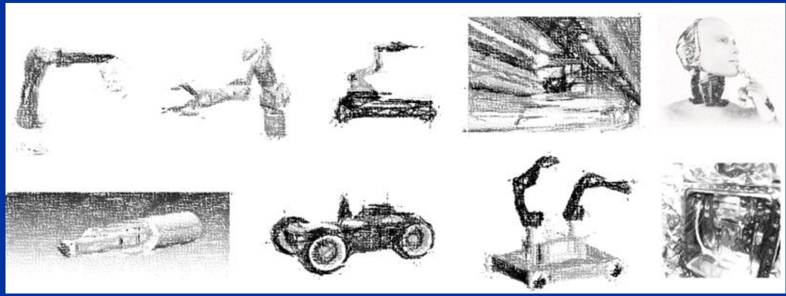


Control Design Optimisations of Robots for the Maintenance and Inspection of Particle Accelerators

Alejandro DIAZ ROSALES

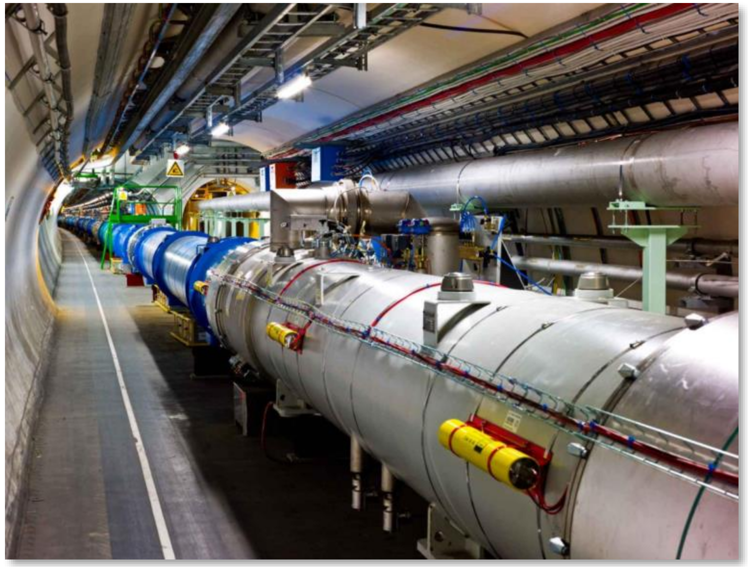
Hannes GAMPER

Mario DI CASTRO

*ICALEPCS23, 7-13 October 2023, Cape Town, Paper **MO3AO07***

Main needs for robotics at CERN

- Inspection, operation and maintenance of radioactive particle accelerators devices for **safety, maintainability, reliability and availability increase**
  - ✓ **Experimental areas and objects not built to be remote handled/inspected**
    - ✓ Any intervention may lead to “**surprises**”
    - ✓ Several risks, including **contamination**



The LHC tunnel

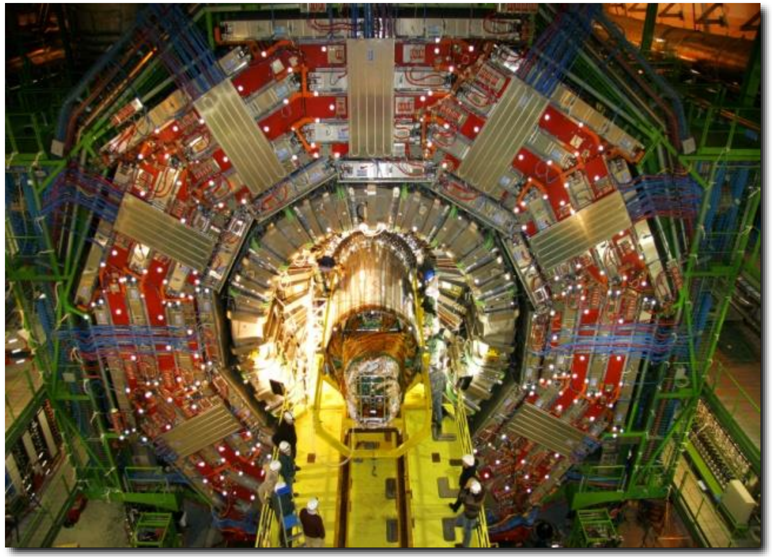
North Area experimental zone

Radioactive sample handled by a robot

Main difficulties for robotics at CERN

- **Harsh and semi-structured environments, accessibility**
- **Radiation, magnetic disturbances**, delicate equipment not designed for robots, big distances, communication, time for the intervention, highly skilled people often required (non robotic operators), etc.

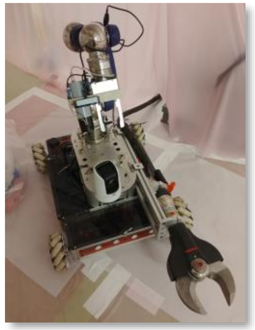


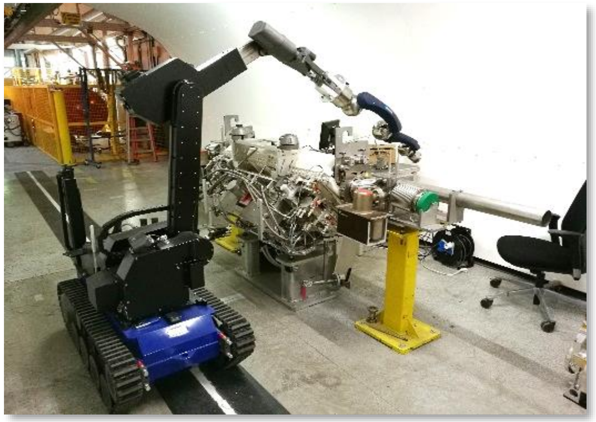
The Robotic Service at CERN: Overview of robots pool

Telemax robot

Train Inspection Monorail (CERN made)

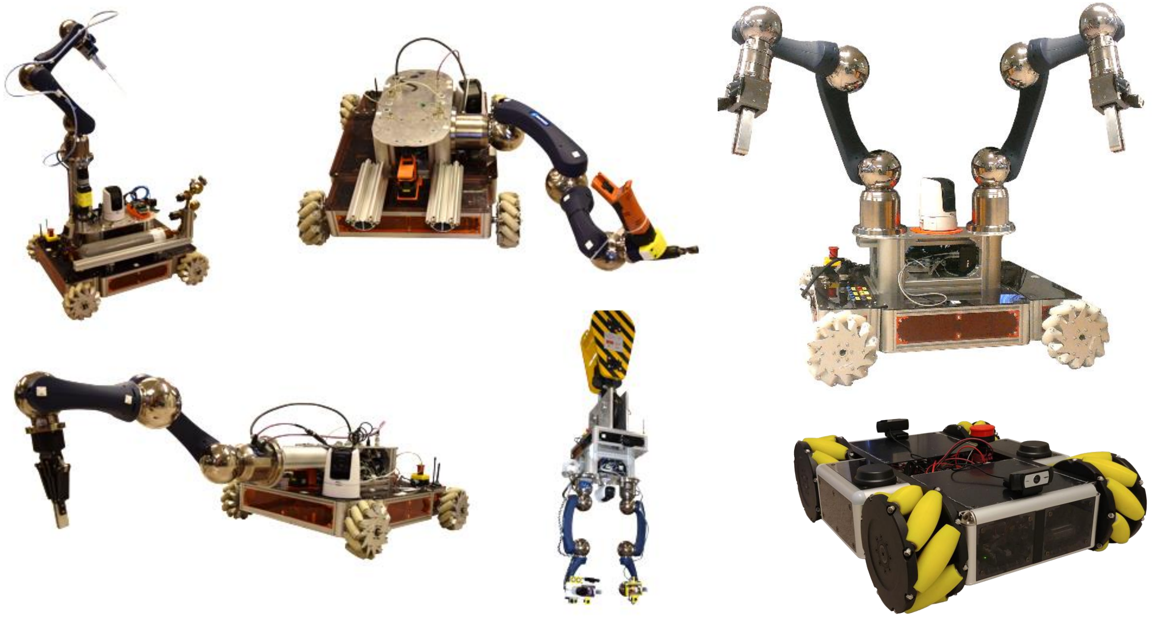


More than 20 robots (custom made and/or industrial with custom controls) are in operation. Mechatronics conceptions, designs, proof of concepts, prototyping, series productions, operations, maintenance, tools and procedures



Teodor robot

EXTRM robot (CERN controls)



CERNBot in different configurations (CERN made)

High payload manipulator

Drone for tele-operation support

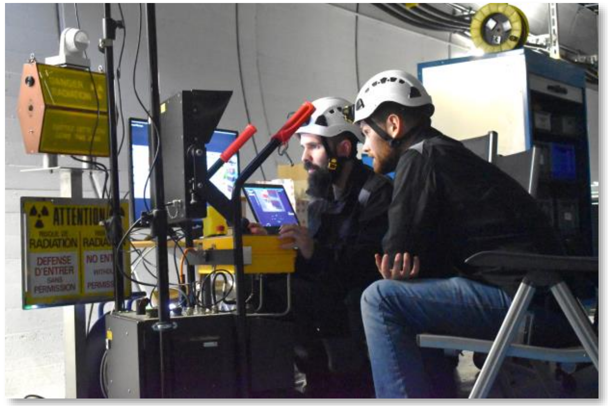
Quadrupeds for “difficult” zones

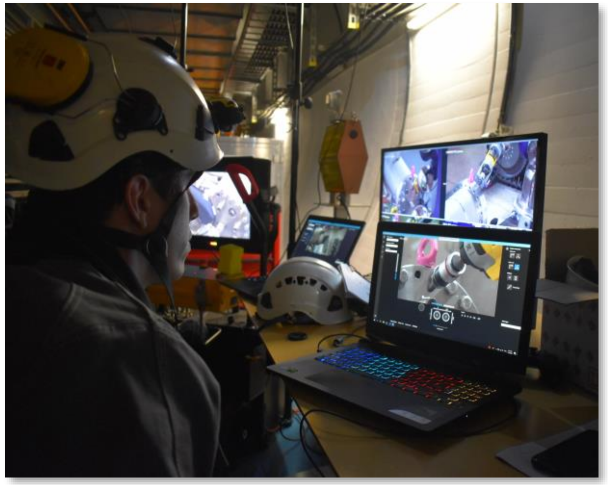
The Robotic Service at CERN

BEAMS

Robotics technologies are mainly used for:

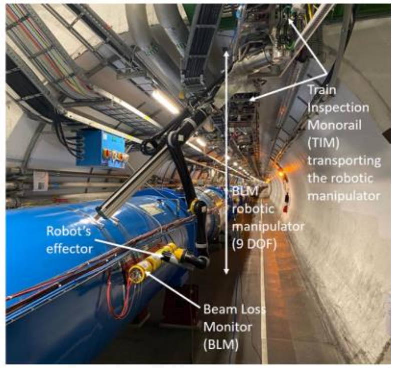
- Remote maintenance
- Human intervention procedures preparation
- Quality assurance
- Post-mortem analysis
- Reconnaissance
- Search and rescue
- And more…

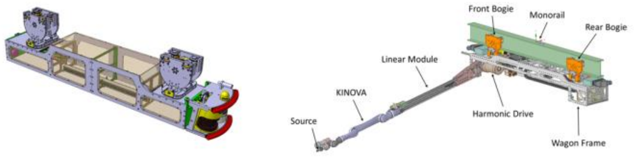


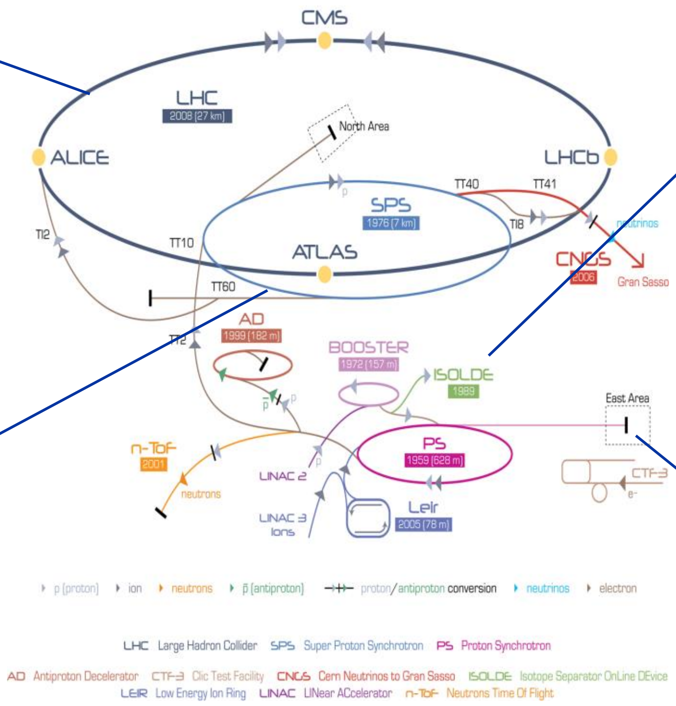

Robots integrated within accelerator facilities

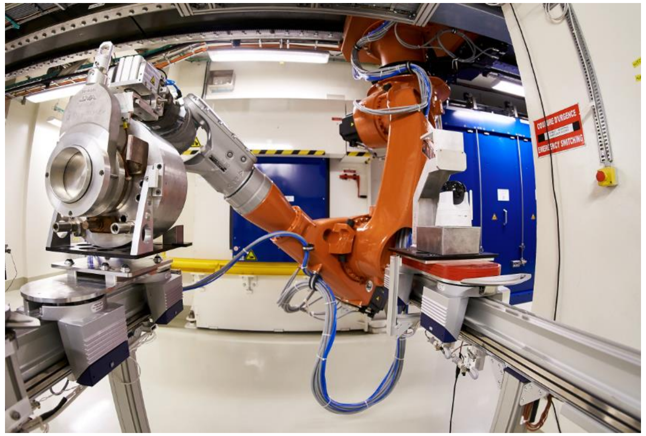
More info on Tuesday mini-oral and poster session (paper TUMBCMO25)



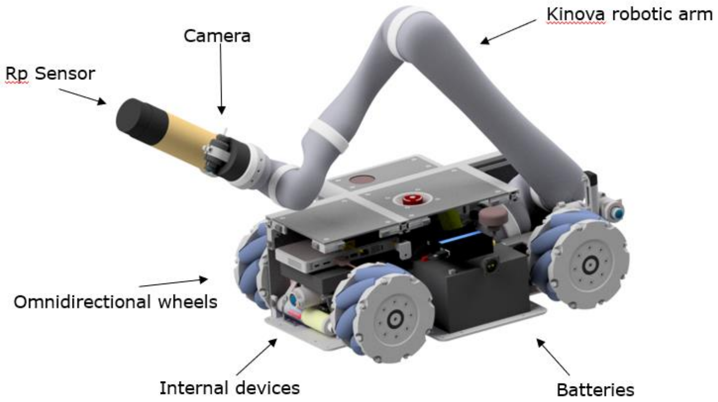


4x Train Inspection Monorail (TIM)

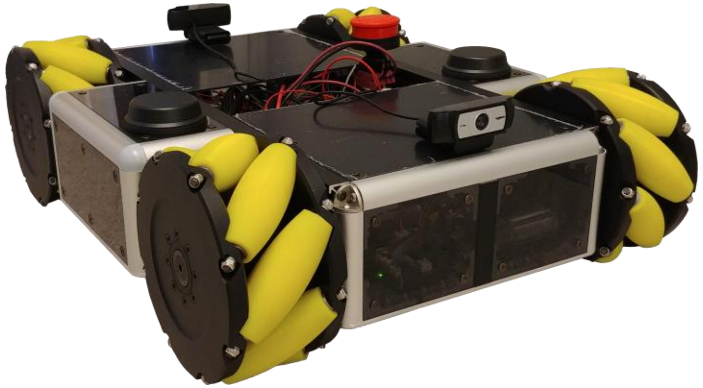




3x ISOLDE / MEDICIS high payload industrial robots



2x SPS robot

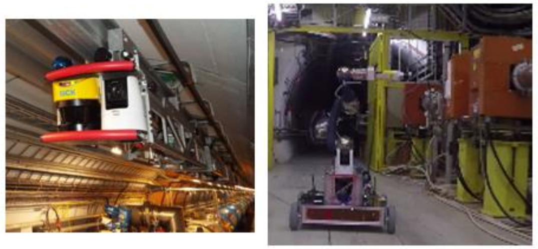


CHARM robot

Robotics Interventions

- More than **1000 robotic operations** over the last 8 years
- More than **1500 hours of in-situ robotic operations**
- Strong machine **availability boost** thanks to planned and unplanned/emergency missions
- ✓ Continuing developing **best practices** for equipment design and robotic intervention procedures and tools including recovery scenarios

SPS MKP oilers refill



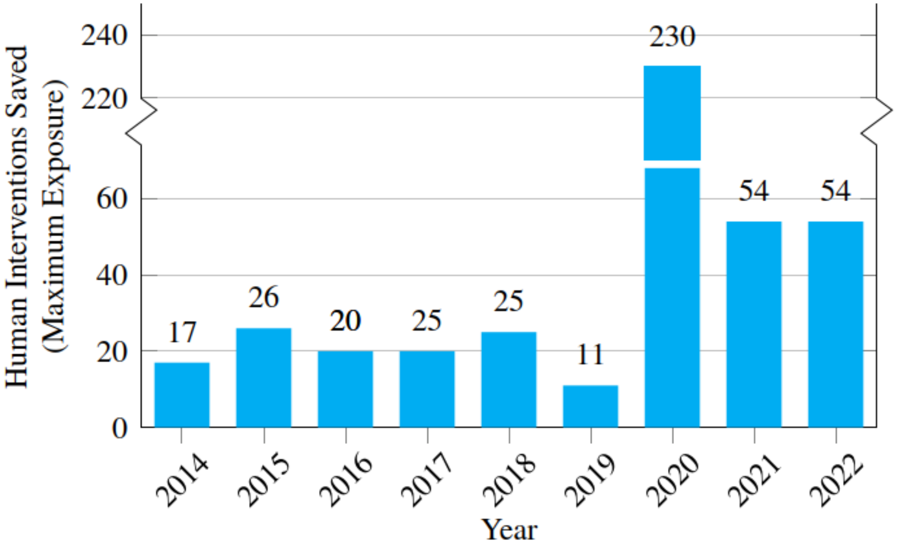
Remote radioprotection surveys

Cabling status inspection

Temperature sensor installation on AD target

Tunnel structure monitoring

Remote Vacuum Leak detection



The equivalent number of human interventions saved with robotic interventions assuming maximum annual exposure

Suitable robots for Big Science Facilities

- ➢No single existing solution can fulfill different 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**

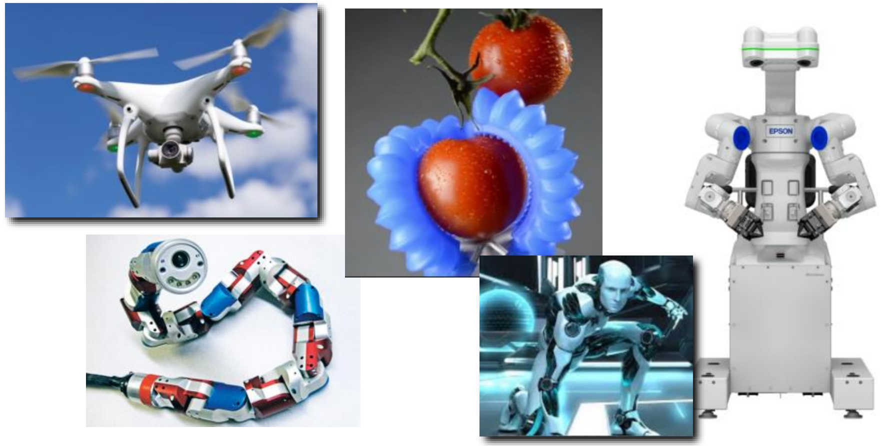
Novel Modular framework

MODULAR HARDWARE

+

MODULAR SOFTWARE

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.

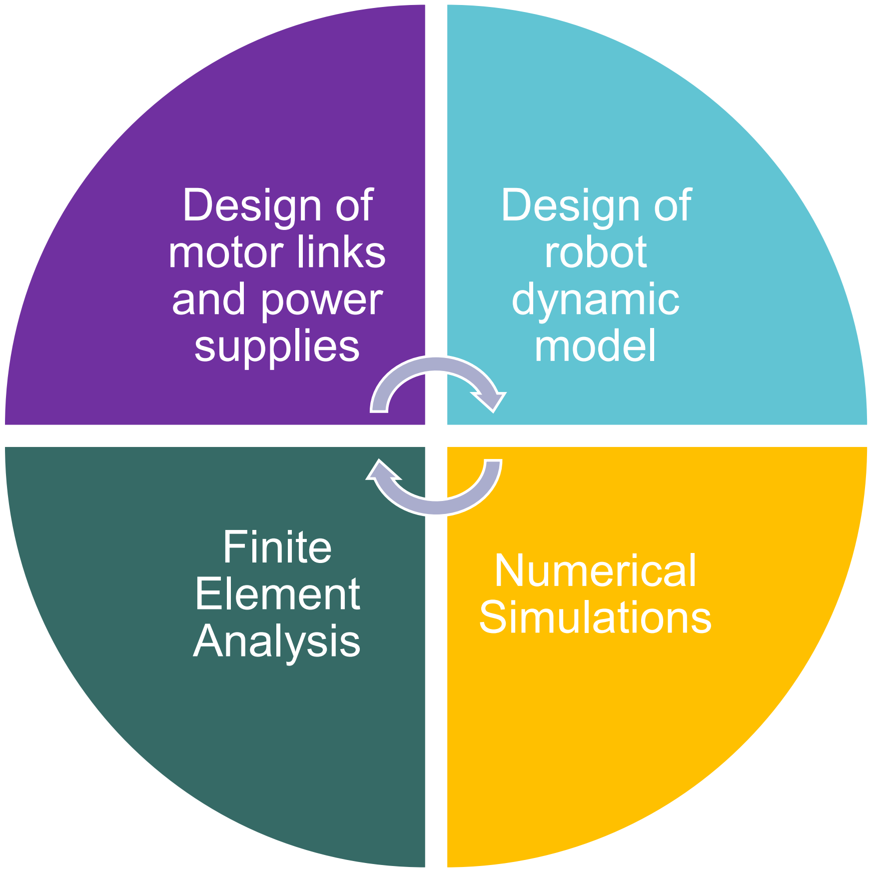


Requirement or remote maintenance: **Be strong while stay gentle**

TOPOLOGY AND CONTROL DESIGN OPTIMIZATIONS

Robot Topology Design Optimizations

- Main general requirements when optimizing a robotic solution
  - ✓ Accessibility/compliance with environment
  - ✓ Supervised or fully Autonomous Interventions.
  - ✓ Detect Hazards.
  - ✓ Robust Control.
  - ✓ Low Maintenance.
  - ✓ Reliable/Redundant Power Supply.
  - ✓ Intuitive Human-Robot Interface (HRI).
  - ✓ Dexterity in Maneuverability.



- Novel algorithm for **simultaneous optimization** of **topology** and **geometry**
  - ✓ p contains the N **links length**
  - ✓ x contains the **point** of interest to **reach**

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

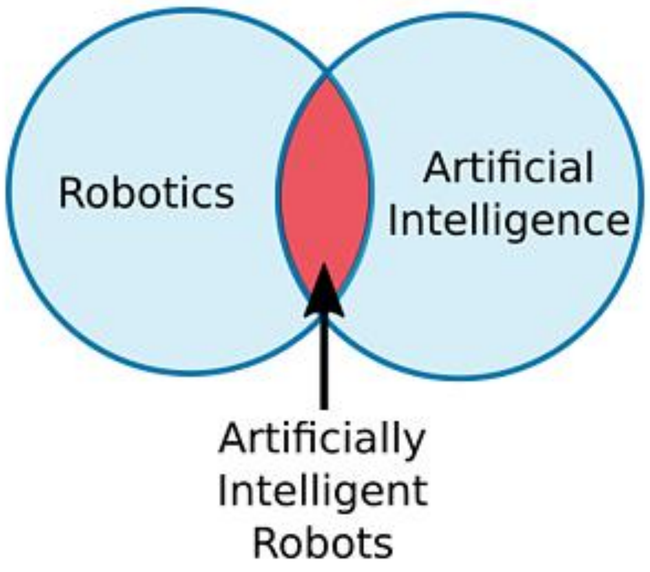
→ Constraint to ensures that the desired end position will be reached

→ Constraint for collision avoidance

→ Constraints for mechanical joint limits

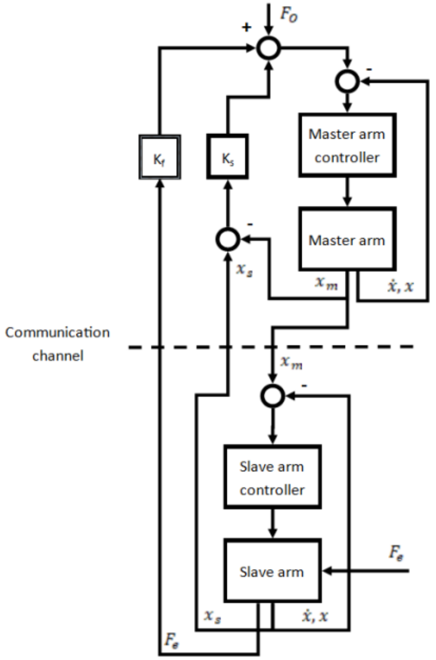
Controls Optimization Are Essential for Physical Interaction

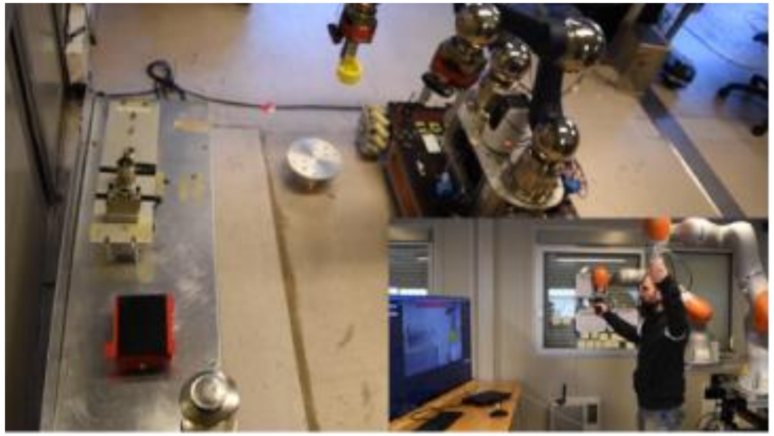
- Main difference between a robot and a computer is a physical action
- In robotics → dealing not only with information technology but with **“interaction” technology**
  - ✓ Physical interaction (e.g. human-robot interaction) that should be threated with specific robotic controls
  - ✓ Compliant robotics controls (**shared controls**, **haptics, perception, proprioception etc**.)
  - ✓ Compliant mechanics, soft materials etc.



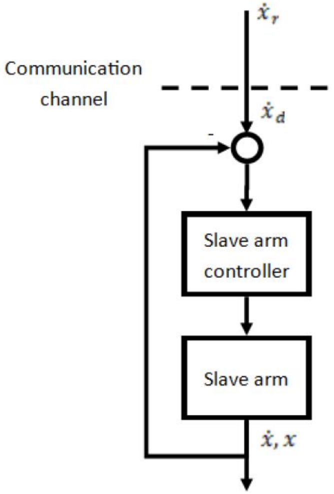
Control Strategies: from standard teleoperation to shared controls

- Improve operation efficiency by moving from **standard teleoperation controls** (unilateral and bilateral) to supervised autonomy
- The control of the robot must be able to adapt to what the human operator believes is pertinent → **Shared Controls**

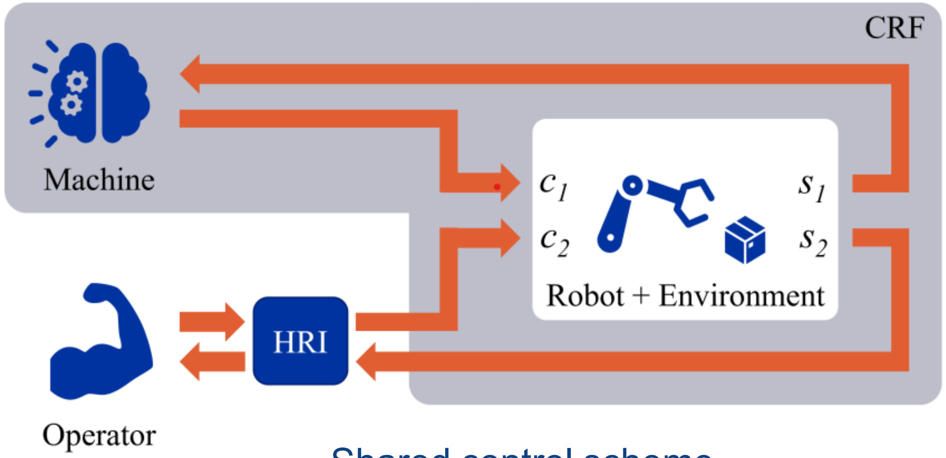




Bilateral teleoperation

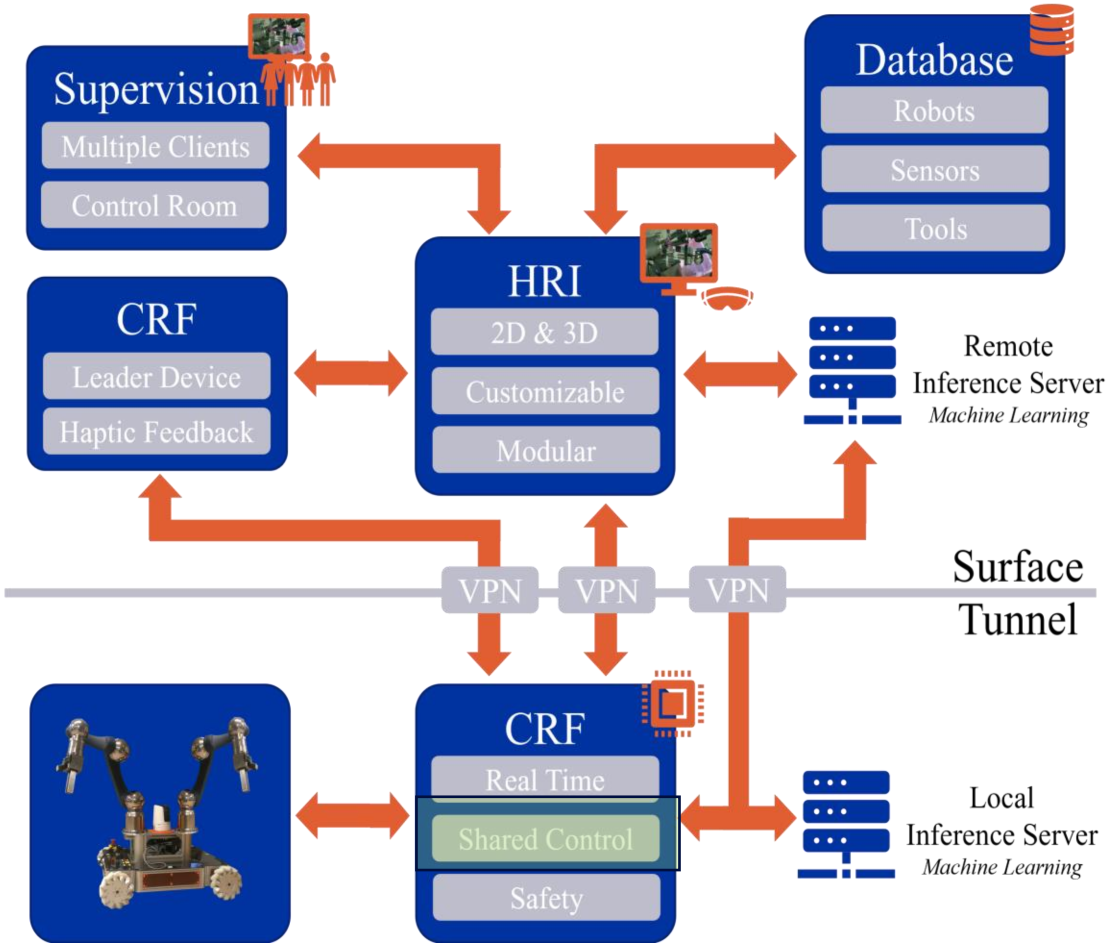


Unilateral teleoperation



Shared control scheme

Shared Controls

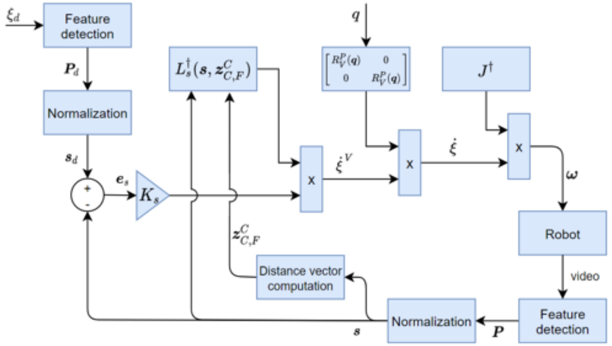


Simplified architecture of the different systems involved in the control of the robots

Shared Controls

Morra, D., Cervera, E., Buonocore, L. R., Cacace, J., Ruggiero, F., Lippiello, V., & Di Castro, M. (2022, June). Visual control through narrow passages for an omnidirectional wheeled robot. In *2022 30th Mediterranean Conference on Control and Automation (MED)* (pp. 551-556). IEEE.

- **Semi-Autonomous Control (SAC)**
  - ✓ **Parallel autonomy**
    - ❑ Involves both human operators and autonomous controllers concurrently controlling separate variables



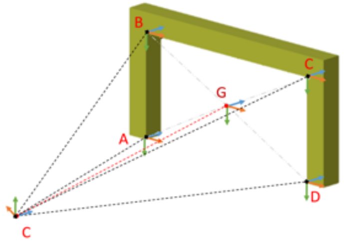


Image-based visual servoing system using ML

SPS robot

Parallel autonomy: Variable Impedance Control

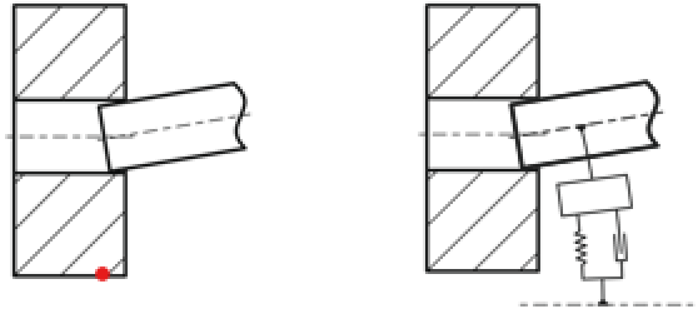
- **Adapts the contact forces to the task characteristics**
  - ✓ Imitation on how we/humans naturally adjust the stiffness of our muscles when we interact with objects that have varying rigidity.

$$\boldsymbol{F} = \boldsymbol{M}\ddot{\boldsymbol{x}} + \boldsymbol{D}\dot{\boldsymbol{x}} + \boldsymbol{K}\boldsymbol{x} + \boldsymbol{f} + \boldsymbol{s}$$

Mass-spring dumper model for the variable impedance

The impedance can be adapted to the task characteristics.

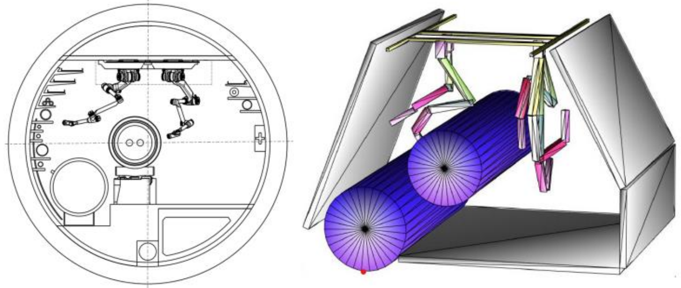
- Compliant robot for delicate tasks.
- Stiff robot for high precision tasks.



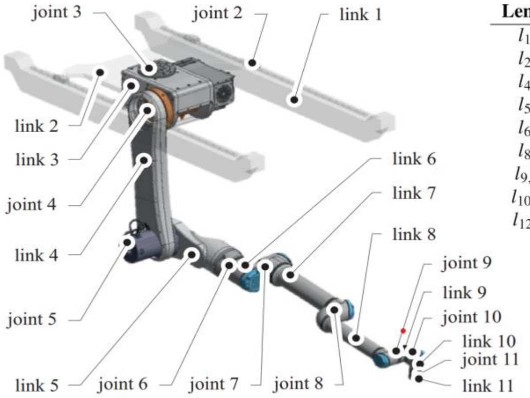
Peg-In-Hole

Case Study #1: FCC Robot Design

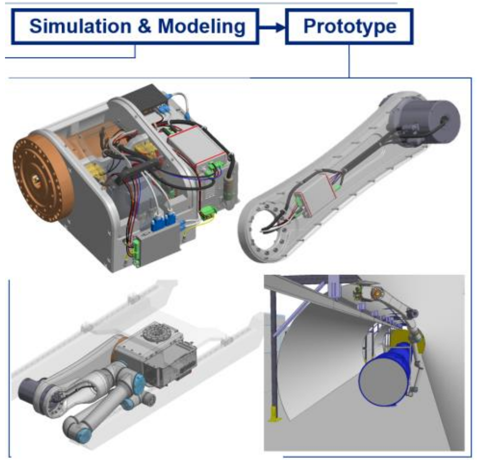
	Requirements
Maintenance	Cover full work space
	Stable movement along tunnel axis
	Pass Fire Doors
	Robust Collision Avoidance
	High Dexterity Manipulator
	Autonomous operation
	Operate in cluttered work space
	Specific Tools
	Tool Changer
	Fast Interventions
	Modularity
	Teleoperation with Haptic Feedback
	End-effect payload ~ 15 kg
	Material transport Payload ~> 50 kg
Emergency	Not Blocking Emergency Ways
	Specific Tools (Infrared Camera, Radar, Locate & extinguish fire)
	Move in Harsh Cluttered Environment
	Robot Speed ~ 34.2 km/h



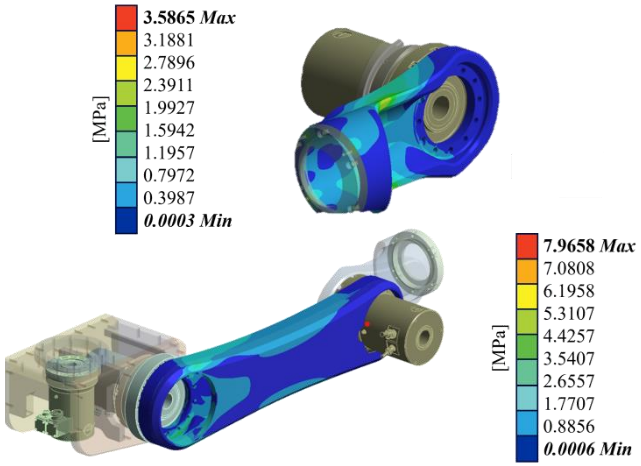
Requirement studies

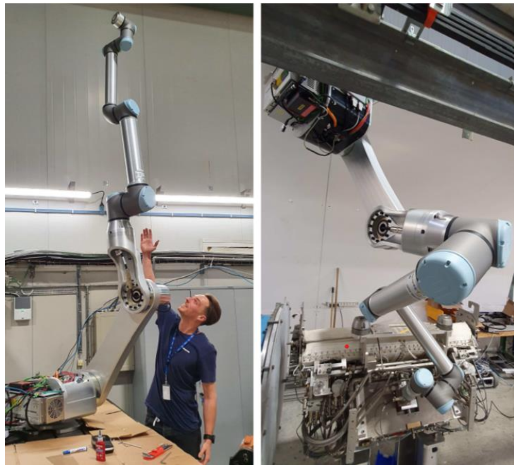


Length	[mm]
$l_{1,2}$	var.
$l_{2,4}$	288
$l_{4,5}$	927
$l_{5,6}$	0
$l_{6,8}$	754
$l_{8,9}$	0
$l_{9,10}$	635
$l_{10,12}$	518
$l_{12,E}$	100



Optimized Geometry and topology

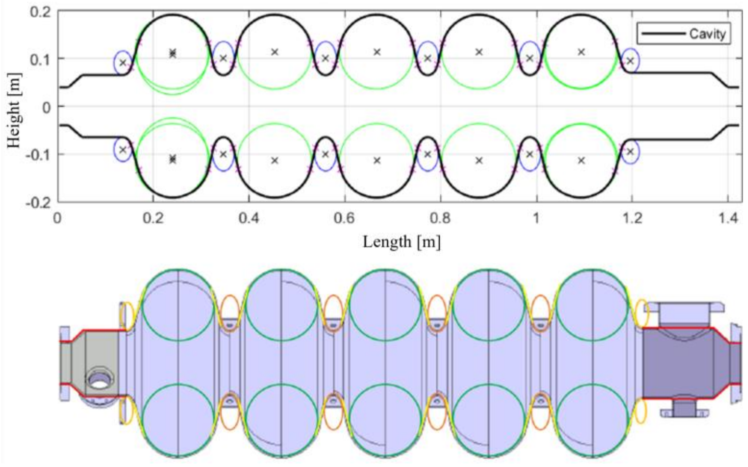




Topology optimization results and device realization

Case Study #2: RF cavity inner surface visual inspection

- The optimal design of the inspection arm gives the starting point for the mechanical design of the robotic system.



The operation requirement/environment of the cavity inspection robot

- **Defintions**

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

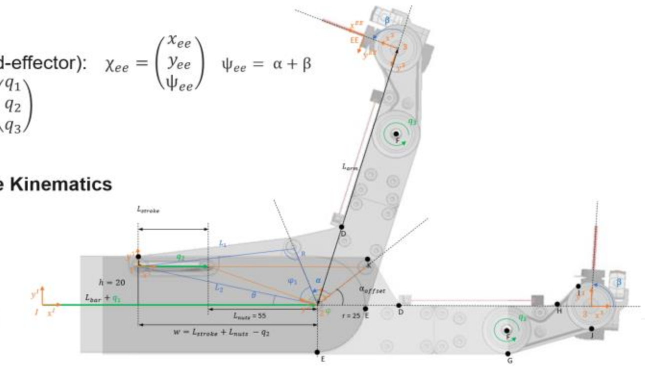
Joints Space: $q_{ee} = \begin{pmatrix} q_1 \\ q_2 \\ q_3 \end{pmatrix}$

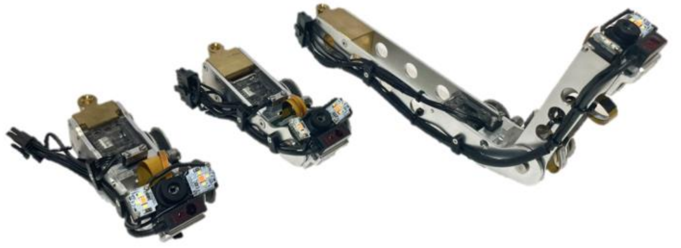
- **Forward & Inverse Kinematics**

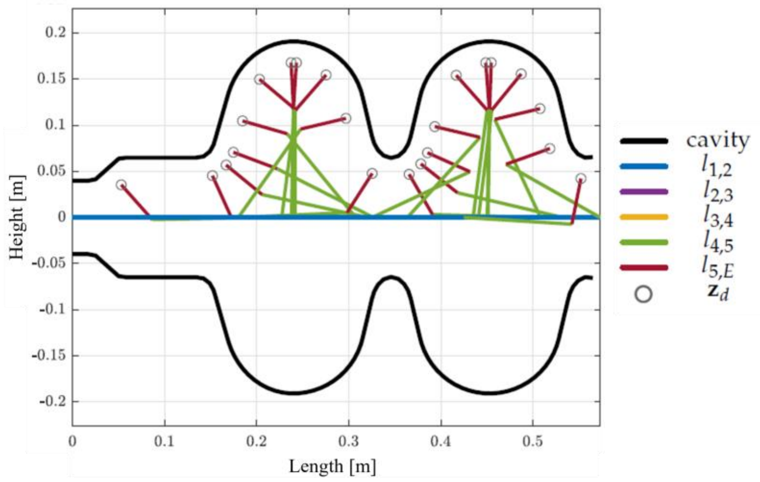
$\dot{\chi}_{ee} = J_A(q)\,\dot{q}$

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

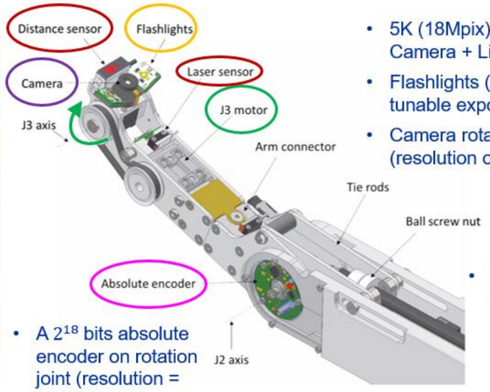
$qNext \cong qActual + \Delta q$



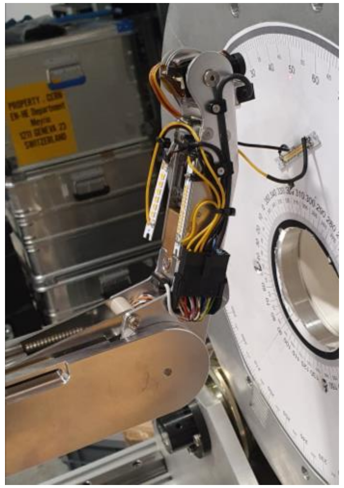




The optimal topology and geometry of the cavity inspection arm after applying the model pruning technique

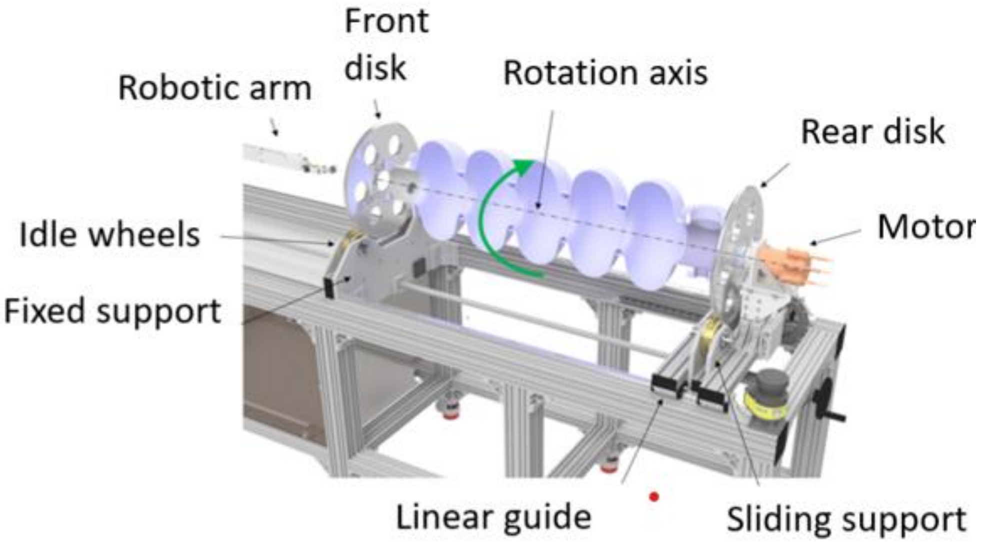


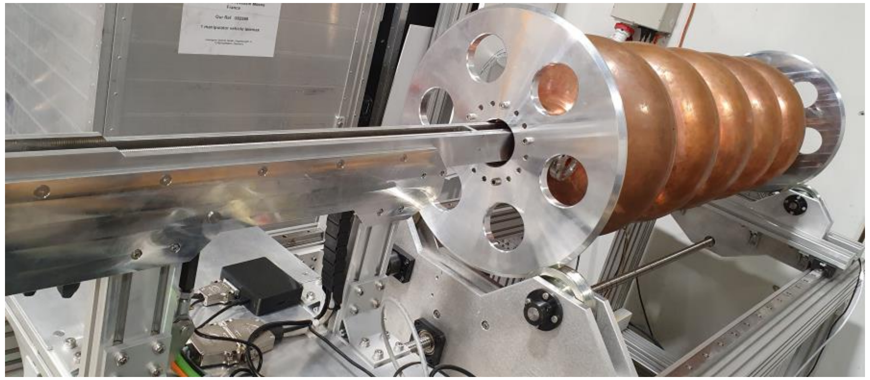
- 5K (18Mpix) miniature Camera + Liquid lens
- Flashlights (2x300 lm) with tunable exposure time (µs)
- Camera rotation – servomotor (resolution of 0.29 deg)
- Avoidance Collision system
- A 2^{18} bits absolute encoder on rotation joint (resolution = 0.0014deg)



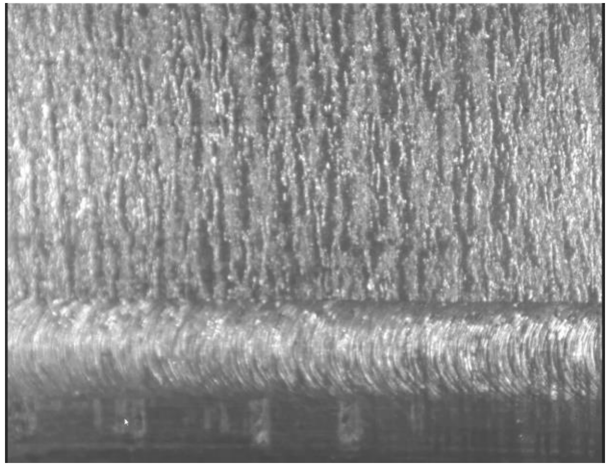
The mechanical design of the robotic arm and its realization based on the optimized design space

Case Study #2: RF cavity inner surface visual inspection





RF cavity inspection test bench



Autofocus on image of the cavity iris welding.
Size: 1 x 1 cm taken at 23 mm distance

Robotic am inside the cavity

Conclusions

- Significant impact of Industry 4.0 technologies, specifically robotics, on improving maintenance and inspection in challenging environments such as those found in particle accelerators

- By considering robotic interventions during the early design phase of new machines, we can optimize solutions to meet the specific requirements of complex environments

- To fulfil challenging needs for remote maintenance and quality assurance, robots topology and kinematics designs can be optimized thanks to the proposed work

- This proactive strategy not only ensures higher efficiency but also contributes to the safety and availability in harsh environment

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

BEAMS

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 UZH
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
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

www.cern.ch

CERN

More on : Academic training lectures on robotics,
https://indico.cern.ch/event/1055745/

“If you have an apple and I have an apple and we exchange these apples then you and I will still each have one apple. But if you have an idea and I have an idea and we exchange these ideas, then each of us will have two ideas.”
George Bernard Shaw

Mario.Di.Castro@cern.ch