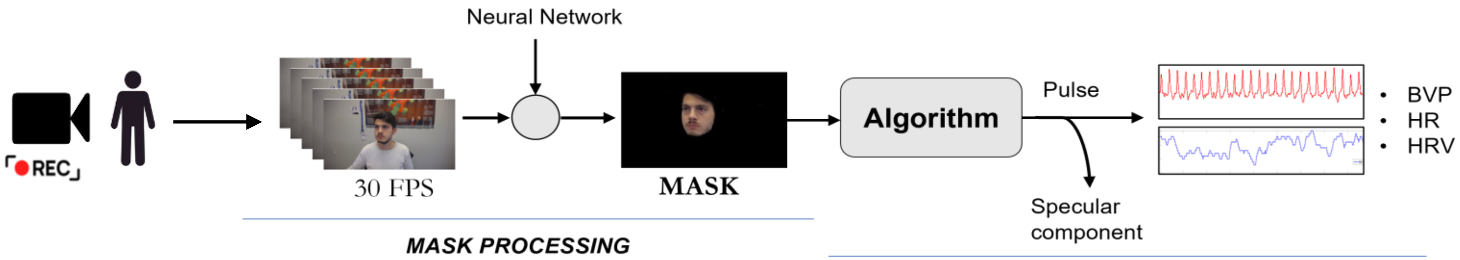
DIFFUSE REFLECTION is associated with the absorption of the light in skin tissues. The hemoglobin contents in skin tissues lead to a specific chromaticity.



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**





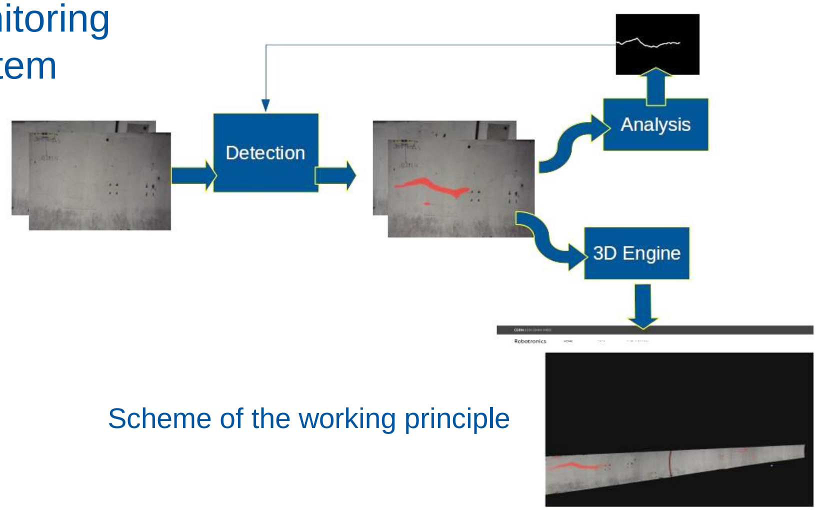
In collaboration and funded by KT group

Online Tunnel Structure Monitoring

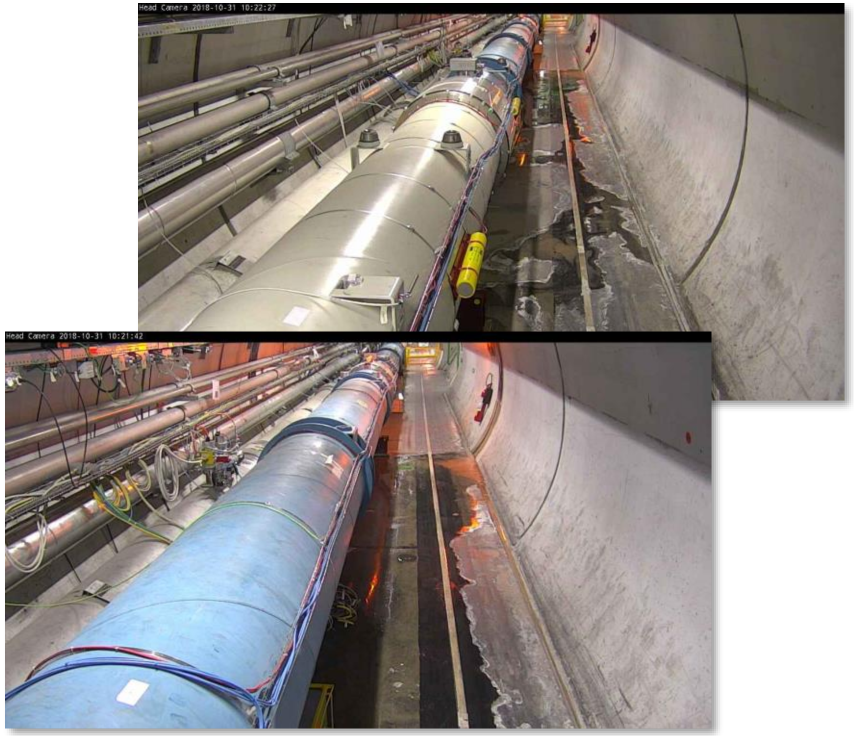
Collaboration with SCE-DOD

- Detects defects (cracks, water leaks, changes) using a Mask-RCNN network.
- High-definition picture collection using TIM and CERNBot
- 3D reconstruction of wall using Structure from Motion techniques to compare time evolution of defects (available on web browser or virtual reality headset)
- **HL-LHC condition survey of existing infrastructure carried out with TIM to monitor impact of new civil works**

Structural Health Monitoring System

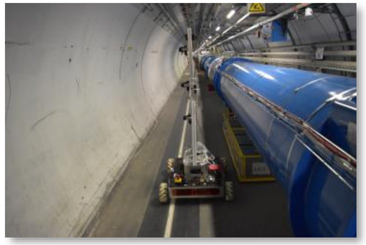


Scheme of the working principle

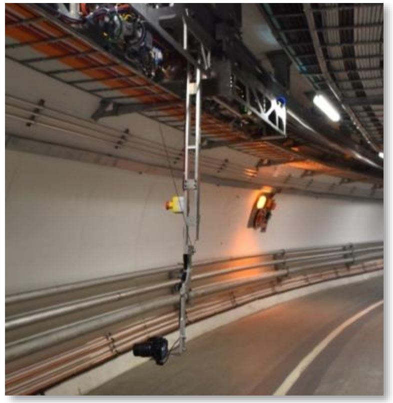


Example of water leak found by TIM2 during TS3 2018

HD camera system for tunnel dome view



System integrated also on other robots

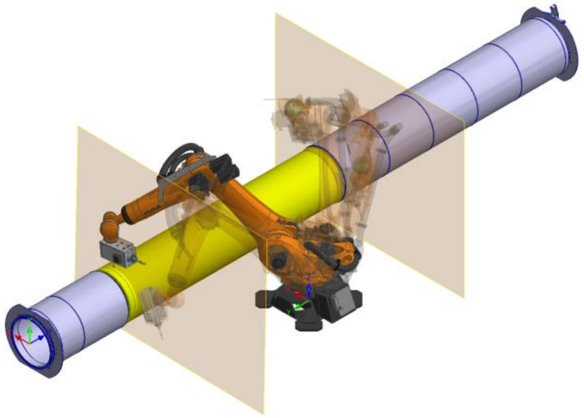


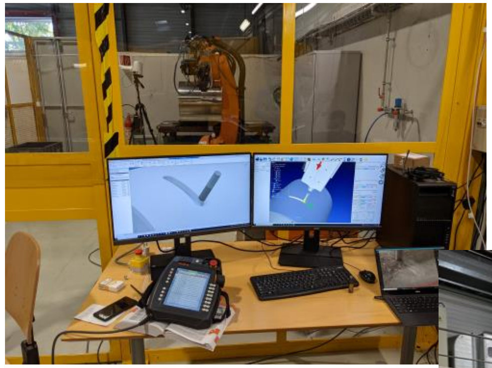
HD cameras mounted on TIM

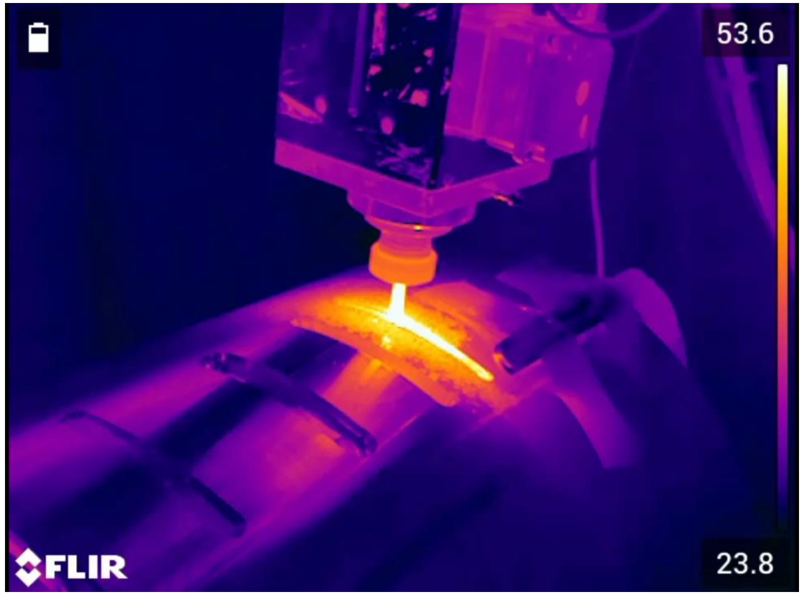
Example of crack found using vision based machine learning techniques

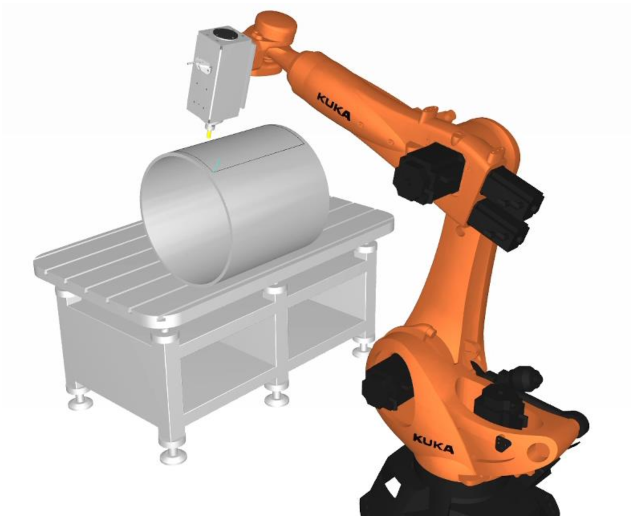
Robotics used for postmortem analysis

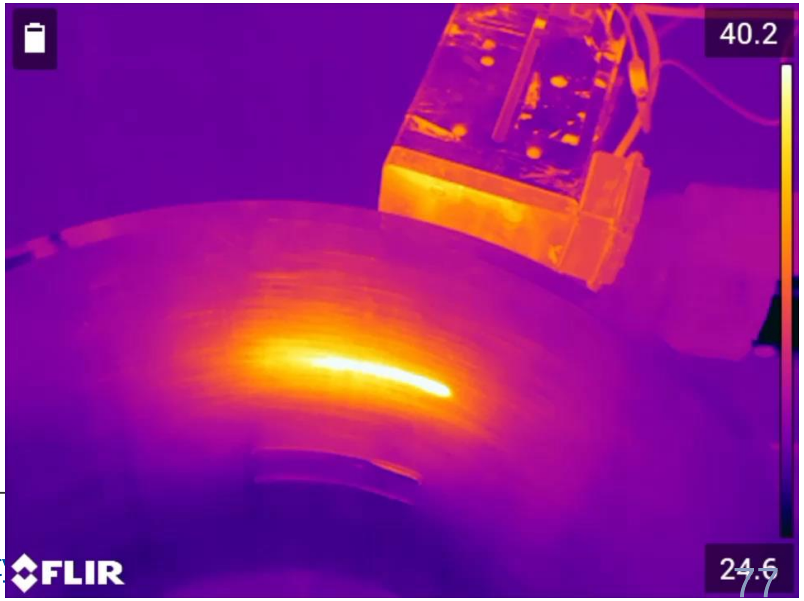
- Robotic milling to machine stainless steel, aluminum, iron etc.











Robot realized for Quality assurance: RF cavity visual inner inspection

- ✓ Automatic system
- ✓ 8-10h hours of scan per part
- ✓ ~19’000 photos per scan
- ✓ ~1.5 Tb data per scan
- ✓ Anti-collision system based on lasers
- ✓ High resolution camera and Liquid lens
- ✓ System unique in the world

- **Defintions**

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

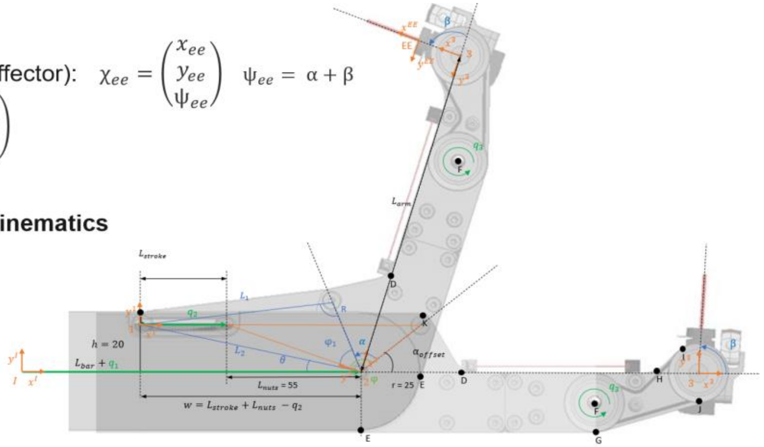
Joints Space: $q_{ee} = \begin{pmatrix} q_1 \\ q_2 \\ q_3 \end{pmatrix}$

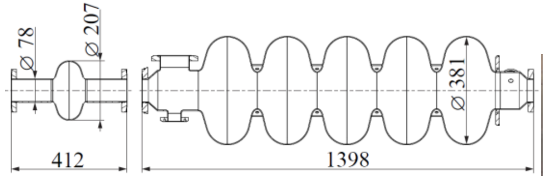
- **Forward & Inverse Kinematics**

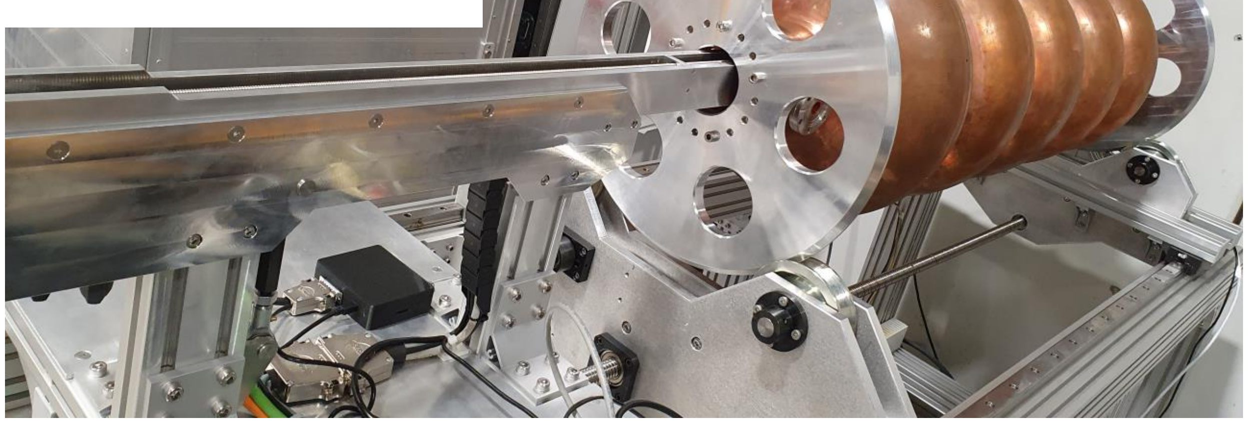
$\dot{\chi}_{ee} = J_A(q)\,\dot{q}$

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

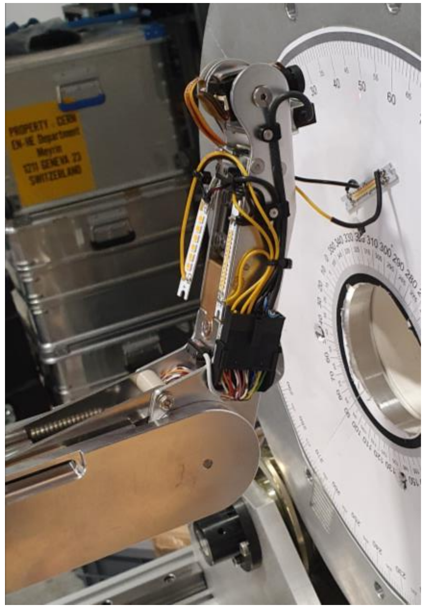
$qNext \cong qActual + \Delta q$

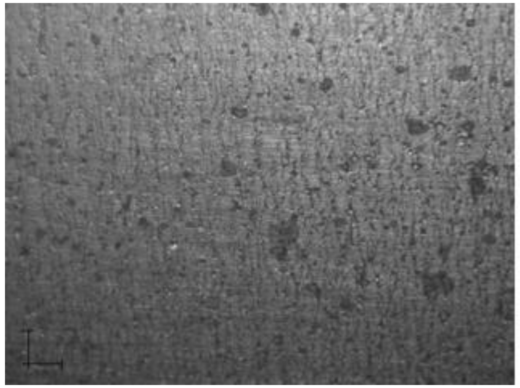






Collaboration with SY-RF, Courtesy of A. Luthi

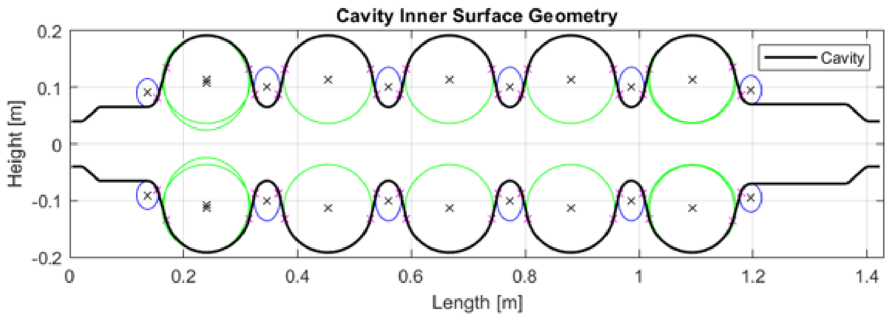




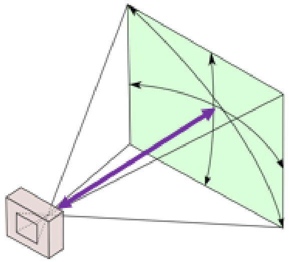
Images size: 1 x 1 cm taken at 23 mm distance

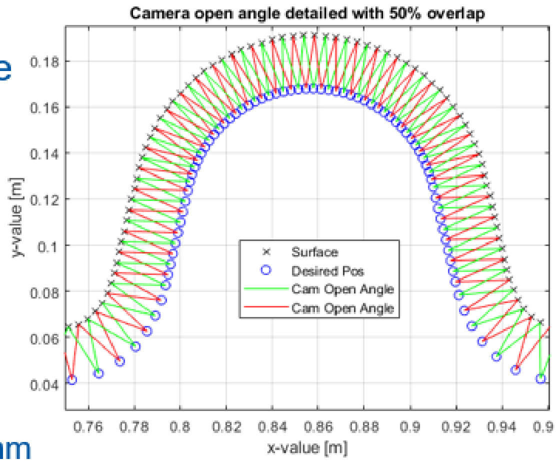
Design and robotic trajectory optimization

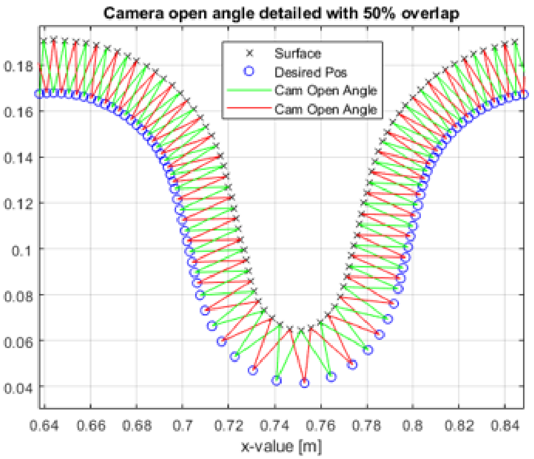
1) Cavity Inner Surface Reconstruction (based on fabrication drawings)



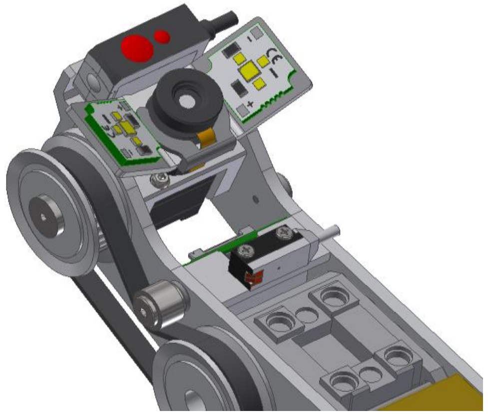
2) Trajectory Generation
- Perpendicular to the surface
- 30% of overlap



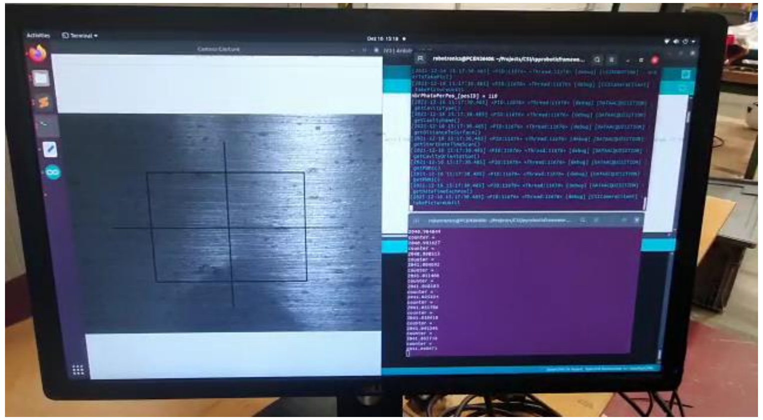




- Camera Working distance: 23mm

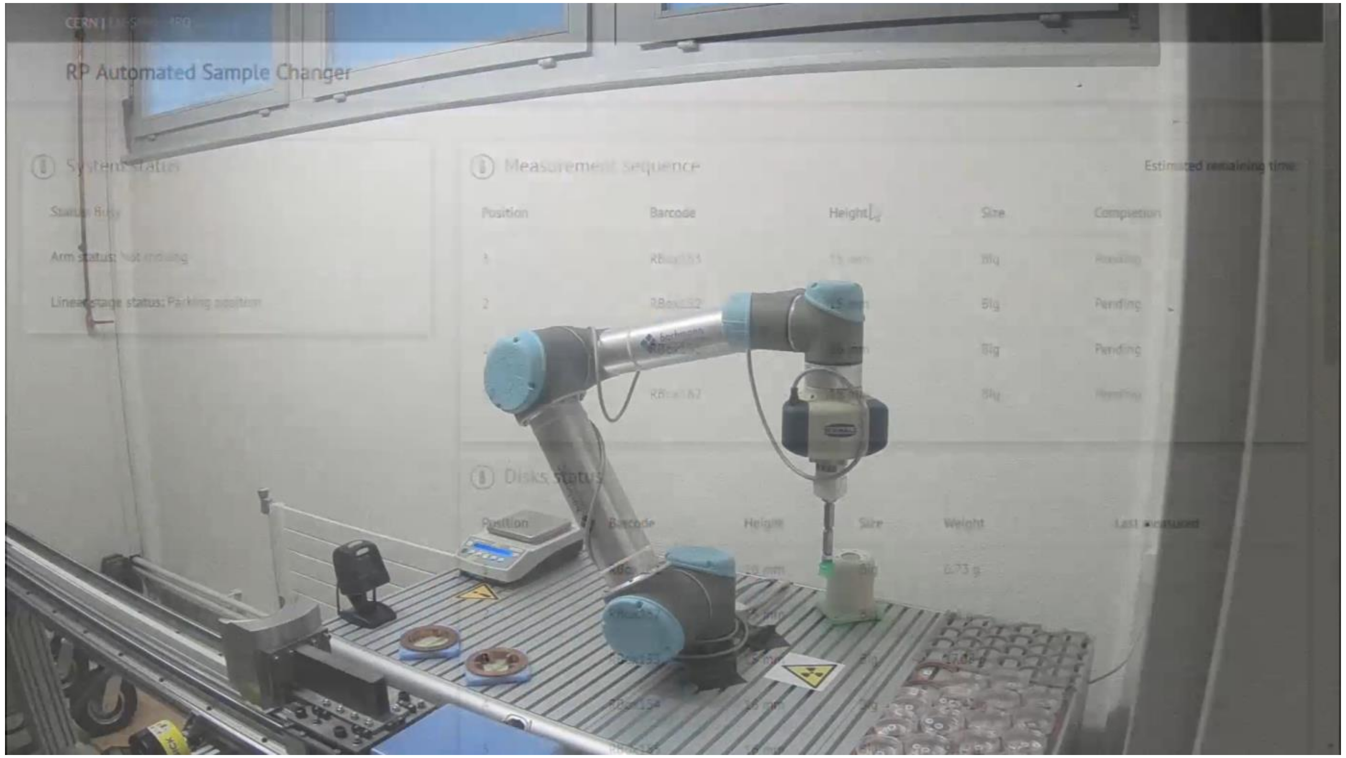


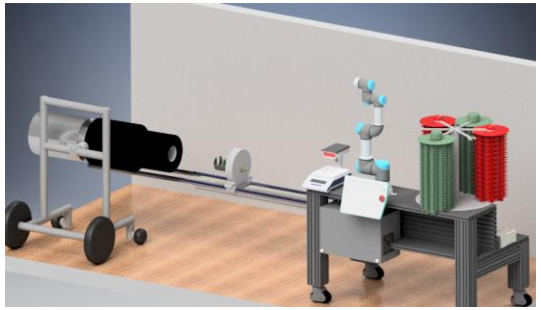
New light system design (camera triggered LED flash)

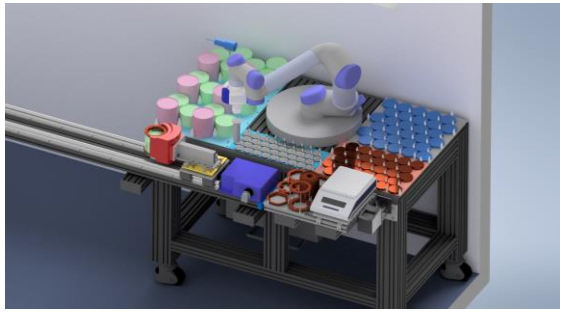


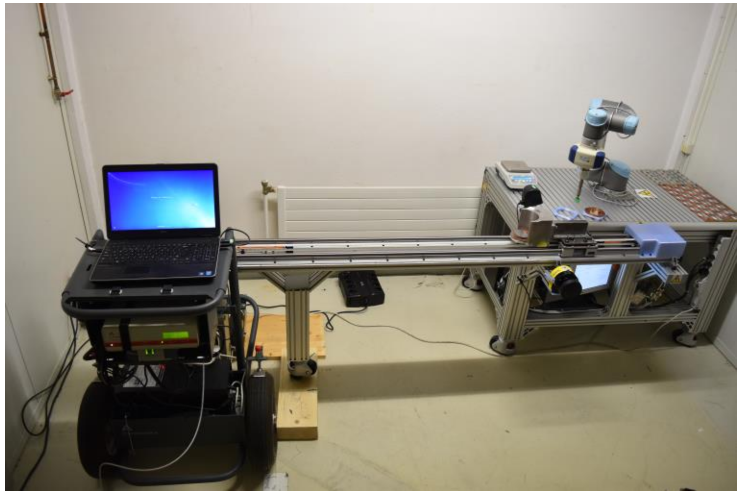
Quality control for RP sample positioning

- RP sample changer enhances throughput for spectrographic analysis of samples
- Supervised deep learning helps in ensuring heterogeneous sample position for measurement quality control









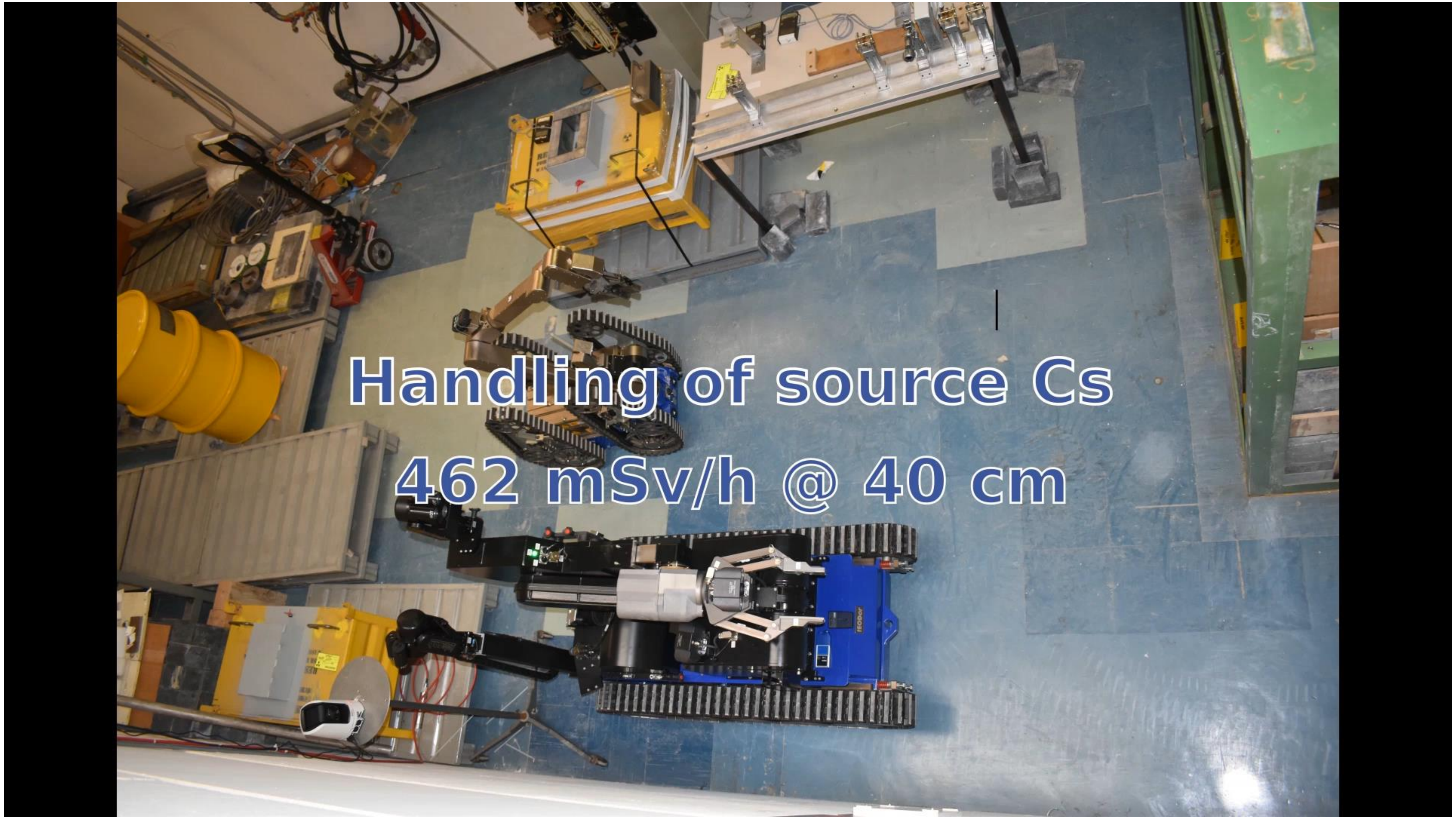
Collaboration with HSE-RP

Content

- Introduction to robotics
- Needs and challenges for robotics at CERN
- The robotic service in BE-CEM
- Some challenging robotic missions
- Future objectives
- Conclusions

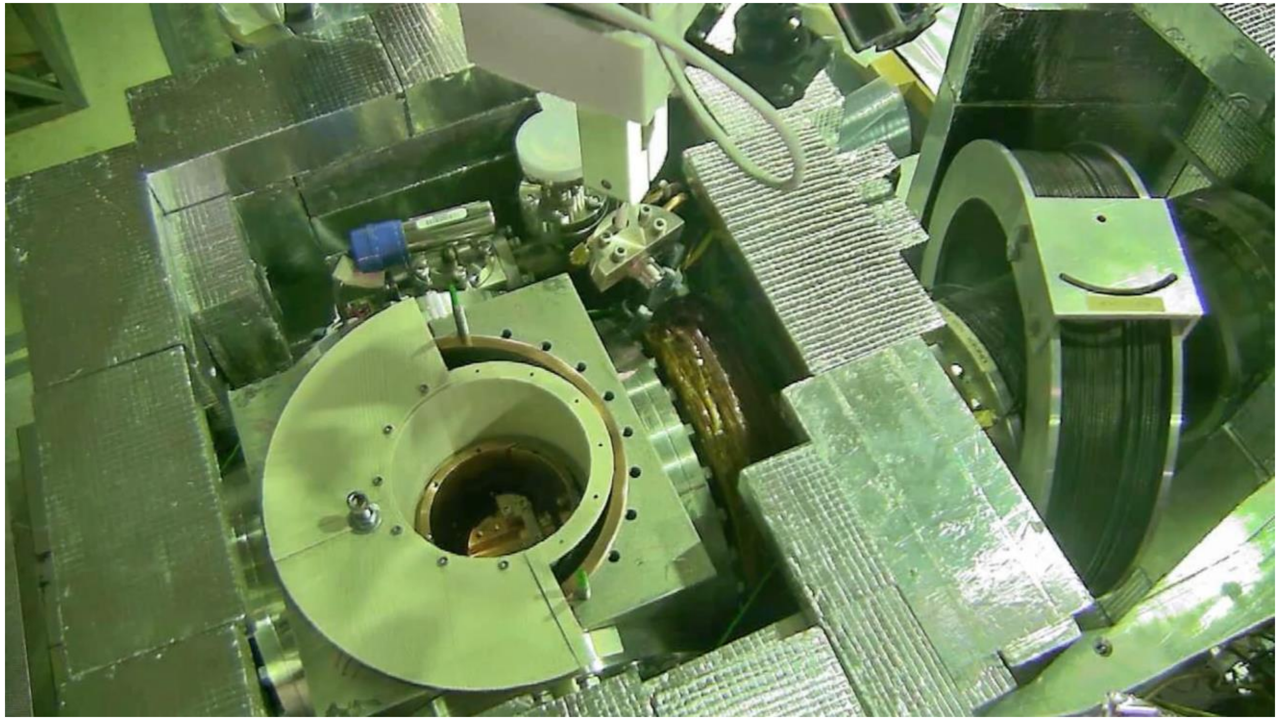
Intervention done in 2015

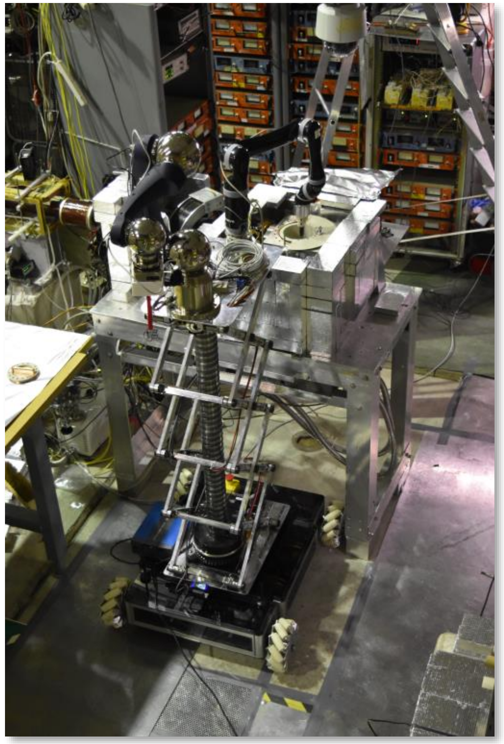
Intervention done in 2015, b172

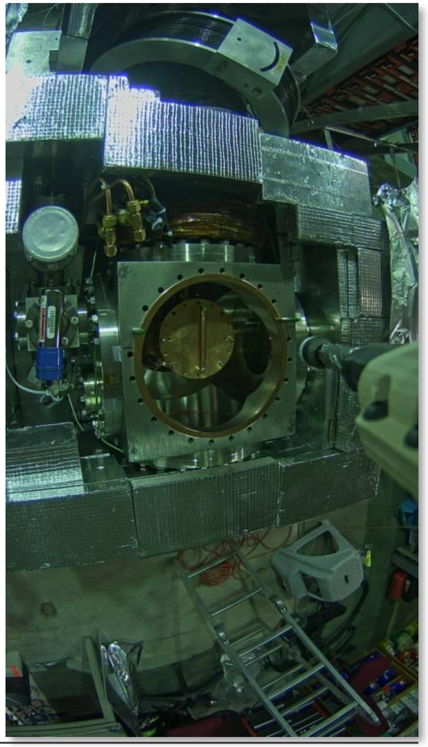


Challenging Teleoperation Example#1

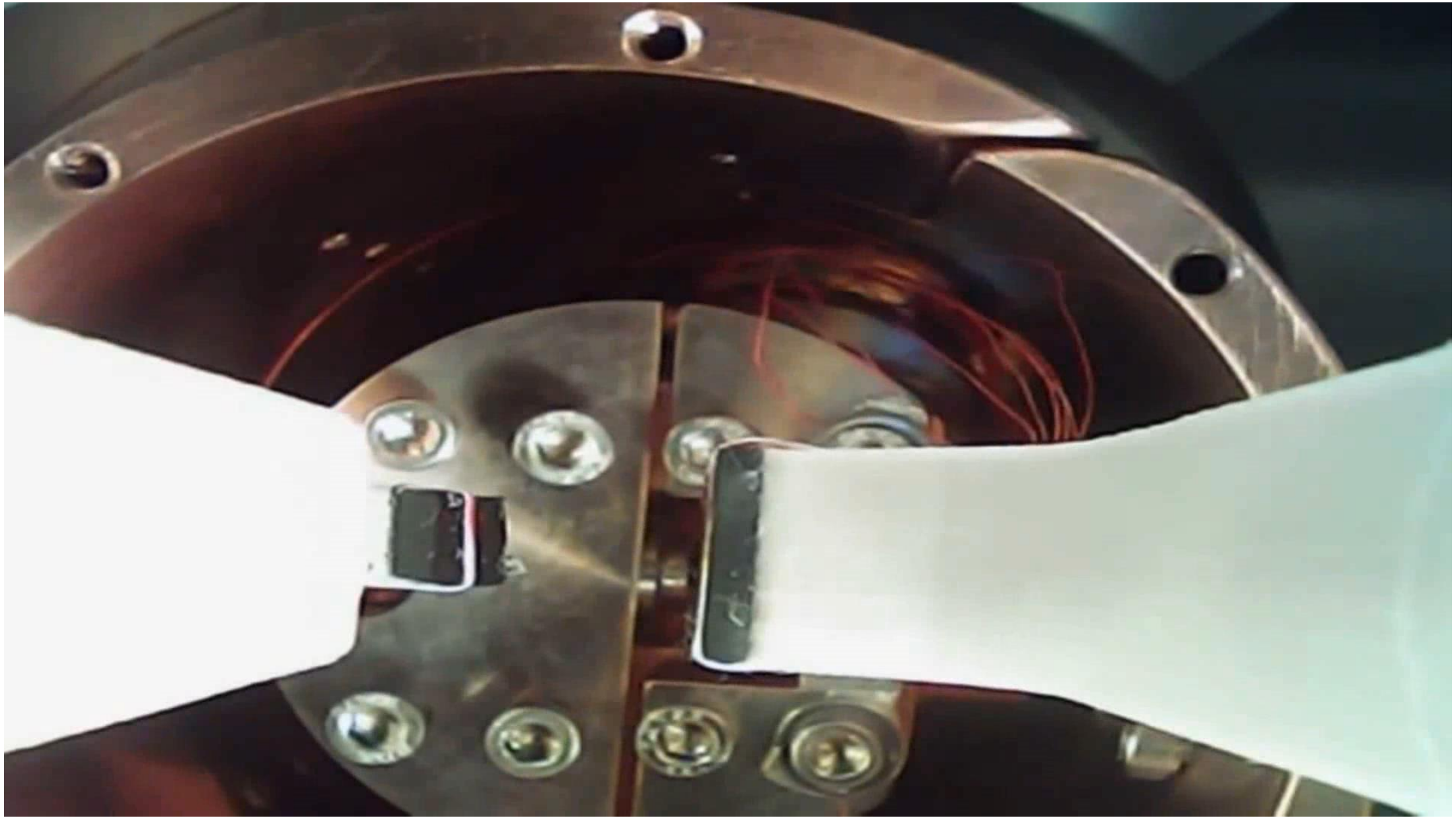
- Radioactive source handling at 2.5 m height using CERNbot 2
  - ✓ **Intervention not possible to be performed by humans**
  - ✓ Bimanual operation, novel procedures and tooling
  - ✓ **CERNTAURO RH procedures and recovery scenarios allowed intervention acceptance by big science facility management**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







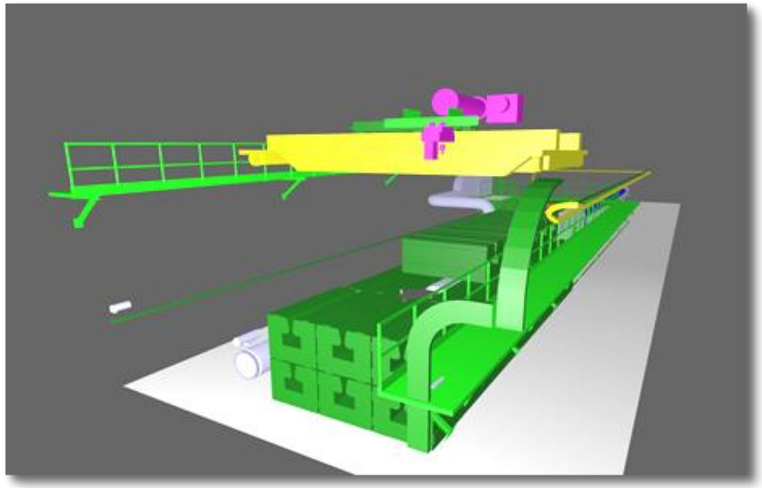
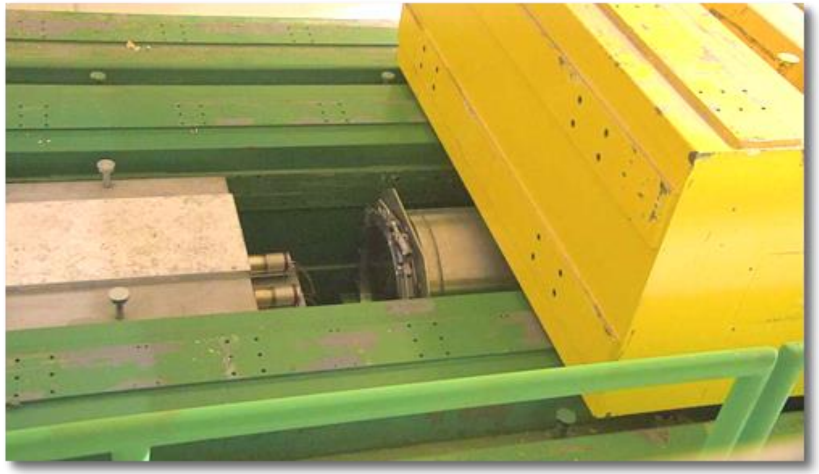
Challenging Teleoperation Example#1

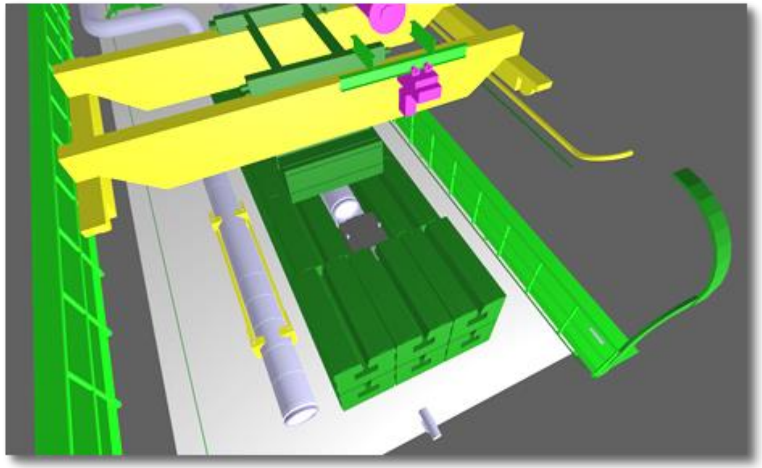
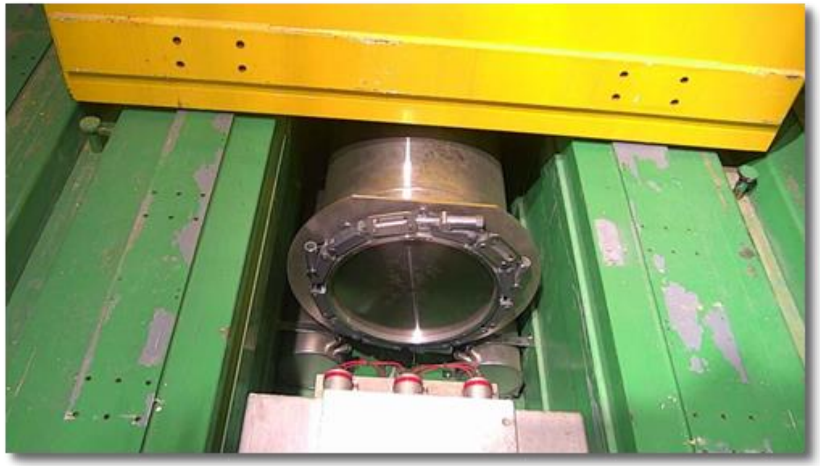


Challenging Teleoperation Example#2

- LHC TDE inspection

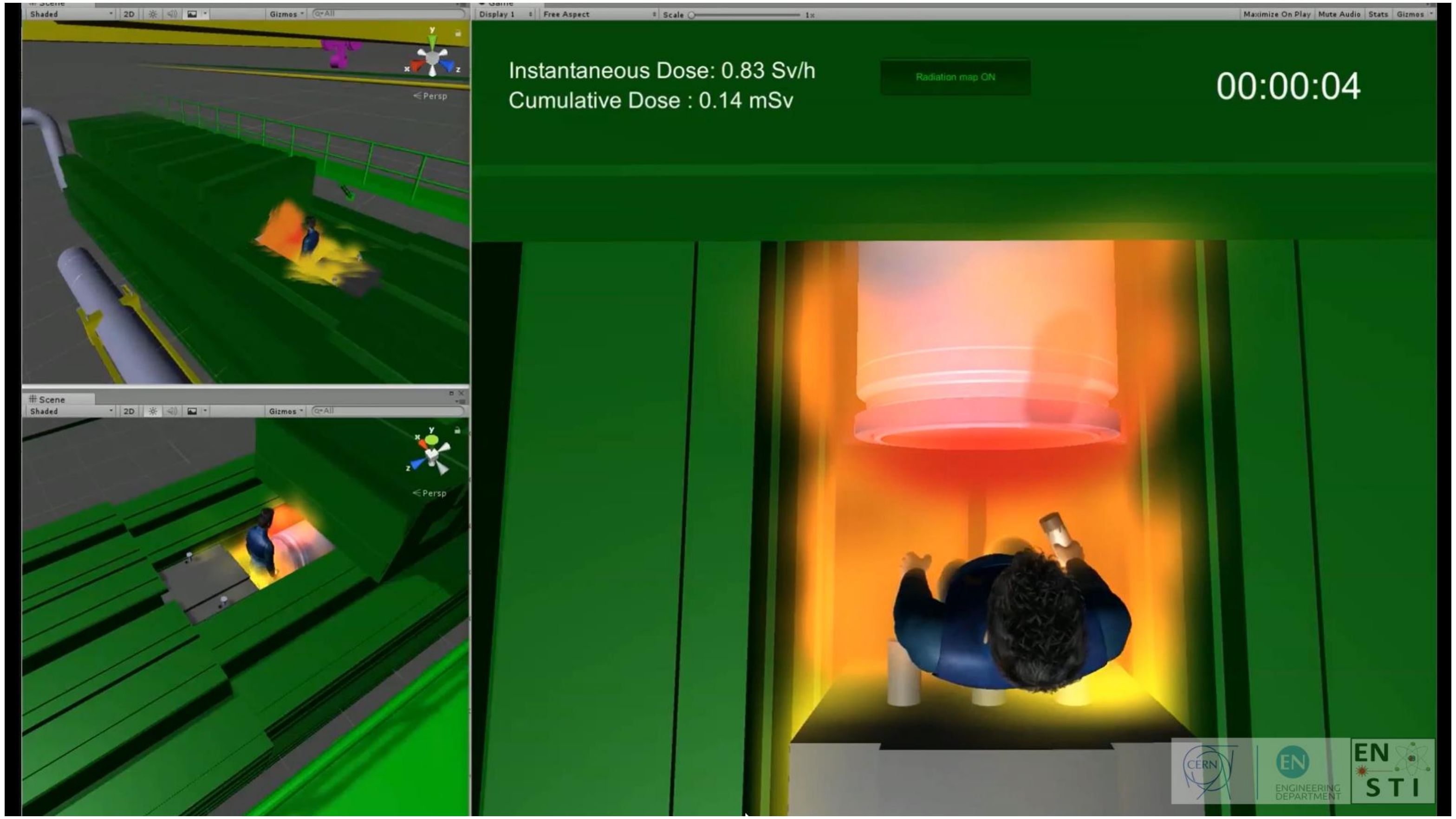
CERNbot v1.0 core

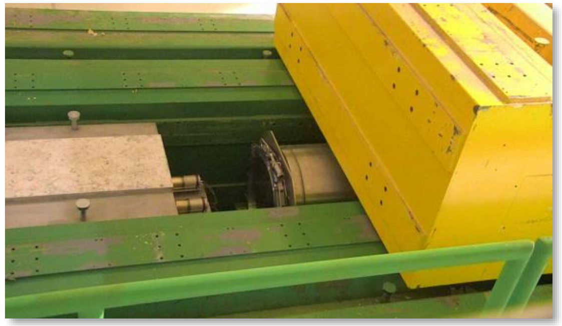



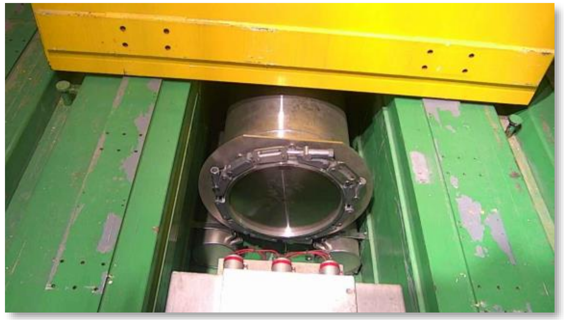



Challenging Teleoperation Example#2

- LHC TDE inspection

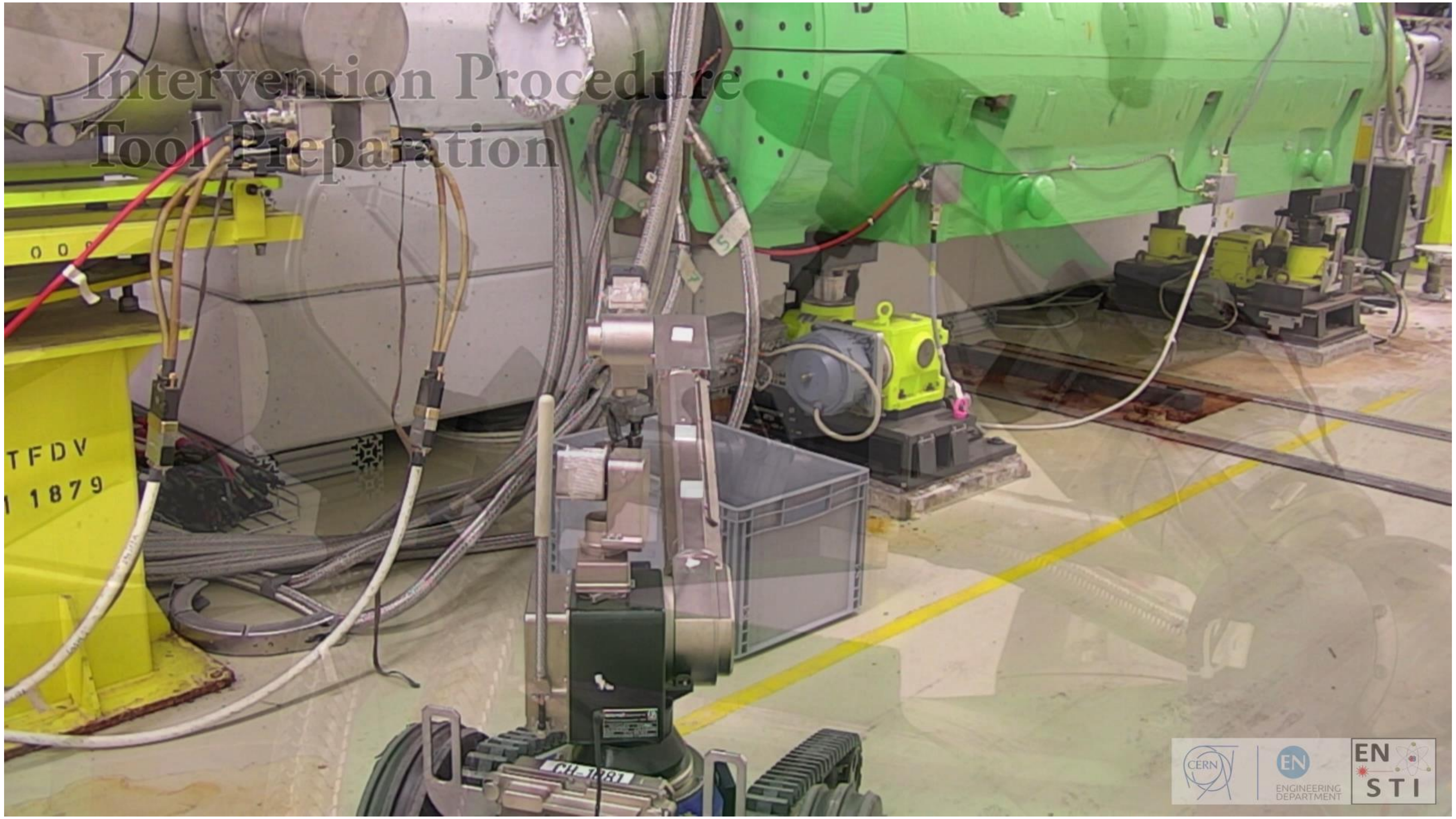






Challenging Teleoperation Example#3
Support for the dismantling of n_ToF target

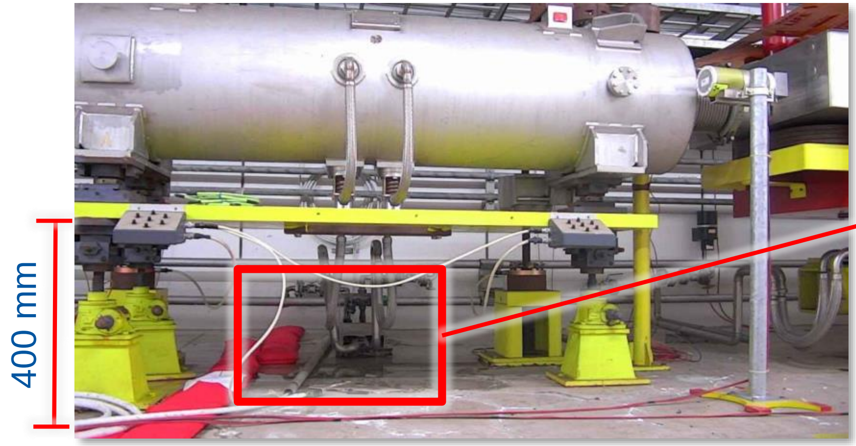
Robotics used for postmortem analysis (SPS - TIDVG)



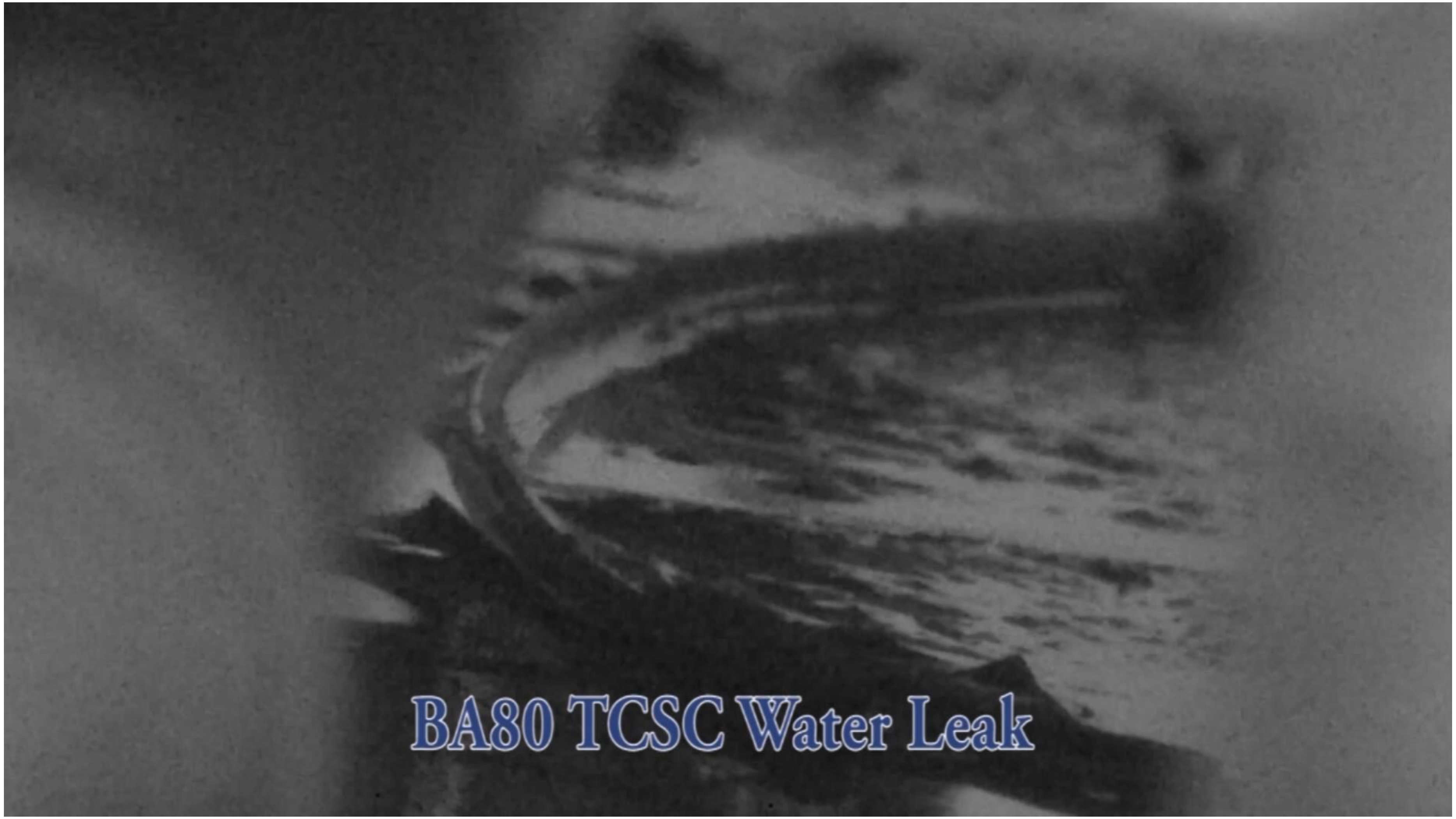
Main Robotics Interventions in 2020

Challenging Teleoperation Example

- 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



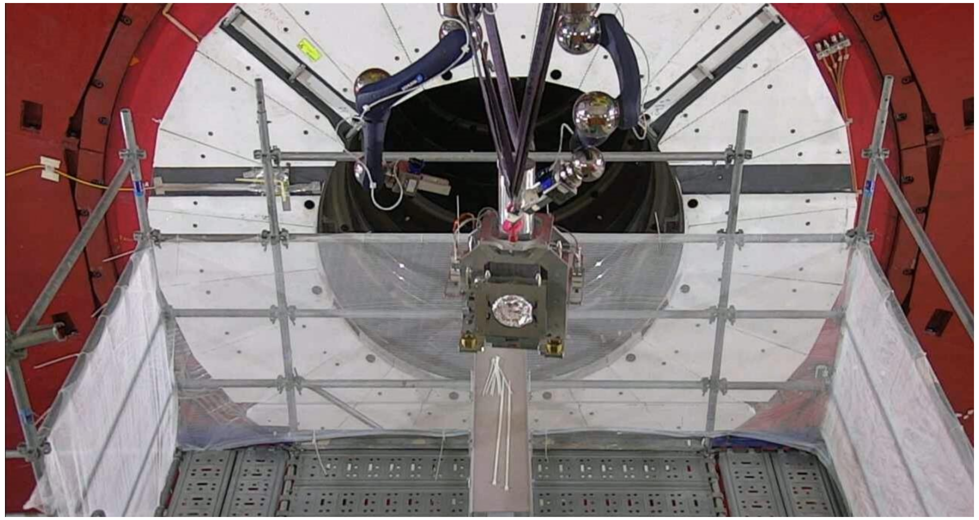
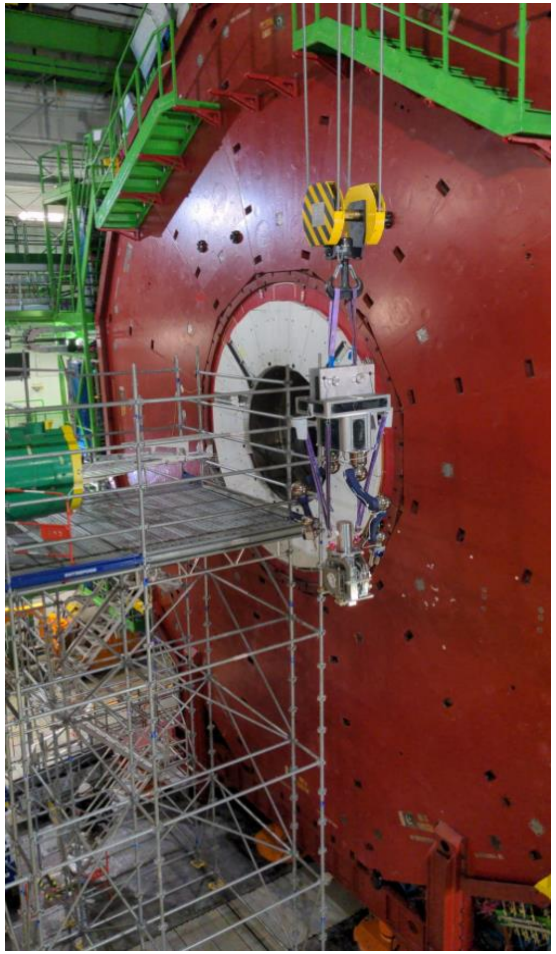
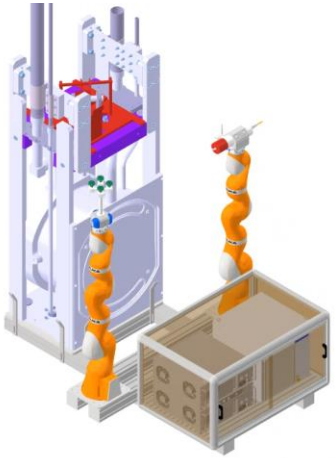
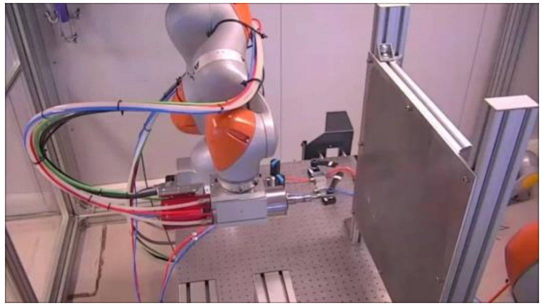
Content

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

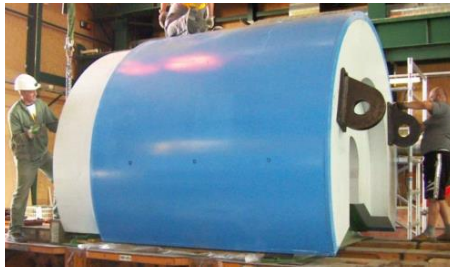
- **VAX remote maintenance**



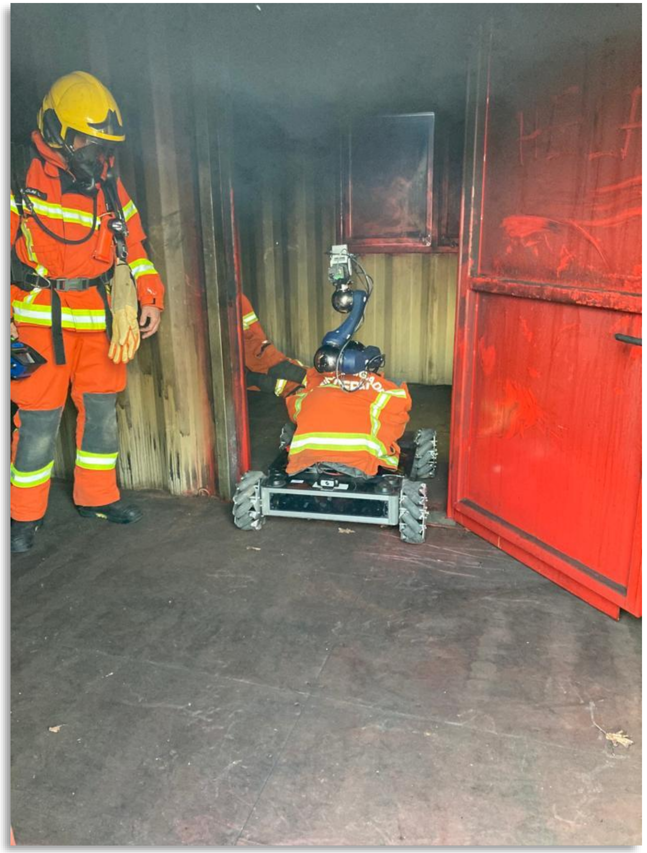
- **old n_ToF target opening**

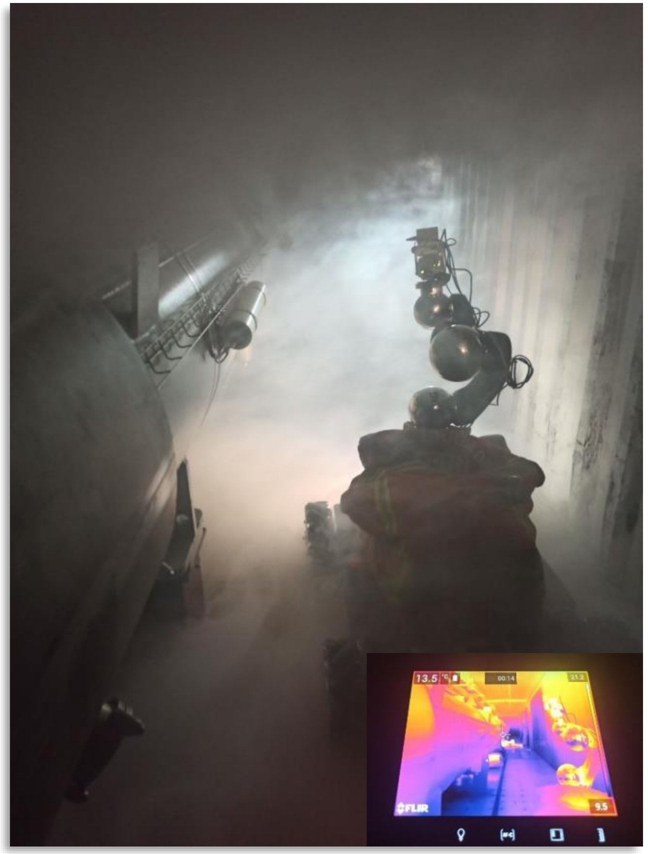
- **ATLAS shielings modification using robotic CNC techniques developed in-house**

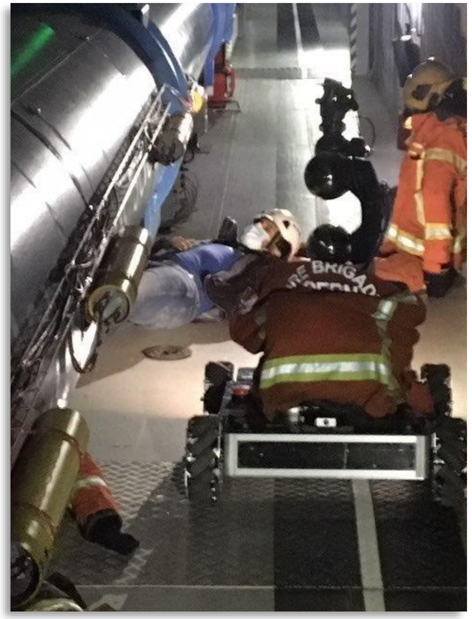



Robots for Search and Rescue

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



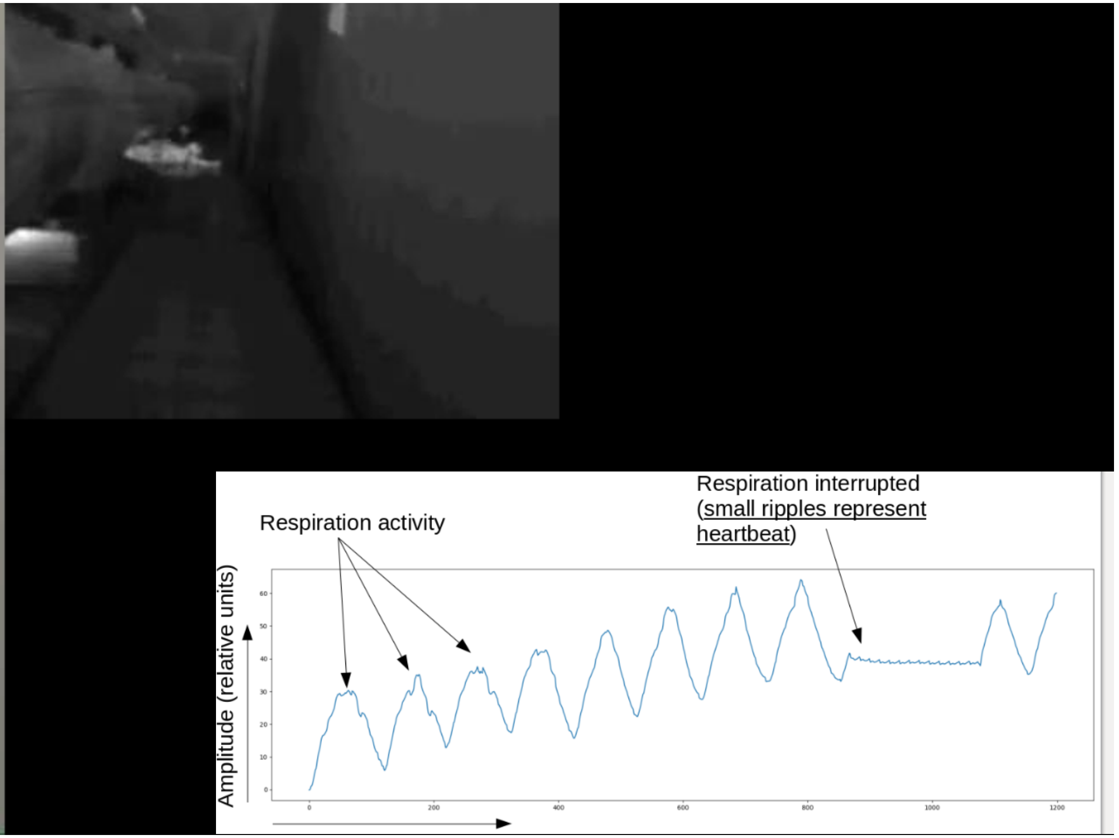




Collaboration with HSE-FRS

Robots for Search and Rescue

Collaboration with HSE-FRS



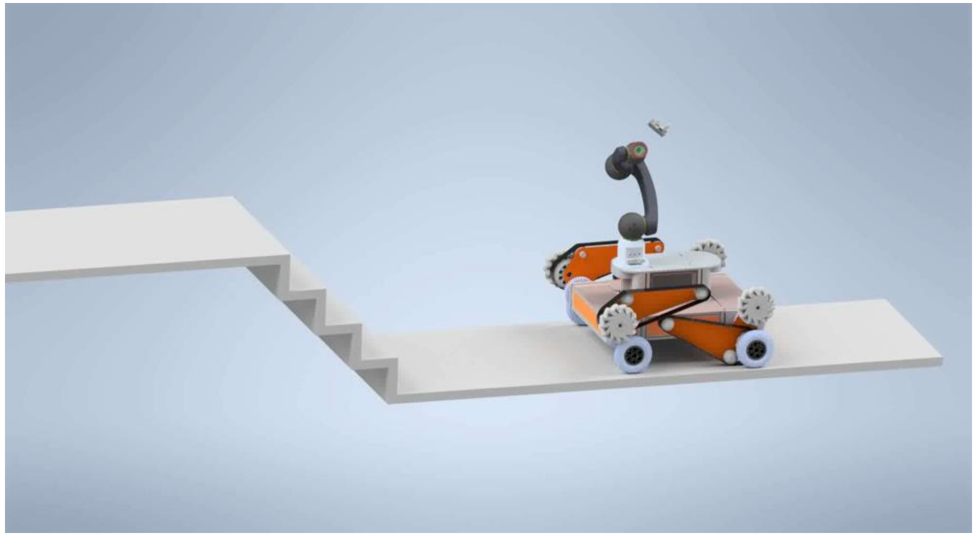
2D IMAGE

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

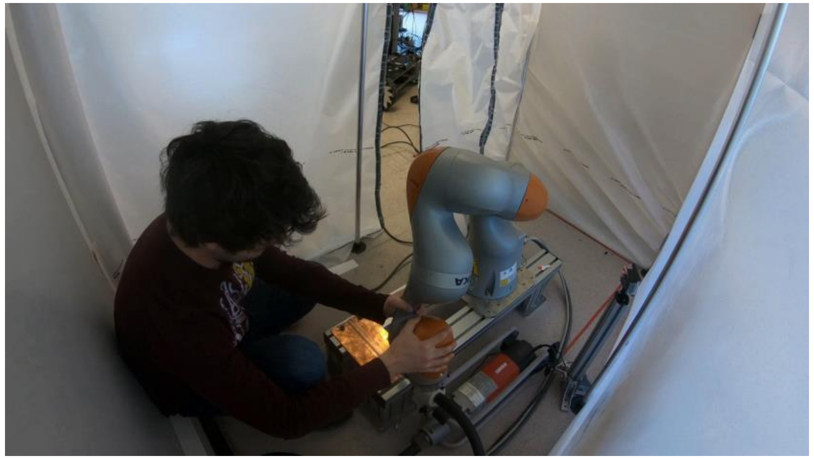
Modular Robots

- 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

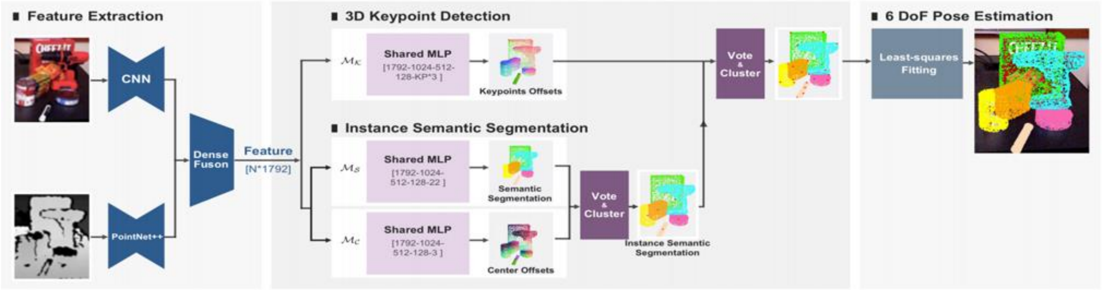


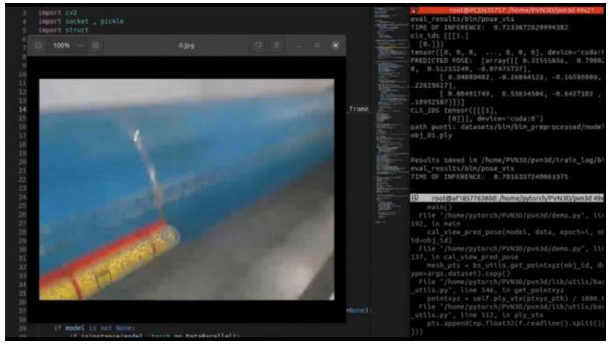
User-friendly teleoperation system

- 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

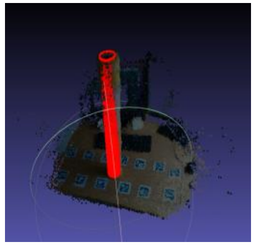


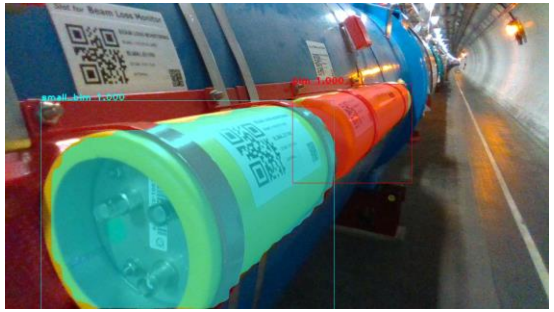
BLMs detection and 6 DoF pose estimation using ML

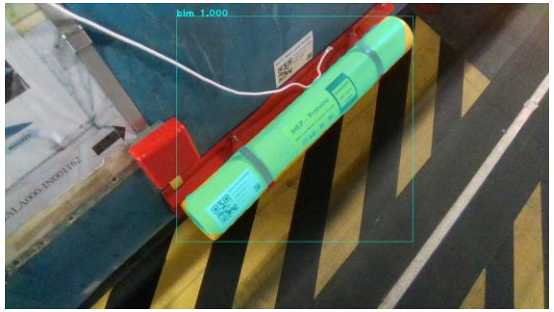


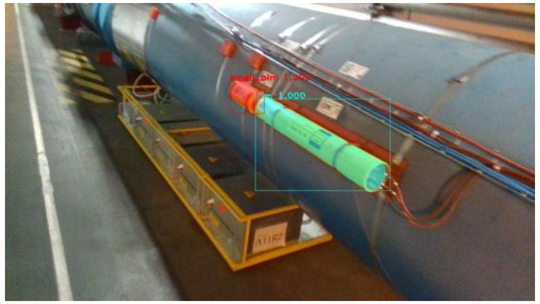


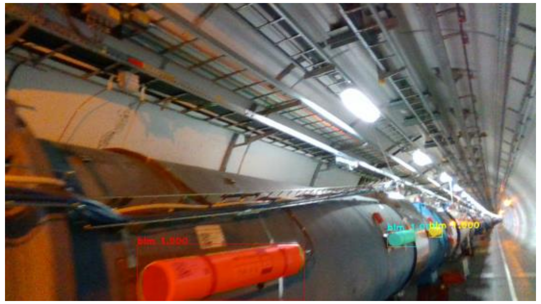
BLMs detection and pose estimation framework

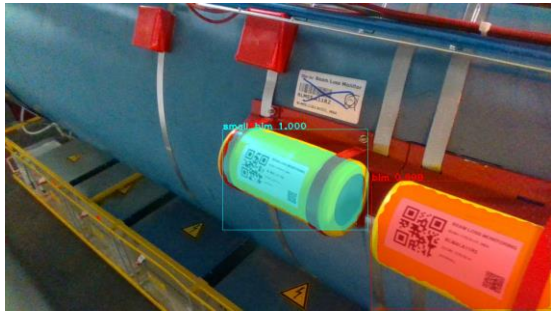


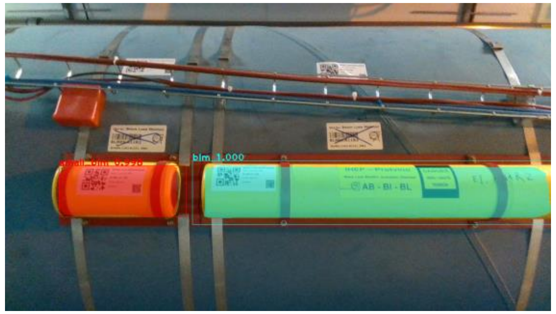


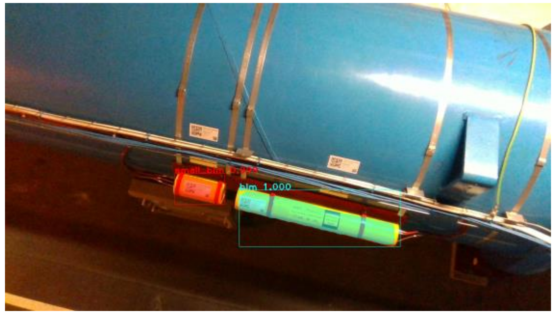








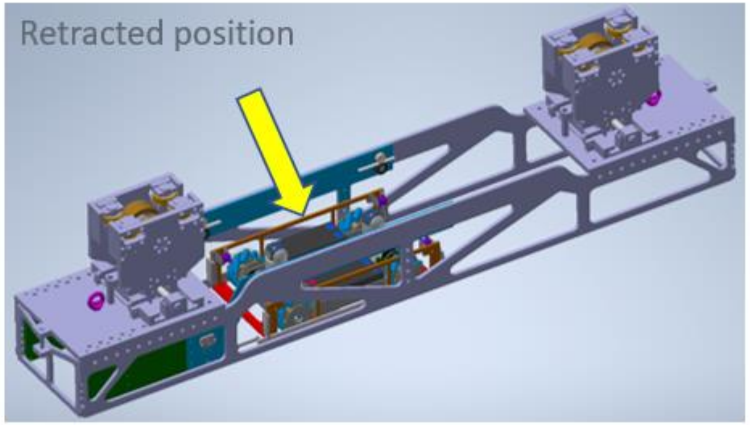


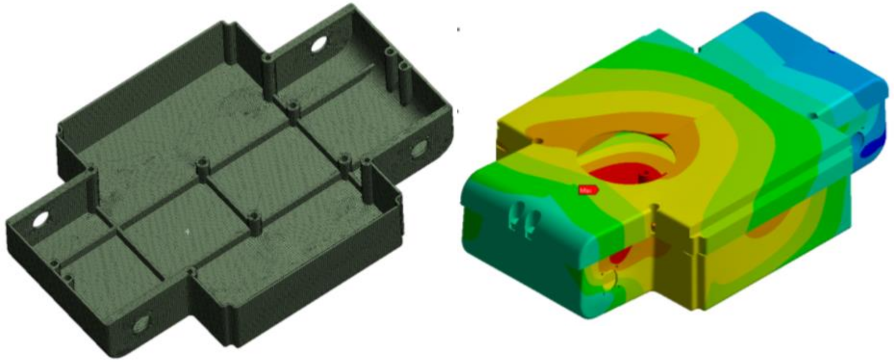


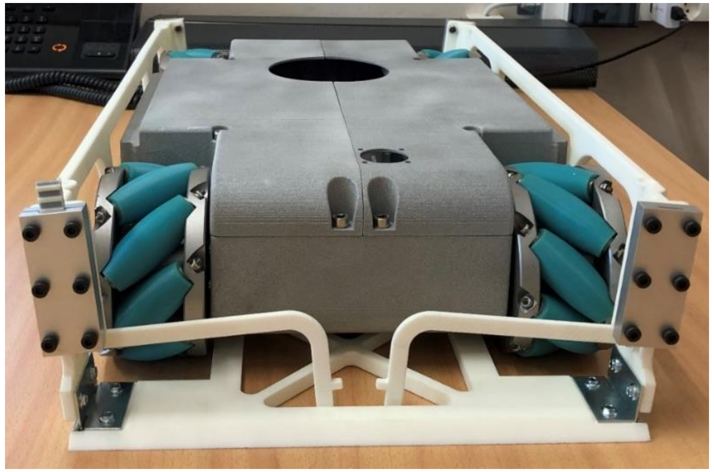
Examples of BLMs detection/segmentation using ML

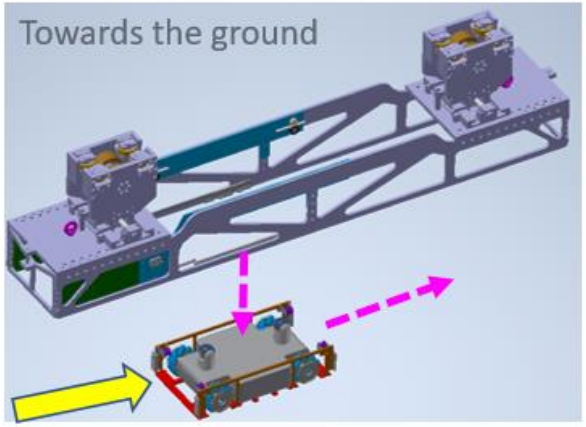
TIM Junior

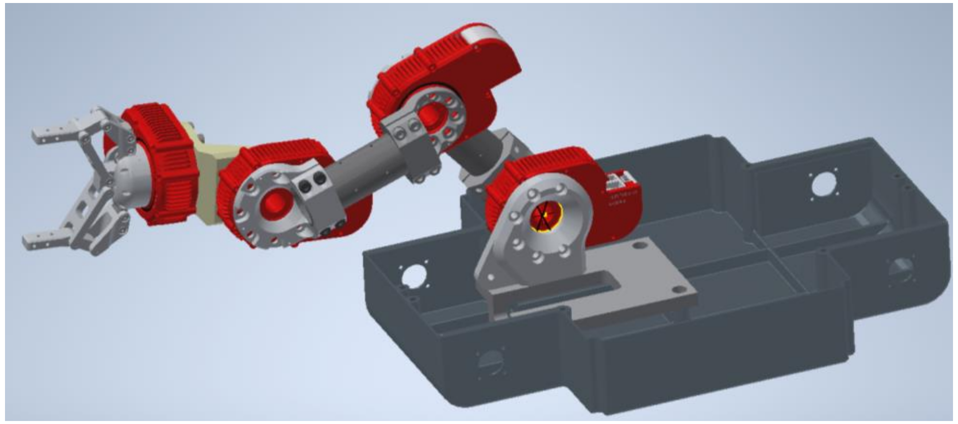
- ROV inside TIM wagon to be lowered down in the LHC

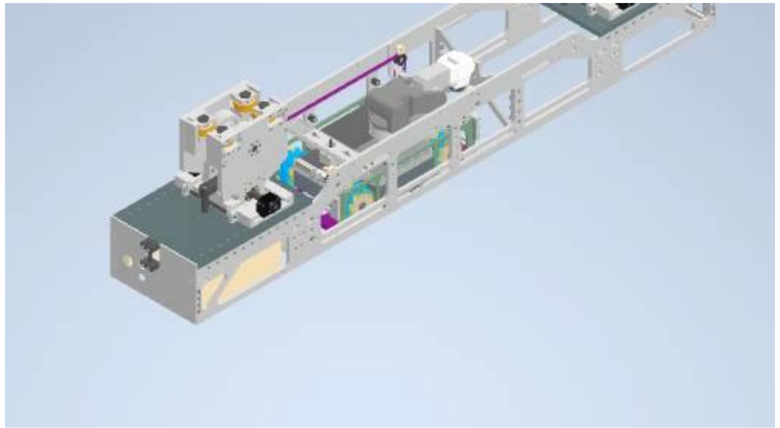






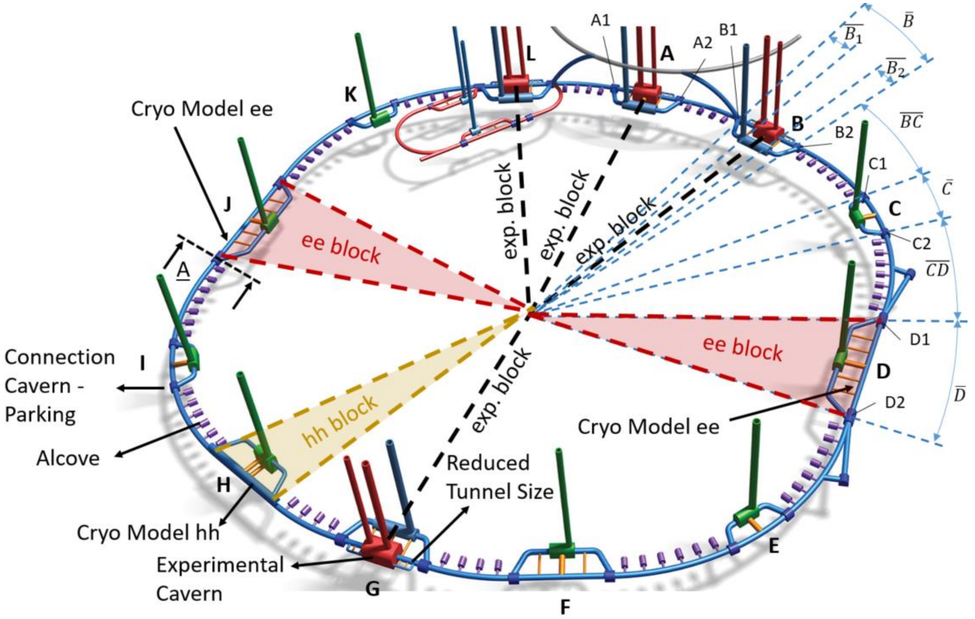


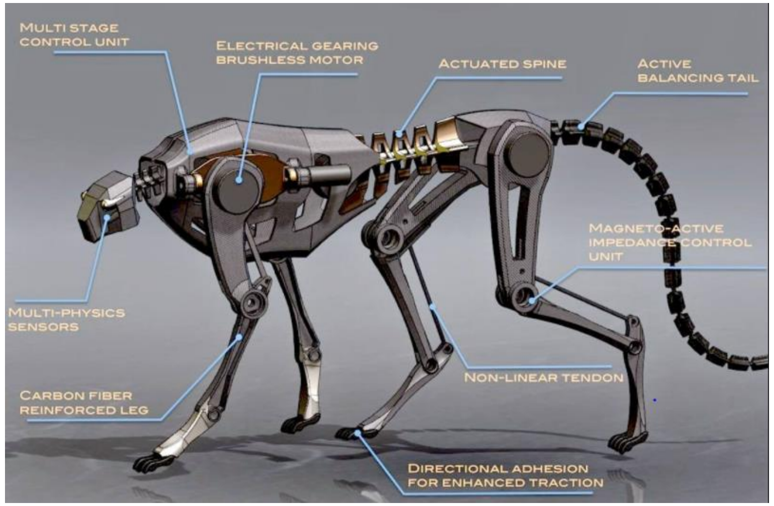




Robots for Future Accelerators (FCC)

- Novel robotics platforms and controls for remote maintenance and interventions



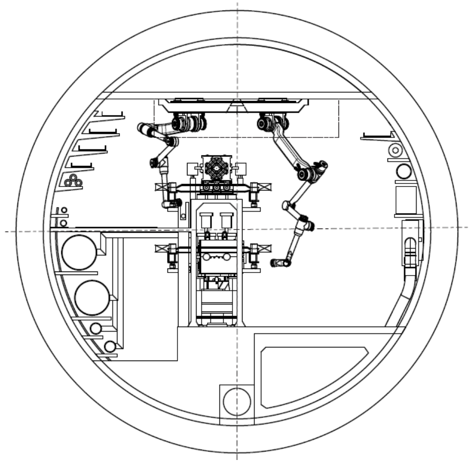


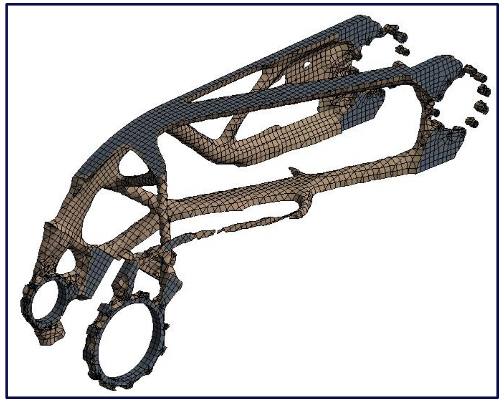
More on H. Gamper Academic lecture, https://indico.cern.ch/event/1055745/

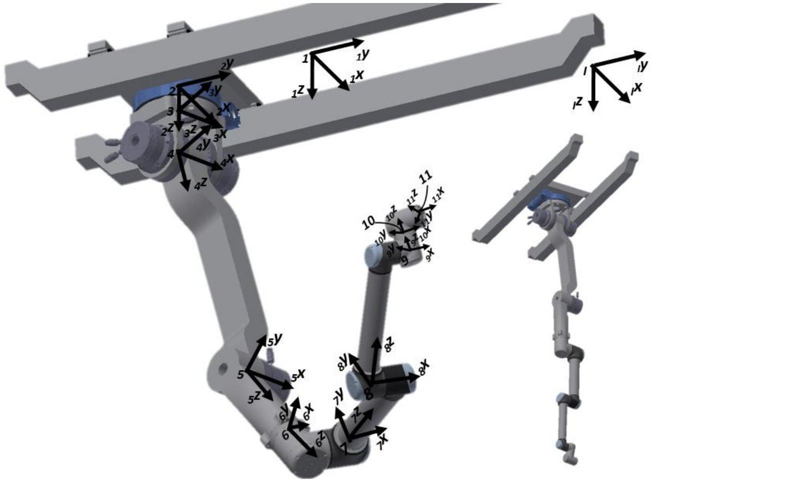
Robots for Future Accelerators (FCC)

H. Gamper PhD work

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







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

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

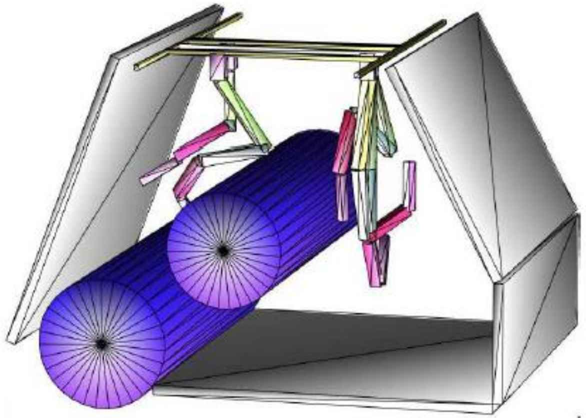
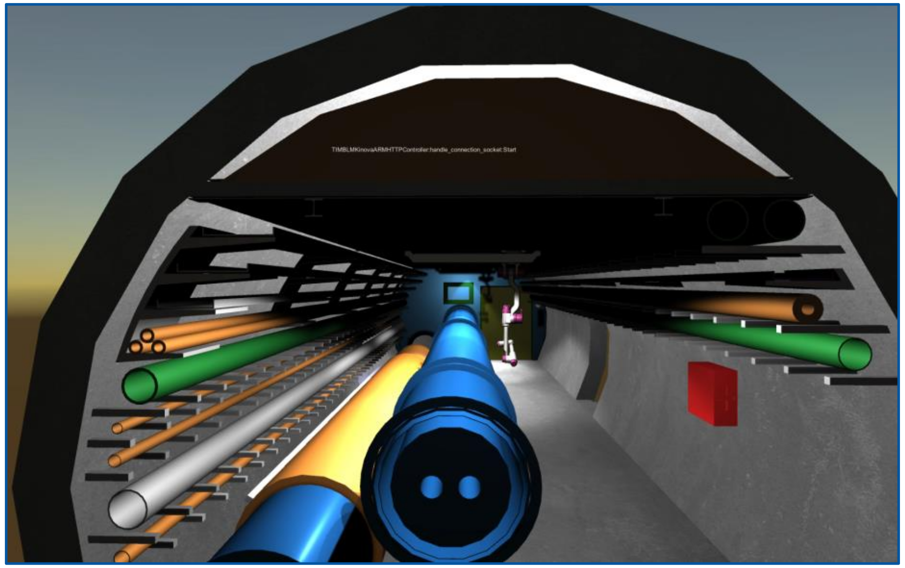


Figure 11: Optimization results FCC-hh (collision objects)



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

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

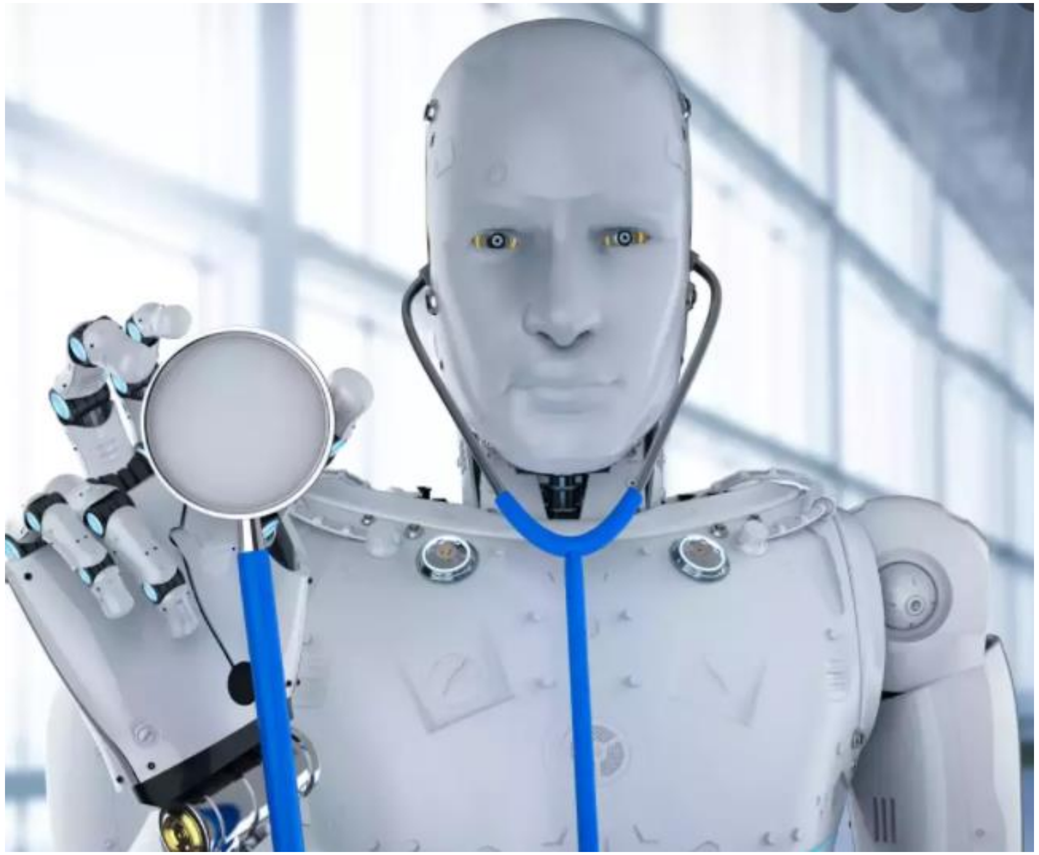
KT: CERNTAURO running on Industrial Robots

- KT contract with Ross Robotics (KM3211) that is using CERNTAURO controls on their robotic platform

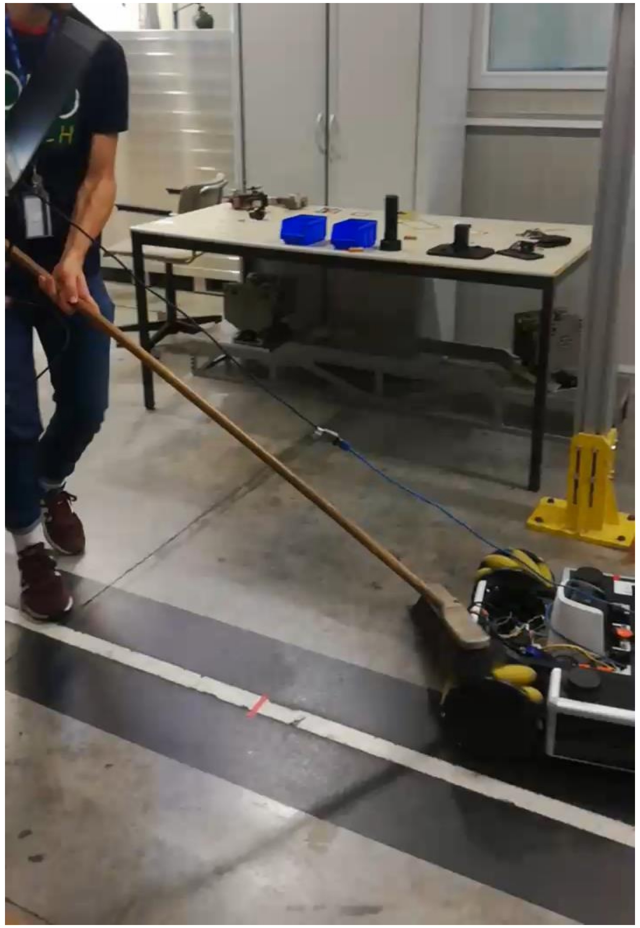
Conclusions

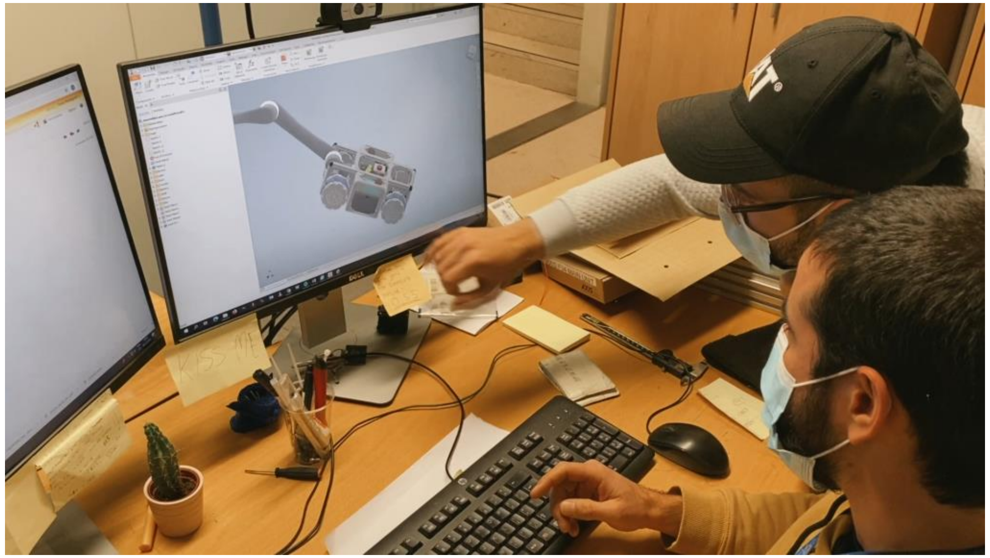
- Particle accelerators devices are normally installed for many years and tasks of dismantling radioactive objects is inherited by the future generation of physicists/technicians/engineers
- Maintenance and dismantling tasks, over a lifetime of a particle accelerator device, must be taken into account 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

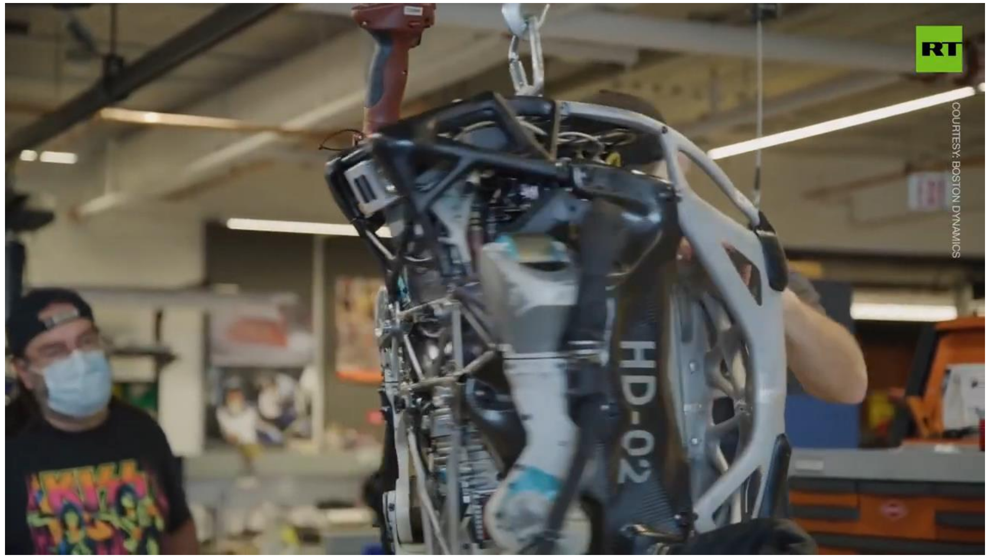
Are Robot "serving" humans?



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 - Sete
Universidad de Oviedo / Universidá d'Uviéu / University of Oviedo
University of the Aegean
Tampere University of Technology
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

References

[1] Petriu, E. M., and M. Krieger. "Robotic Sensing and Perception as the AI Frontier of the I&M." Instrumentation and Measurement Technology Conference, 19Revisiting92. IMTC'92., 9th IEEE. IEEE, 1992.
[2] Bajcsy, Ruzena, Yiannis Aloimonos, and John K. Tsotsos. " active perception." Autonomous Robots 42.2 (2018): 177-196.
[3] Asaro, Peter M. "What should we want from a robot ethic." International Review of Information Ethics 6.12 (2006): 9-16.
[4] Winfield, Alan. "Roboethics–for humans." New Scientist210.2811 (2011): 32-33.
[5] Buehler, Martin, Karl Iagnemma, and Sanjiv Singh, eds. The 2005 DARPA grand challenge: the great robot race. Vol. 36. Springer, 2007.
[6] Kawatsuma, Shinji, Mineo Fukushima, and Takashi Okada. "Emergency response by robots to Fukushima-Daiichi accident: summary and lessons learned." Industrial Robot: An International Journal 39.5 (2012): 428-435.
[7] Di Castro, Mario, Manuel Ferre, and Alessandro Masi. "CERNTAURO: A Modular Architecture for Robotic Inspection and Telemanipulation in Harsh and Semi-Structured Environments." IEEE Access 6 (2018): 37506-37522.
[8] L. Joseph, "Mastering ROS for robotics programming", Packt Publishing Ltd, 2015.
[9] G. Lunghi, R. M. Prades and M. Di Castro, "An Advanced, Adaptive and Multimodal Graphical User Interface for Human-robot Teleoperation in Radioactive Scenarios," in Proceedings of the 13th International Conference on Informatics in Control, Automation and Robotics, SCITEPRESS-Science and Technology Publications, Lda, 2016.
[10] M. Di Castro e. al., i-TIM: A Robotic System for Safety, Measurements, Inspection and Maintenance in Harsh Environments, presented at SSRR18.
[11] M. Di Castro et al. "A Dual Arms Robotic Platform Control for Navigation, Inspection and Telemanipulation," ICALEPCS2017, 2018.
[12] A. Holmes-Siedle and L. Adams, "RADFET: A review of the use of metal-oxide-silicon devices as integrating dosimeters," Int. J. Radiat. Appl. Instrum. Part C Radiat. Phys. Chem., vol. 28, no. 2, pp. 235–244, Jan. 1986
[13] J. Mekki, M. Brugger, S. Danzeca, L. Dusseau, K. Røed, and G. Spiezia, "Mixed Particle Field Influence on RadFET Responses Using Co-60 Calibration," IEEE Trans. Nucl. Sci., vol. 60, no. 4, pp. 2435–2443, Aug. 2013.
[14] R. Harboe-Sorensen, F.-X. Guerre, and A. Roseng, "Design, Testing and Calibration of a 'Reference SEU Monitor' System," in 8th European Conference on Radiation and Its Effects on Components and Systems, 2005. RADECS 2005, Sept., pp. B3-1-B3-7.
[15] S. Danzeca et al., "Qualification and Characterization of SRAM Memories Used as Radiation Sensors in the LHC," IEEE Transactions on Nuclear Science, vol. 61, no. 6, pp. 3458–3465, Dec. 2014.
[16] T. Granlund and N. Olsson, "SEUs Induced by Thermal to High-Energy Neutrons in SRAMs," in 8th European Conference on Radiation and Its Effects on Components and Systems, 2005. RADECS 2005, Sept., pp. E1-1-E1-4.
[17] M. Di Castro et al, "An incremental slam algorithm for indoor autonomous navigation", presented at IMEKO 2014.
[18] Ruffo, M., et al. "New infrared time of-flight measurement sensor for robotic platforms." (2014).
[19] Nick, Mostafa, Rachid Cherkaoui, and Mario Paolone. "Optimal allocation of dispersed energy storage systems in active distribution networks for energy balance and grid support." IEEE Trans. Power Syst 29.5 (2014): 2300-2310.
[20] G. Welch, G. Bishop, An introduction to the kalman lter. department of computer science, university of north carolina, ed: Chapel Hill, NC, unpublished manuscript.
[21] J. Blair, Sine- tting software for ieee standards 1057 and 1241, in: Instrumentation and MeasurementTechnology Conference, 1999. IMTC/99. Proceedings of the 16th IEEE, Vol. 3, IEEE, 1999, pp. 1504-1506
[22] N. B. Priyantha, A. K. Miu, H. Balakrishnan, S. Teller, The cricket compass for context-aware mobile applications, in: Proceedings of the 7th annual international conference on Mobile computing and networking, ACM, 2001, pp. 1-14.
[23] Ramadan, Rabie A., and Athanasios V. Vasilakos. "Brain computer interface: control signals review." Neurocomputing223 (2017): 26-44.
[24] Wang, Meng, et al. "A Wearable SSVEP-Based BCI System for Quadcopter Control Using Head-Mounted Device." IEEE Access 6 (2018): 26789-26798.
[25] Pacchierotti, Claudio, et al. "Cutaneous haptic feedback to ensure the stability of robotic teleoperation systems." The International Journal of Robotics Research 34.14 (2015): 1773-1787.
[26] M. Ferre et al., eds, "Advances in telerobotics", Heidelberg: Springer, vol. 31, 2007.
[27] H. C. Longuet-Higgins, "A computer algorithm for reconstructing a scene from two projections," Nature, vol. 293, no. 5828, p. 133, 1981.
[28] H. Bay, A. Ess, T. Tuytelaars, and L. Van Gool, "Speeded-up robust features (surf)," Computer vision and image understanding, vol. 110, no. 3, pp. 346–359, 2008.
[29] J. F. Henriques, R. Caseiro, P. Martins, and J. Batista, "High-speed tracking with kernelized correlation filters," IEEE Transactions on Pattern Analysis and Machine Intelligence, vol. 37, no. 3, pp. 583–596, 2015
[30] L. Attard, C. J. Debono, G. Valentino and M. Di Castro, Image mosaicing of tunnel wall images using high level features, Proceedings of the 10th International Symposium on Image and Signal Processing and Analysis, Ljubljana, 2017, pp. 141-146. doi: https://doi.org/doi: 10.1109/ISPA.2017.8073585
[31] Leanne Attard, Carl James Debono, Gianluca Valentino, Mario Di Castro, Vision-based change detection for inspection of tunnel liners, Automation in Construction, Volume 91, 2018, pp. 142-154. doi: https://doi.org/10.1016/j.autcon.2018.03.020
[32] Dag T. Wisland, et.al. "Remote Monitoring of Vital Signs Using a CMOS UWB Radar Transceiver," 14th IEEE International NEWCAS Conference, NEWCAS 2016.
[33] Nakata, Robert H., et.al "Motion Compensation for an Unmanned Aerial Vehicle Remote Radar Life Sensor", 2018, IEEE
X. Hu, T. Jin "Preliminary results of noncontact respiration and heartbeat detection using IR-UWB radar", 2016, IEEE
[34] Fritsche, P., et.al "Fusion of radar, LiDAR and thermal information for hazard detection in low visibility environments", 2017, IEEE
[35]) MITCHELL, Harvey B. Multi-sensor data fusion: an introduction. Springer Science & Business Media, 2007
[36] Rudolph Emil. A new approach to linear filtering and prediction problems. Journal of basic Engineering, 1960, vol. 82, no 1, p. 35-45.
[37] Tingxiang Fan, Pinxin Long, Wenxi Liu and Jia Pan. Fully Distributed Multi-Robot Collision Avoidance via Deep Reinforcement Learning for Safe and Efficient Navigation in Complex Scenarios. Arxiv.
[38] M. di castro et. Al, Object Detection and 6D Pose Estimation for Precise Robotic Manipulation in Unstructured Environments, Lecture Notes in Electrical Engineering, Springer, Volume 495, Chapter 20
[39] Lunghi, G., Marin, R., Di Castro, M., Masi, A., & Sanz, P. J. (2019). Multimodal Human-Robot Interface for Accessible Remote Robotic Interventions in Hazardous Environments. IEEE Access, 7, 127290-127319.
[40] Veiga Almagro, C., Di Castro, M., Lunghi, G., Marín Prades, R., Sanz Valero, P. J., Pérez, M. F., & Masi, A. (2019). Monocular Robust Depth Estimation Vision System for Robotic Tasks Interventions in Metallic Targets. Sensors, 19(14), 3220.
[41] Saliba, C., Bugeja, M. K., Fabri, S. G., Di Castro, M., Mosca, A., & Ferre, M. (2018). A Training Simulator for Teleoperated Robots Deployed at CERN. In ICINCO (2) (pp. 293-300).
[42] J. Marin, M. Di Castro et al., "MiniCERNBot Educational Platform: Antimatter Factory Mock-up Missions for Problem-Solving STEM Learning", MDPI journal 2021, volume 21, issue 4, 10.3390/s21041398
[43] . M. Di Castro PhD thesis. http://cds.cern.ch/record/2729727/files/CERN-THESIS-2019-387.pdf?version=1
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