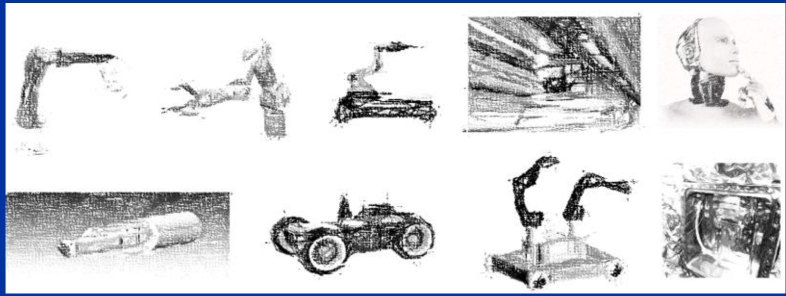


Robotic Framework at CERN in BE-CEM

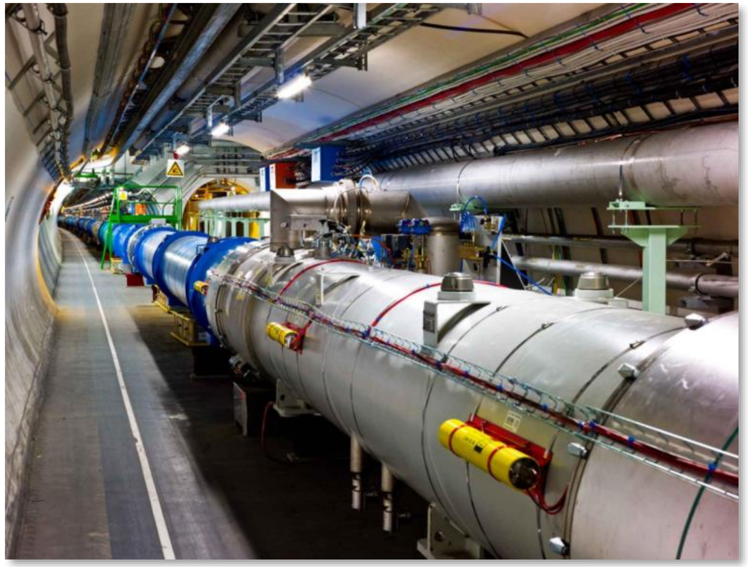
Mario DI CASTRO

CERN, BE-CEM group

MOCRAF WORKSHOP, ICALEPCS23, 8th of October 2023, Cape Town

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**



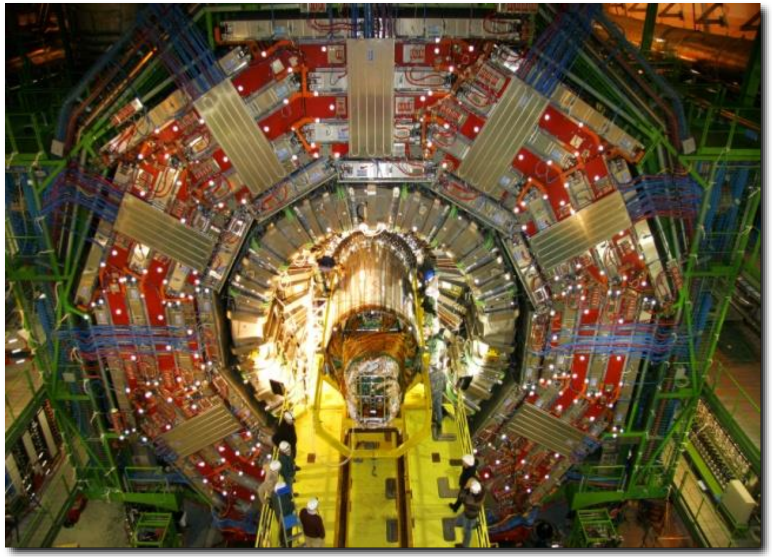
The LHC tunnel

North Area experimental zone

Radioactive sample handled by a robot

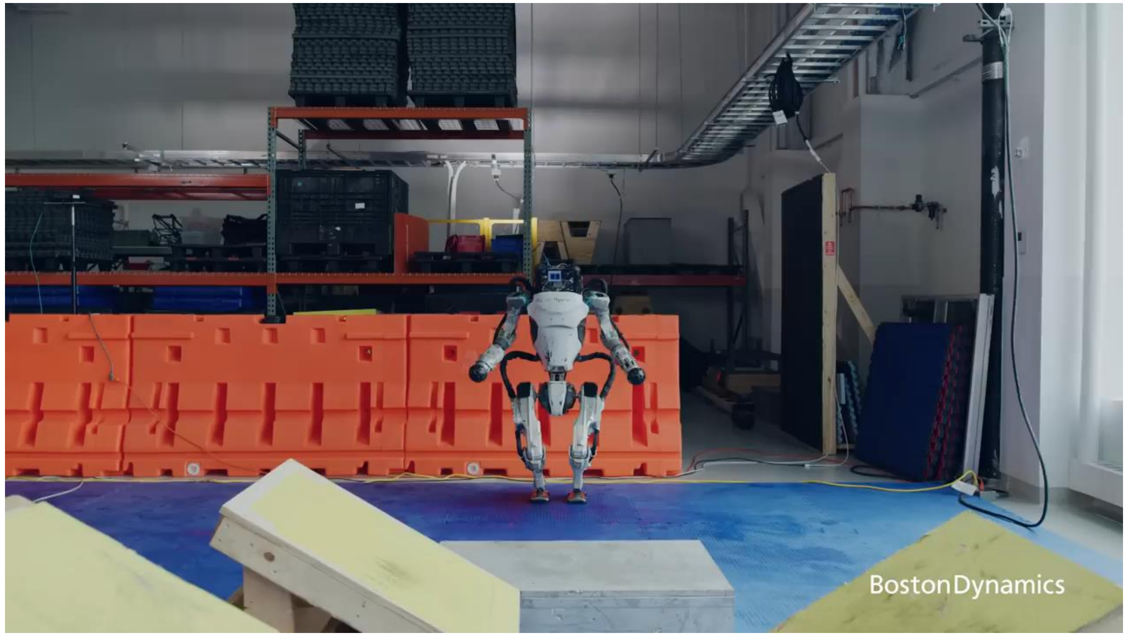
Main difficulties for robotics at CERN

- **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.

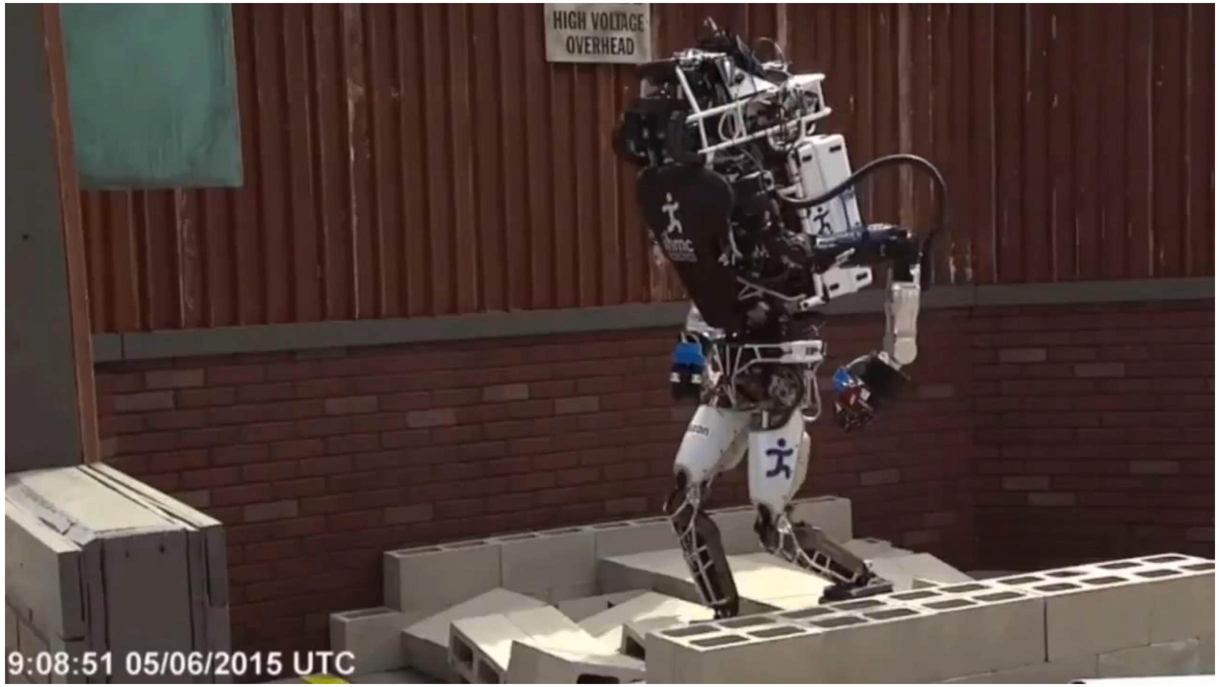


Our dream:
Robots made in Hollywood and by Boston Dynamics

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



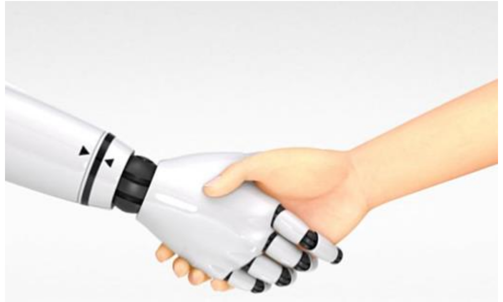
Robots trying to solve "real" tasks in difficult environment



Availability of Particle Accelerators

Reliability	Maintainability	Availability
If Constant	Increase ↑	Increase ↑
If Constant	Decrease ↓	Decrease ↓
Increase ↑	If Constant	Increase ↑
Decrease ↓	If Constant	Decrease ↓

- @ constant machine reliability, maintainability drives availability
- Improve maintainability increasing efficiency of human interventions
  - ✓ using robots in collaborations with humans
- Accelerator Reliability Workshop (ARW)

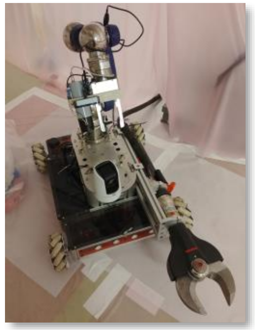


Reliable robots must be developed, and recovery scenarios must be foreseen

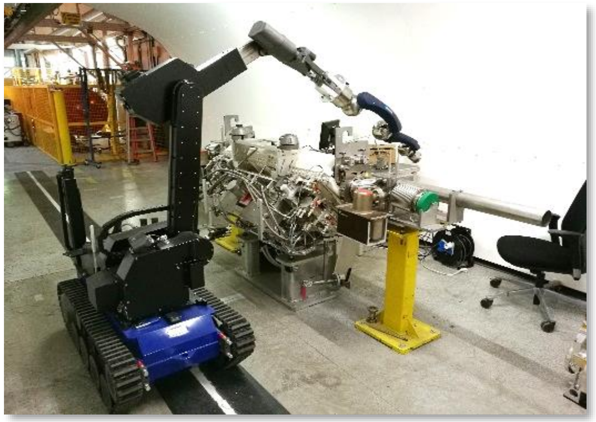
The Robotic Service at CERN: Overview of robots pool

Telemax robot

Train Inspection Monorail (CERN made)

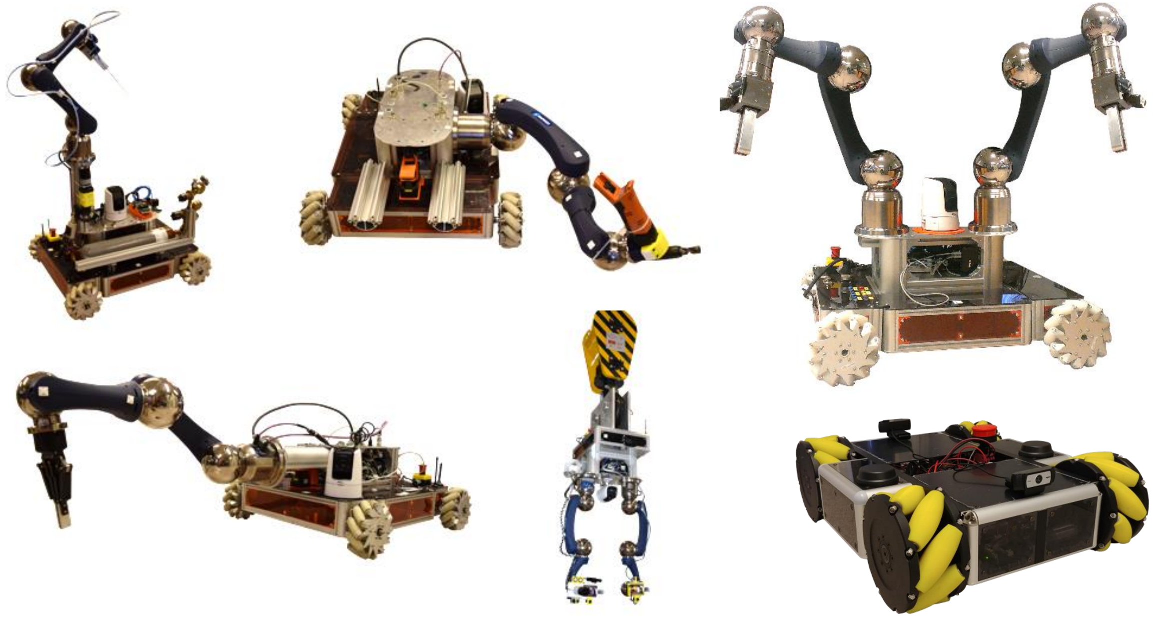


More than 20 robots (custom made and/or industrial with custom controls) are in operation. Mechatronics conceptions, designs, proof of concepts, prototyping, series productions, <u>operations</u>, maintenance, tools and procedures



Teodor robot

EXTRM robot (CERN controls)



CERNBot in different configurations (CERN made)

High payload manipulator

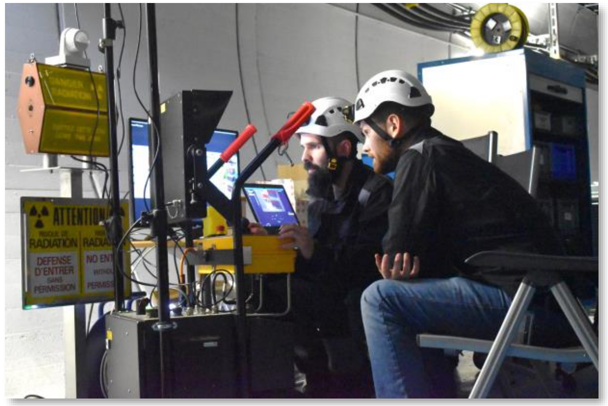
Drone for tele-operation support

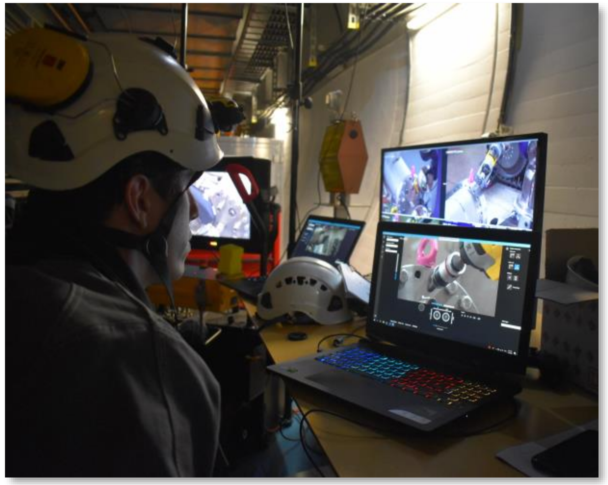
Quadrupeds for “difficult” zones

The Robotic Service at CERN

Robotics technologies are mainly used for:

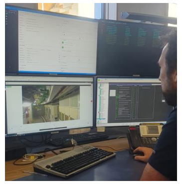
- Remote maintenance
- Human intervention procedures preparation
- Quality assurance
- Post-mortem analysis
- Reconnaissance
- Search and rescue
- And more…

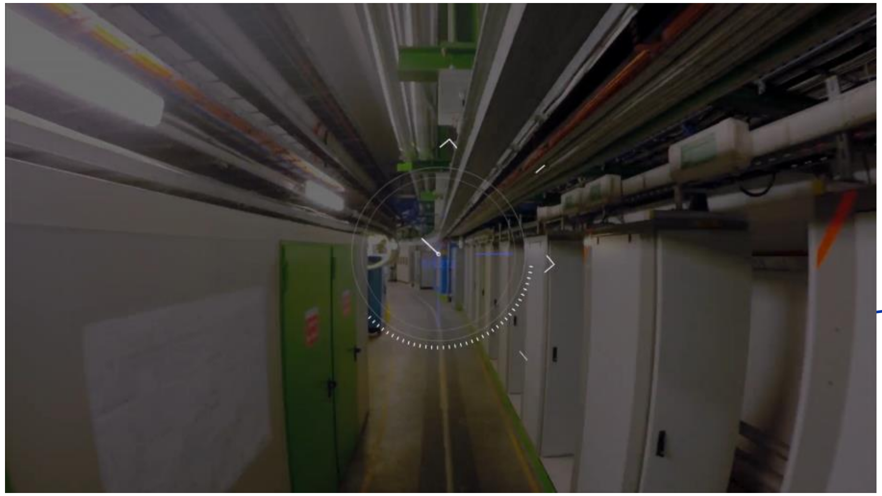


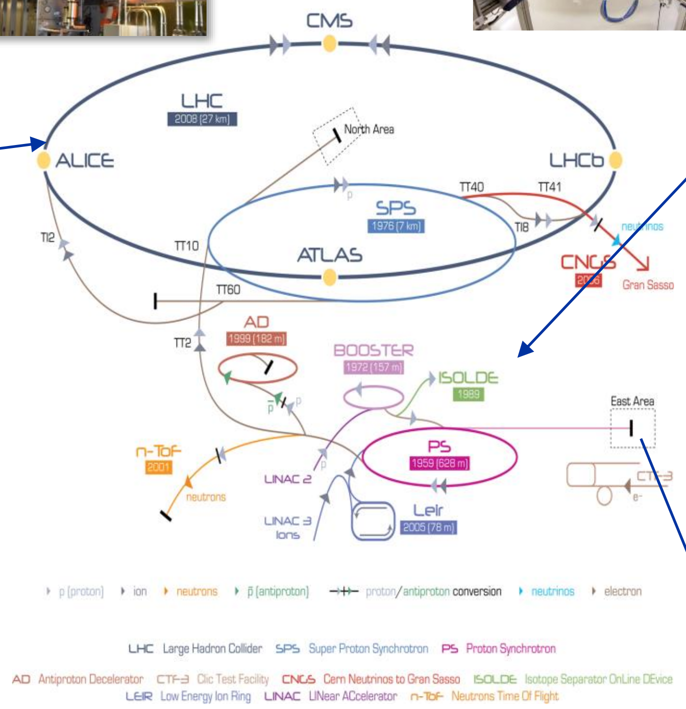

Robots integrated within accelerator facilities

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

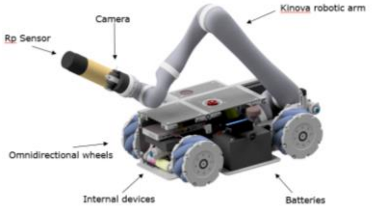




4x Train Inspection Monorail (TIM)



3x ISOLDE / MEDICIS high payload industrial robots

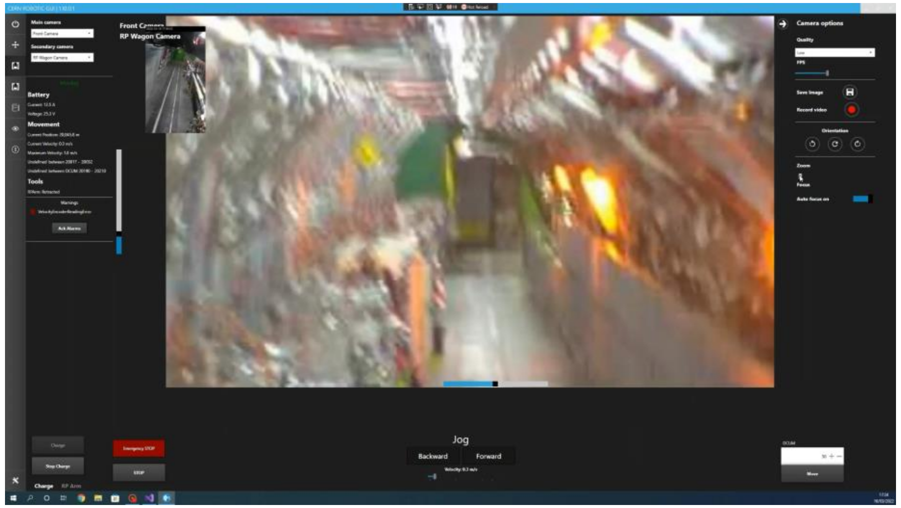


2x SPS robot

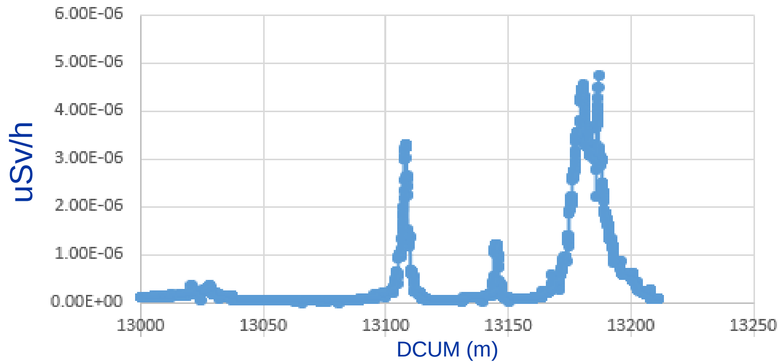
CHARM robot

TIM

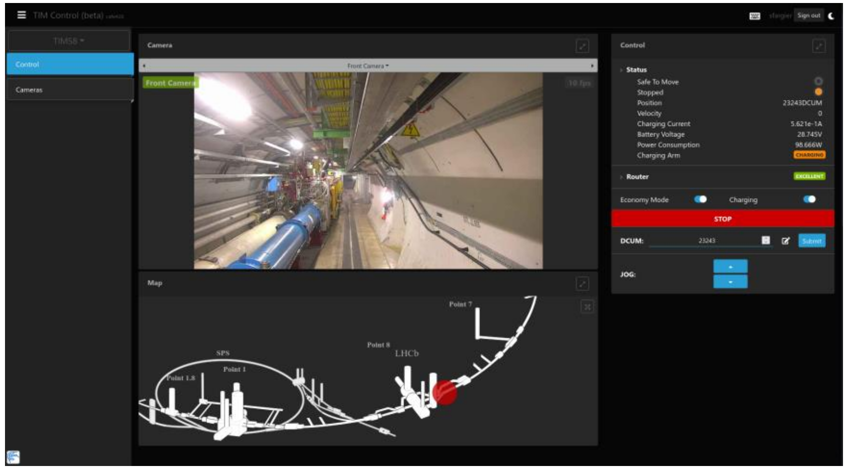
- TIM x4 RP survey to open LHC sectors for access
- Finalization of OP-TIM interface for operations by TI crew from Q1-2023

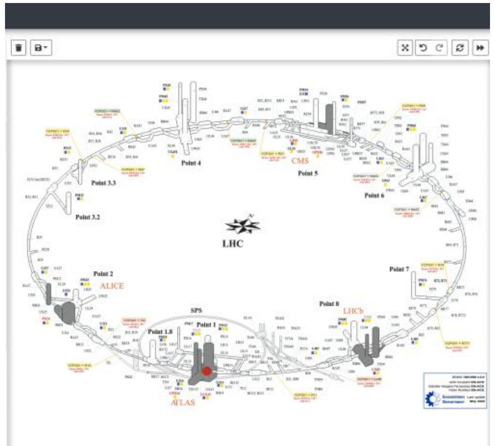


TIM operation for RP measurements through the expert interface from CCC



Example of RP measurement taken with TIM

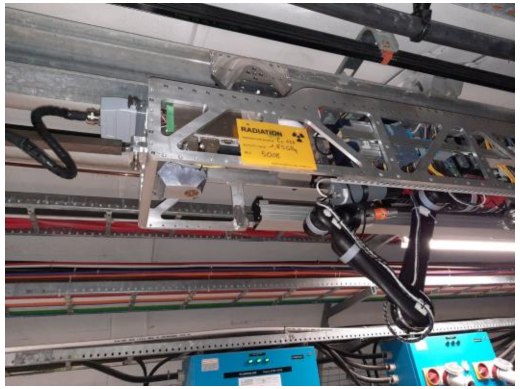


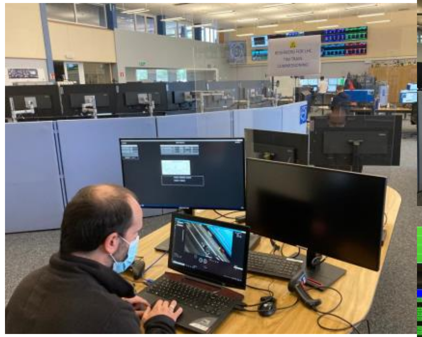


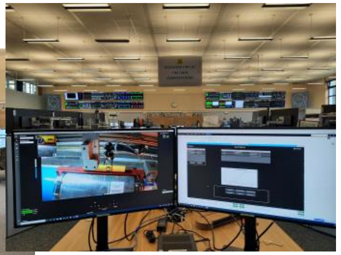
Beta version of the new TIM TI/OP interface through FESA and SSVG part to show the robots location within the LHC

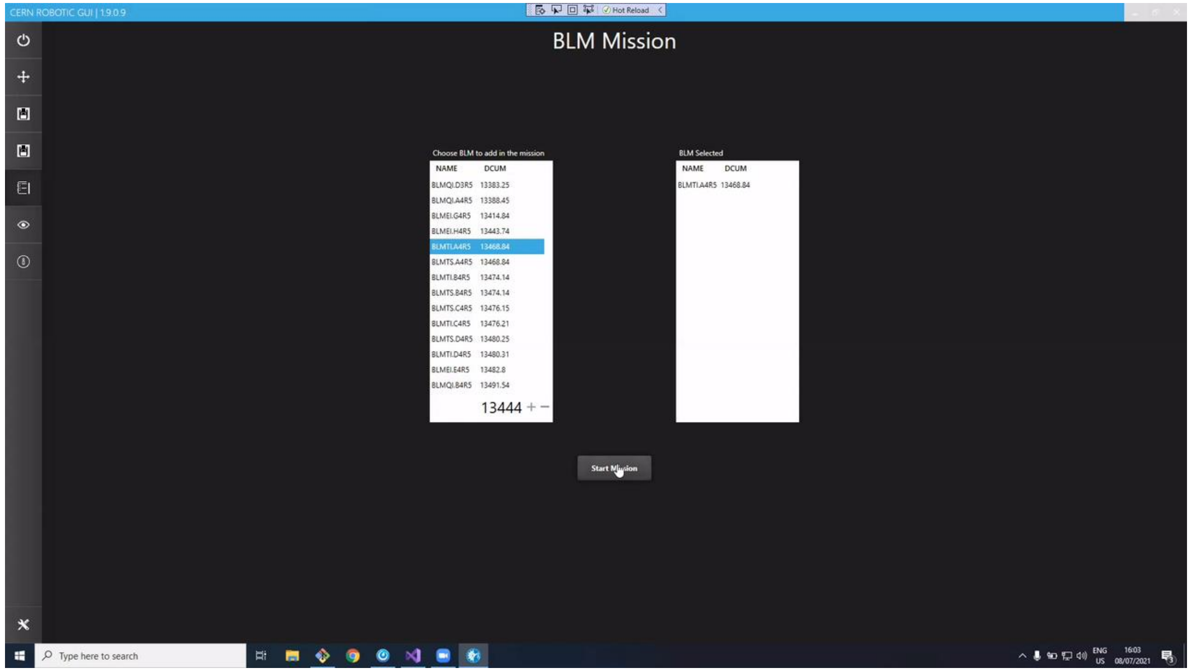
Novel TIM robotic wagon

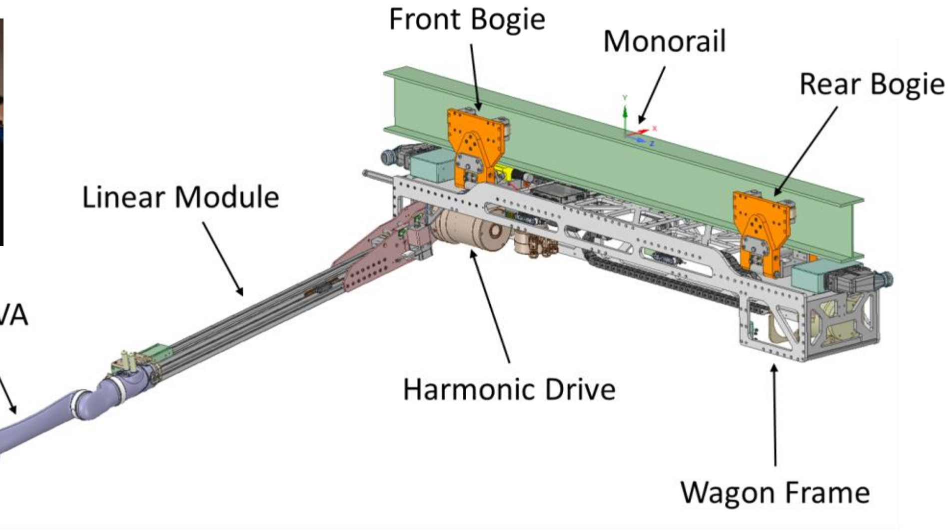
- 6 DoF (rotational axis) + 1DoF (linear axis) for dexterity
- 2 DoF (harmonic drive, backlash-free) for transversal positioning
- 1 stabilization axis
- 5 cameras







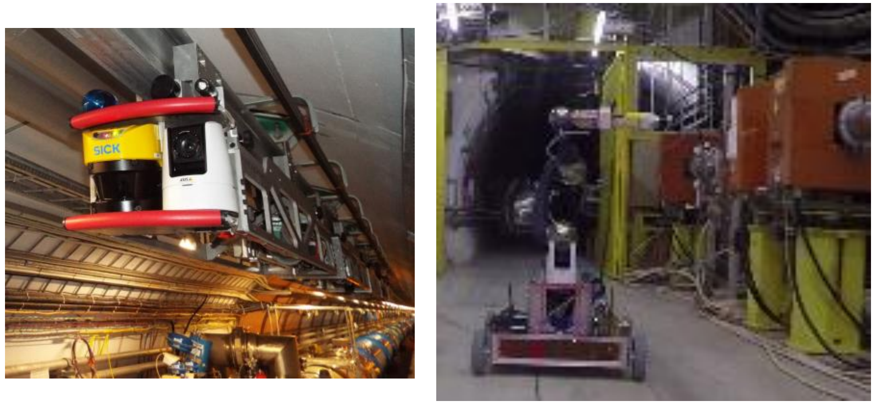




New TIM robotic wagon with extracted arm

Robotic preventive maintenance and inspection

SPS MKP oilers refill

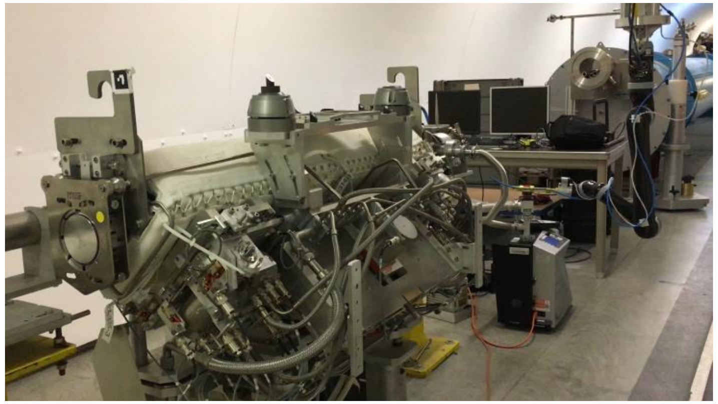


Remote radioprotection surveys

Cabling status inspection

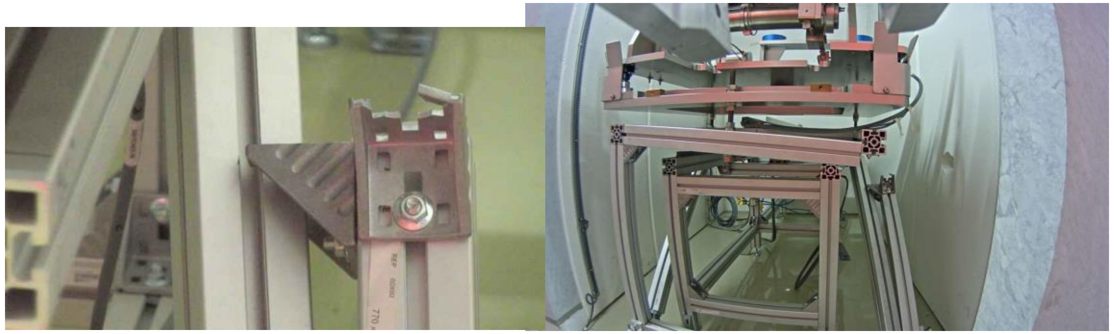
Temperature sensor installation on AD target

Tunnel structure monitoring

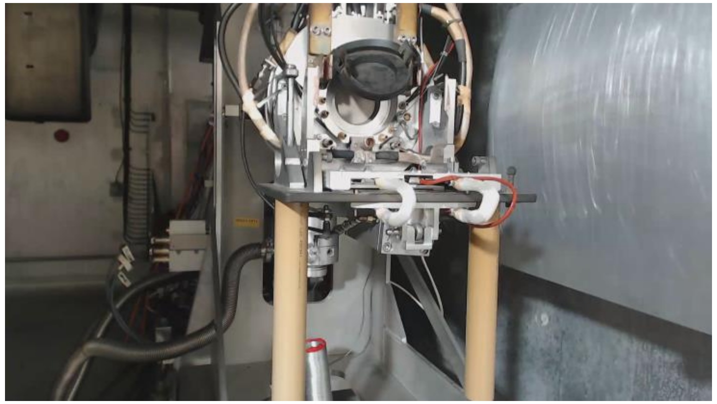


Remote Vacuum Leak detection

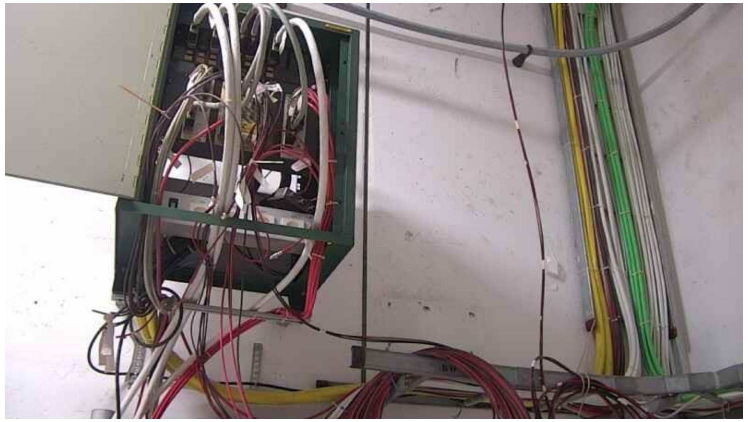
Fast reaction to equipment failures in radioactive areas



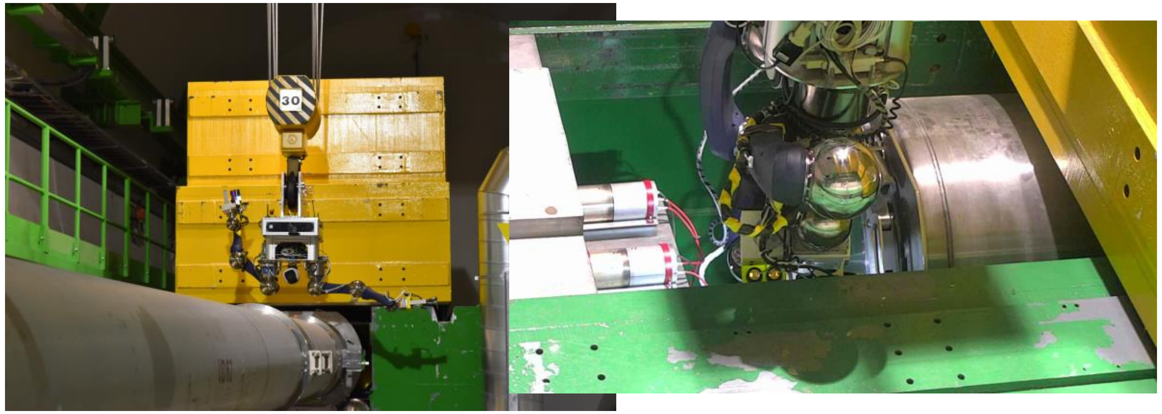
CHARM Target
In place 1 hour after the call




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

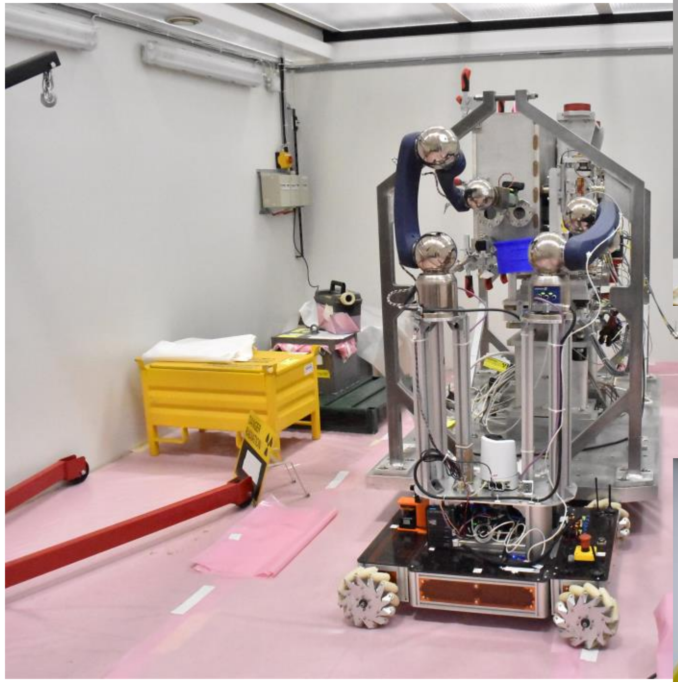


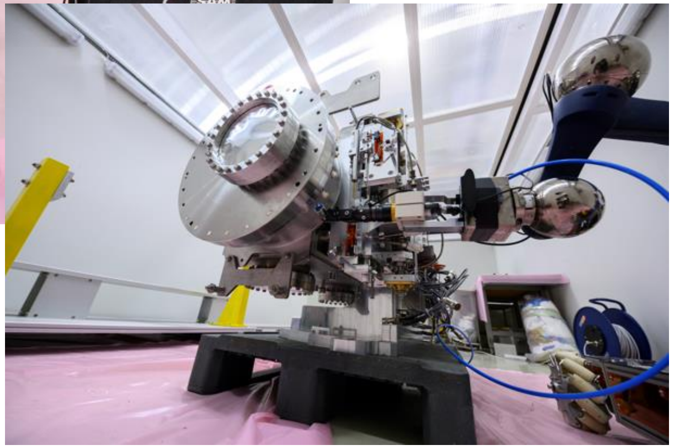
North Area BLM cables connection
In place 50 minutes after the call

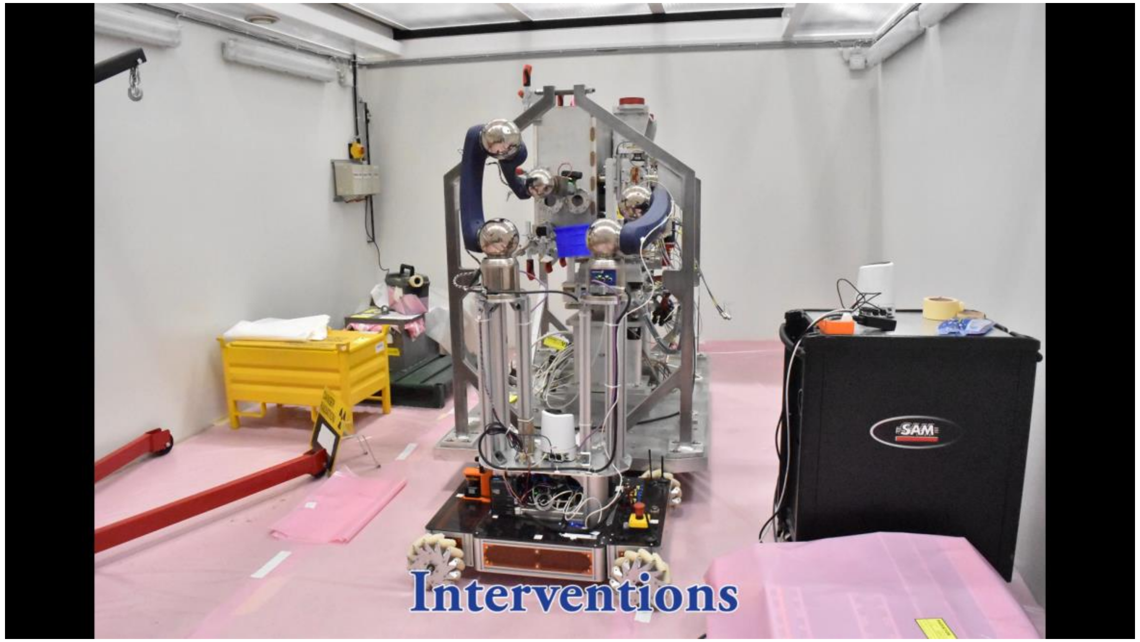


LHC TDE
New robot built in 3 days

Post-Mortem Analysis

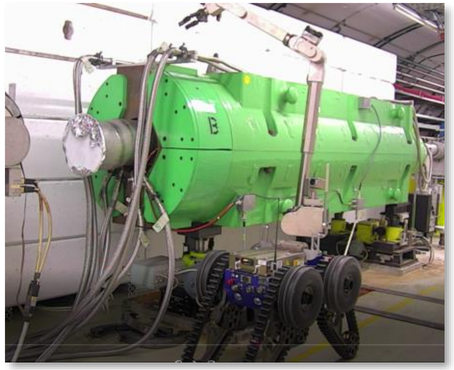


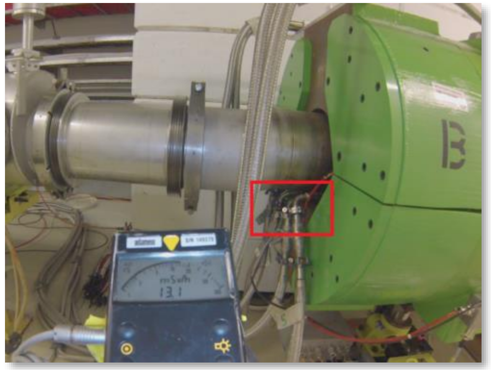


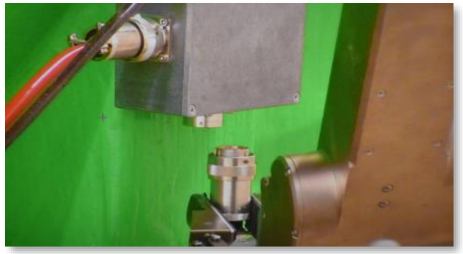


Importance of the design phase

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







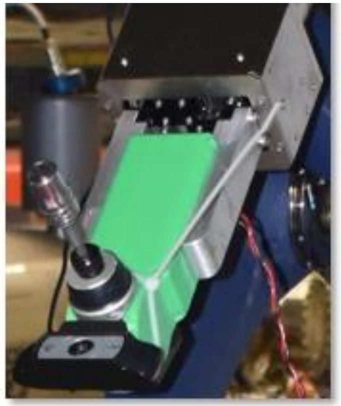
Easier remote or hands-on manipulation than chain-type connection

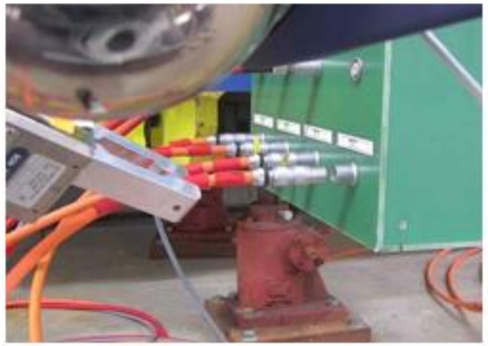
Procedures and Tools

- 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



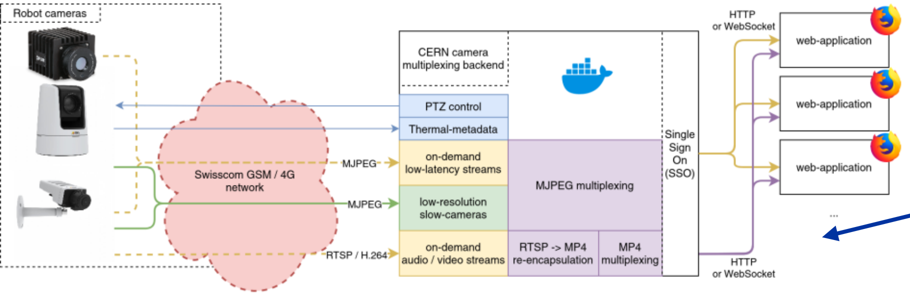




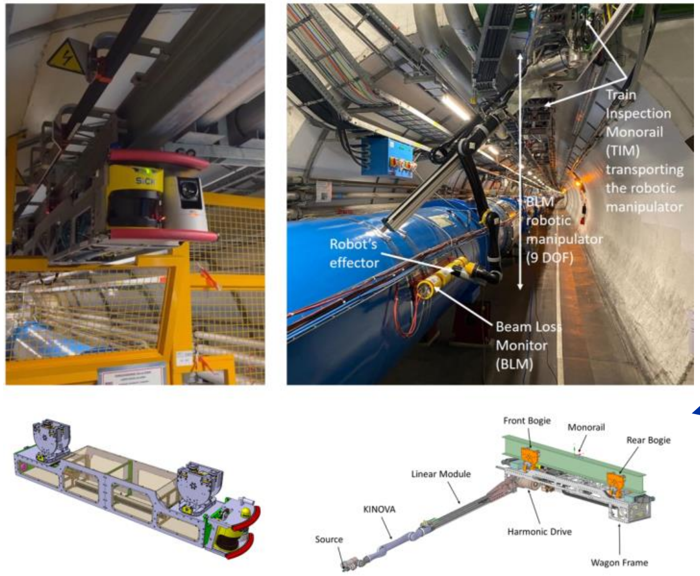



More on L. Buonocore lecture

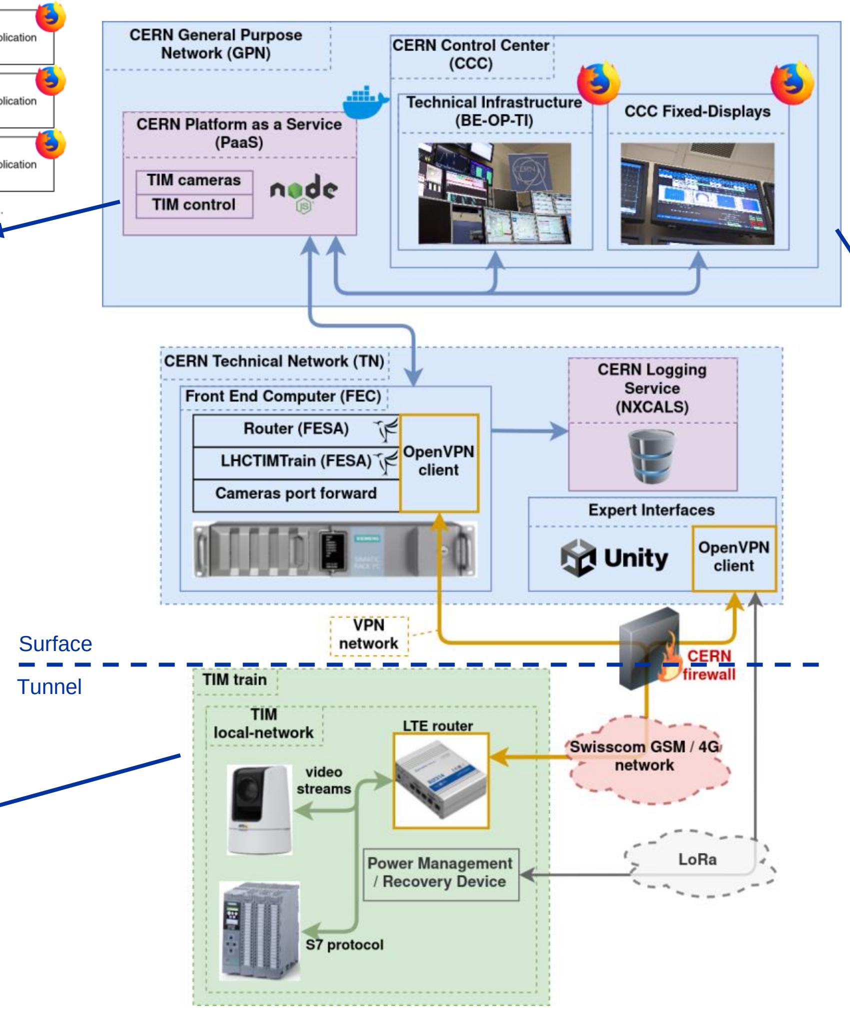
Operational Controls for Robots Integrated in Accelerator Complexes



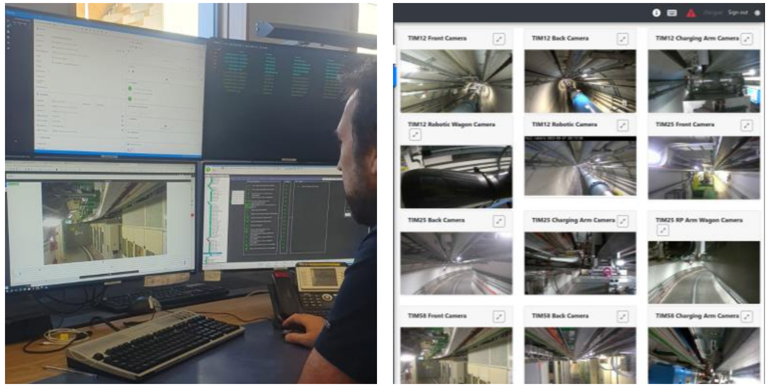
Novel framework developed for camera images streaming from the TIM robot



TIM robot passing the LHC sector doors (top left), 3D view of a TIM wagon (bottom left), 9 degrees of freedom robotic wagon (top right), 3D view of the robotic wagon (bottom right).

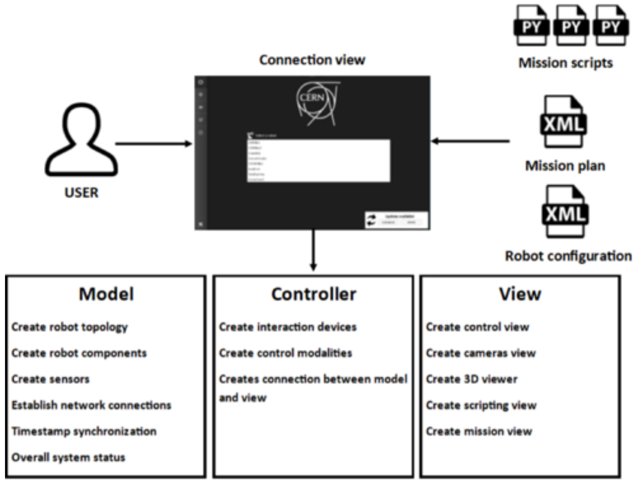


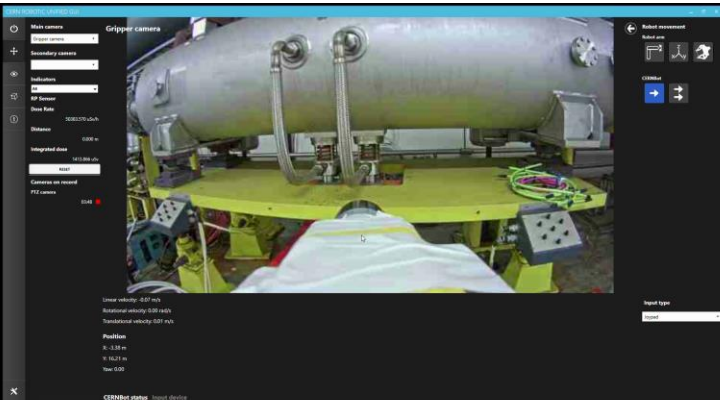
TIM operation general overview.

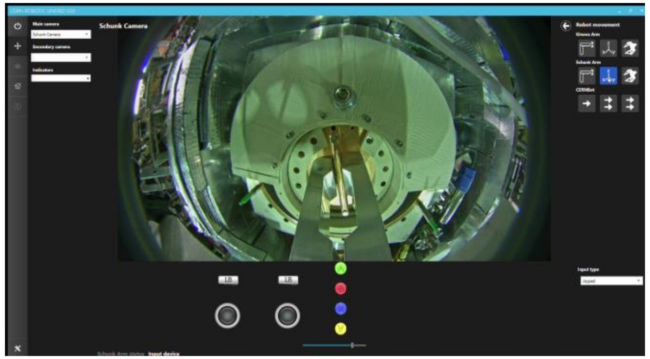


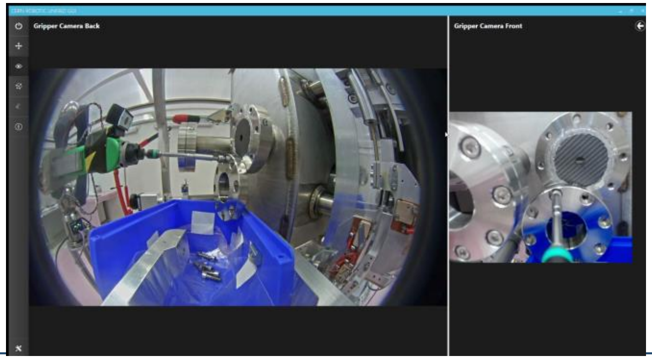
Human-Robot-Interface

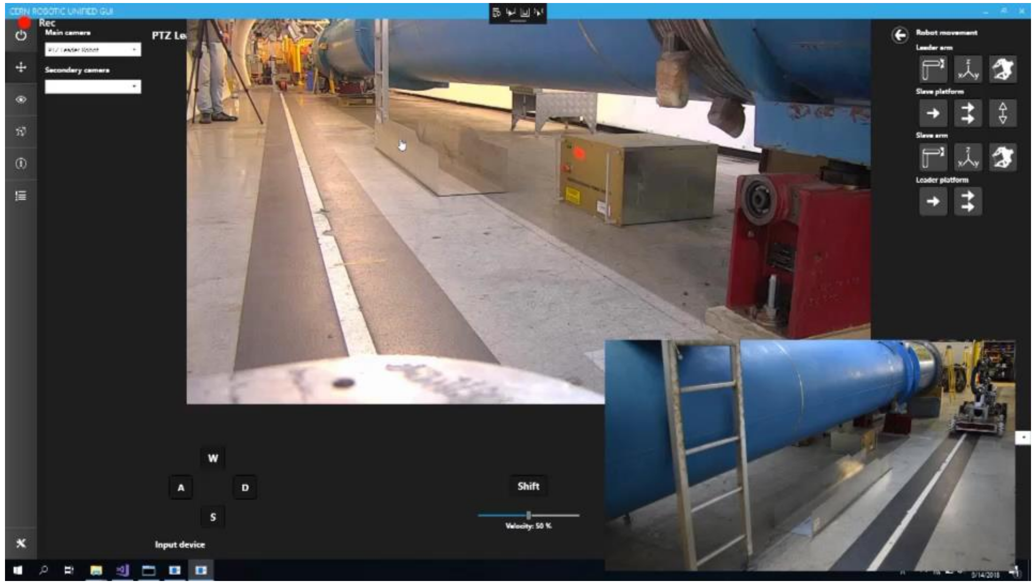
- ➢Controls all the BE-CEM robots
- ➢Includes enhanced reality modules
- ➢Different inputs device (keyboards, joystick, master arm etc.)
- ➢Operators training options
- ➢Multi screens capability
- ➢Time-delay passivation





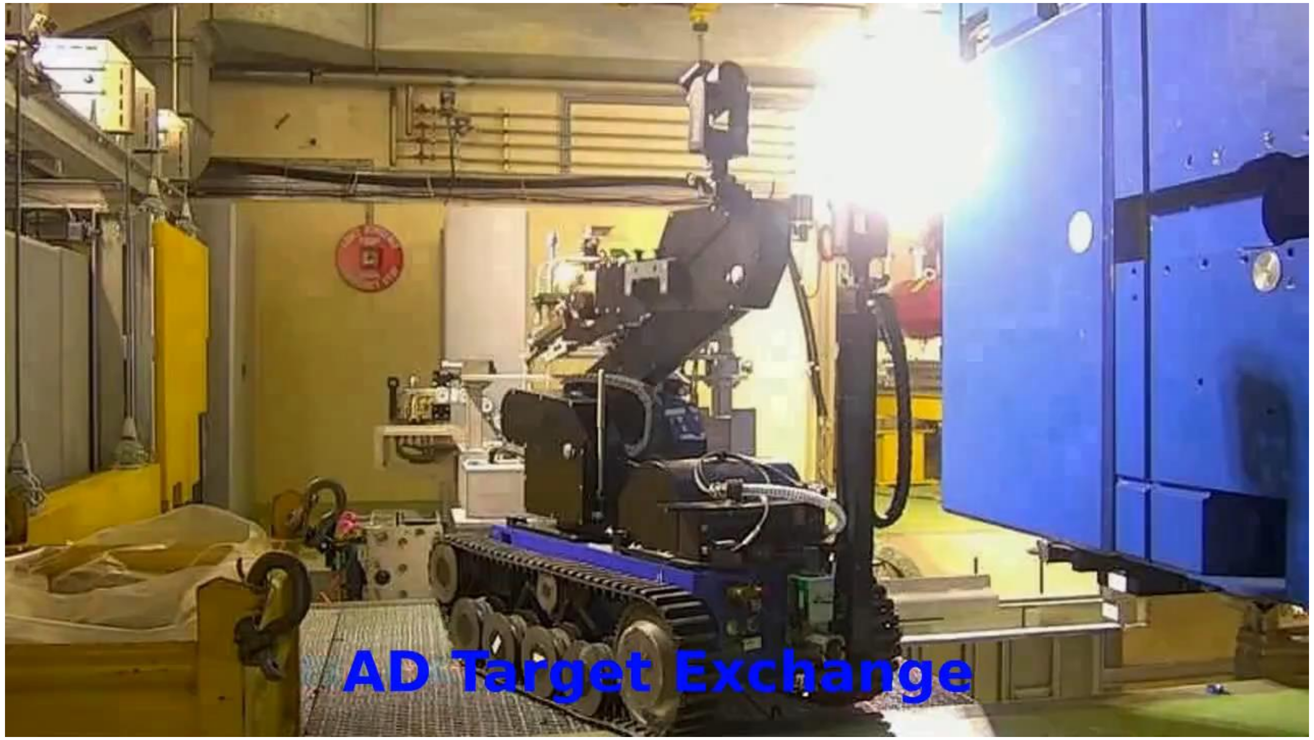


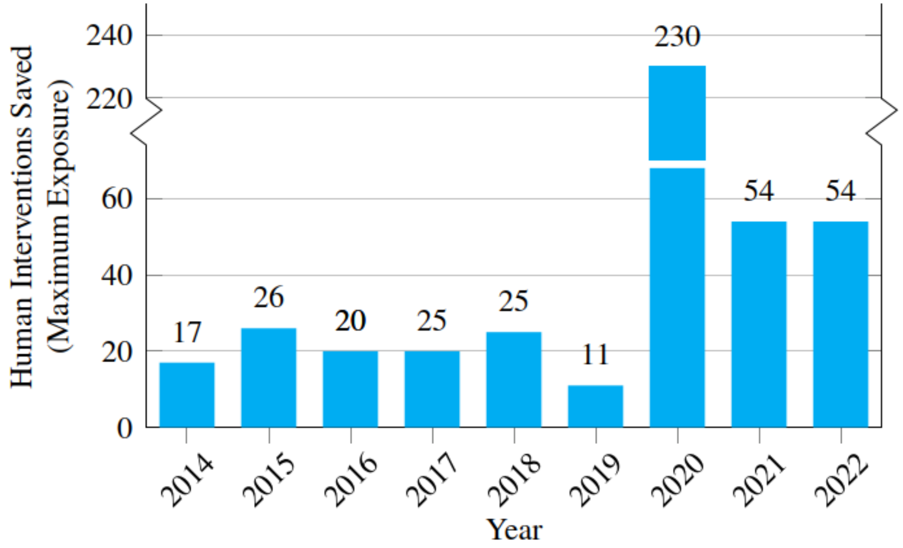




Robotics Interventions

- ➢ 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

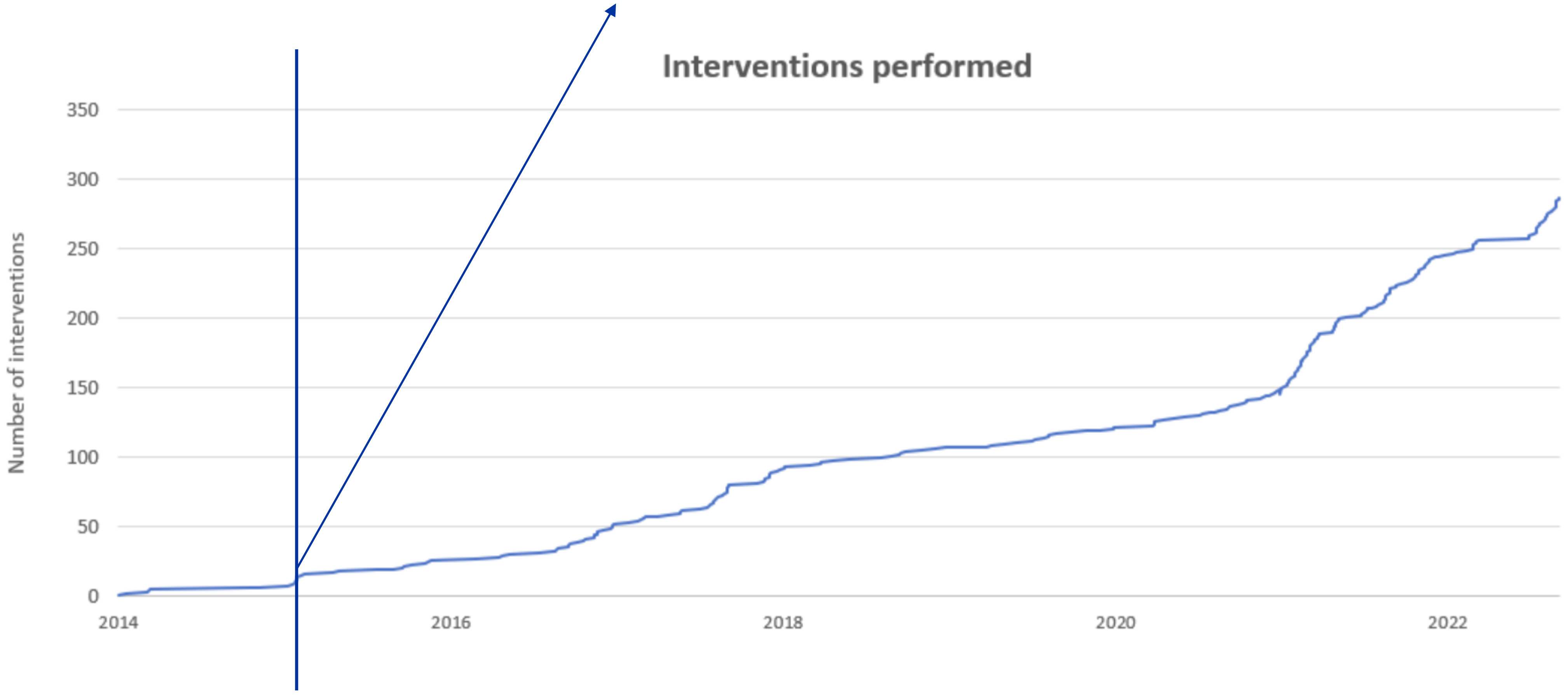




The equivalent number of human interventions saved with robotic interventions assuming maximum annual exposure

Robotics Interventions

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



Main Motivations for Custom Robotic Development #1

- 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**

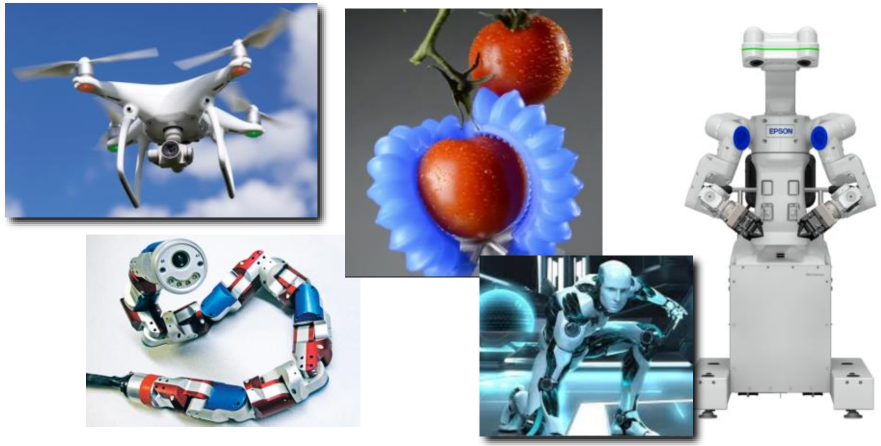
Novel Modular framework

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

Main Motivations for Custom Robotic Development #2

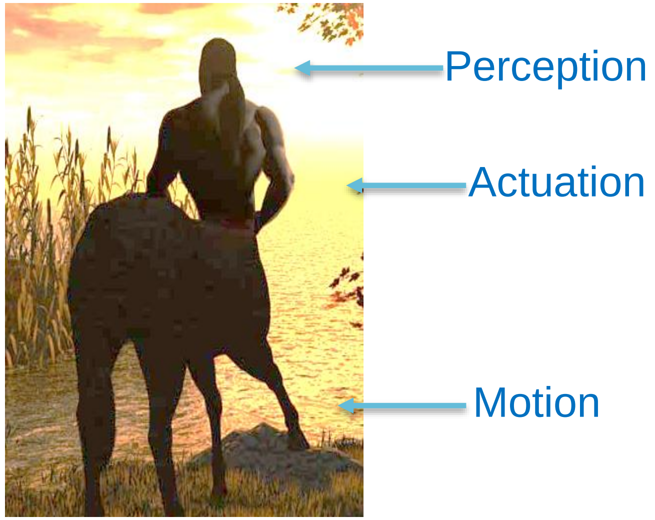
- Industrial robot have **very complicated human-robot interfaces demanding intense operators training**, controls are not open to be integrated in our control system, communication channel is often via radio signal, not built to reduce contamination risks etc.

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

CERNTAURO framework [7]

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

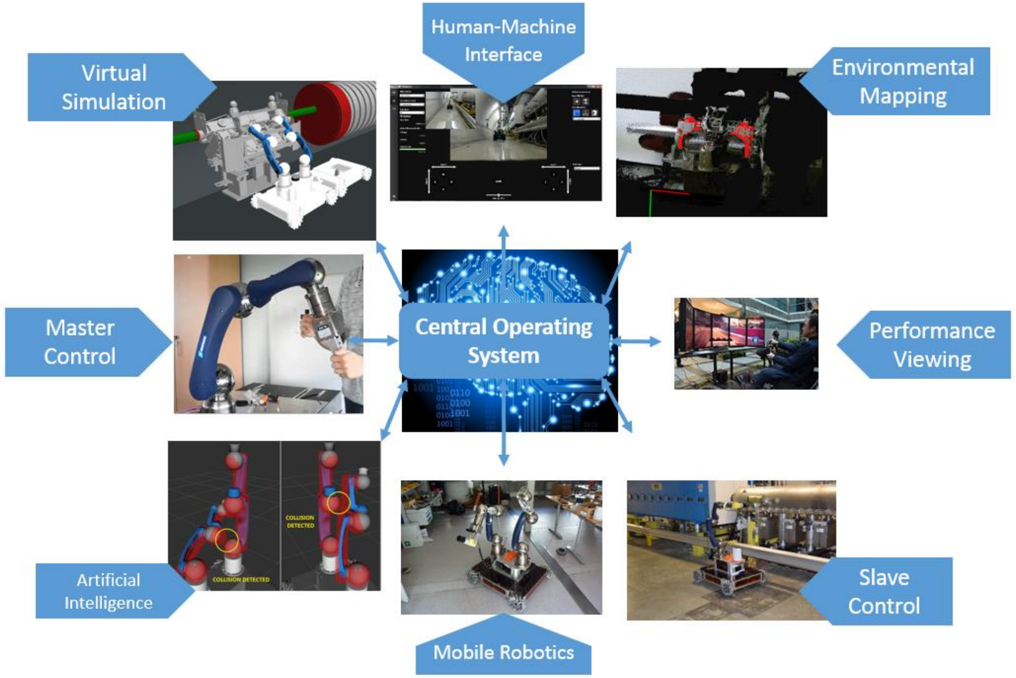
Mechatronic System

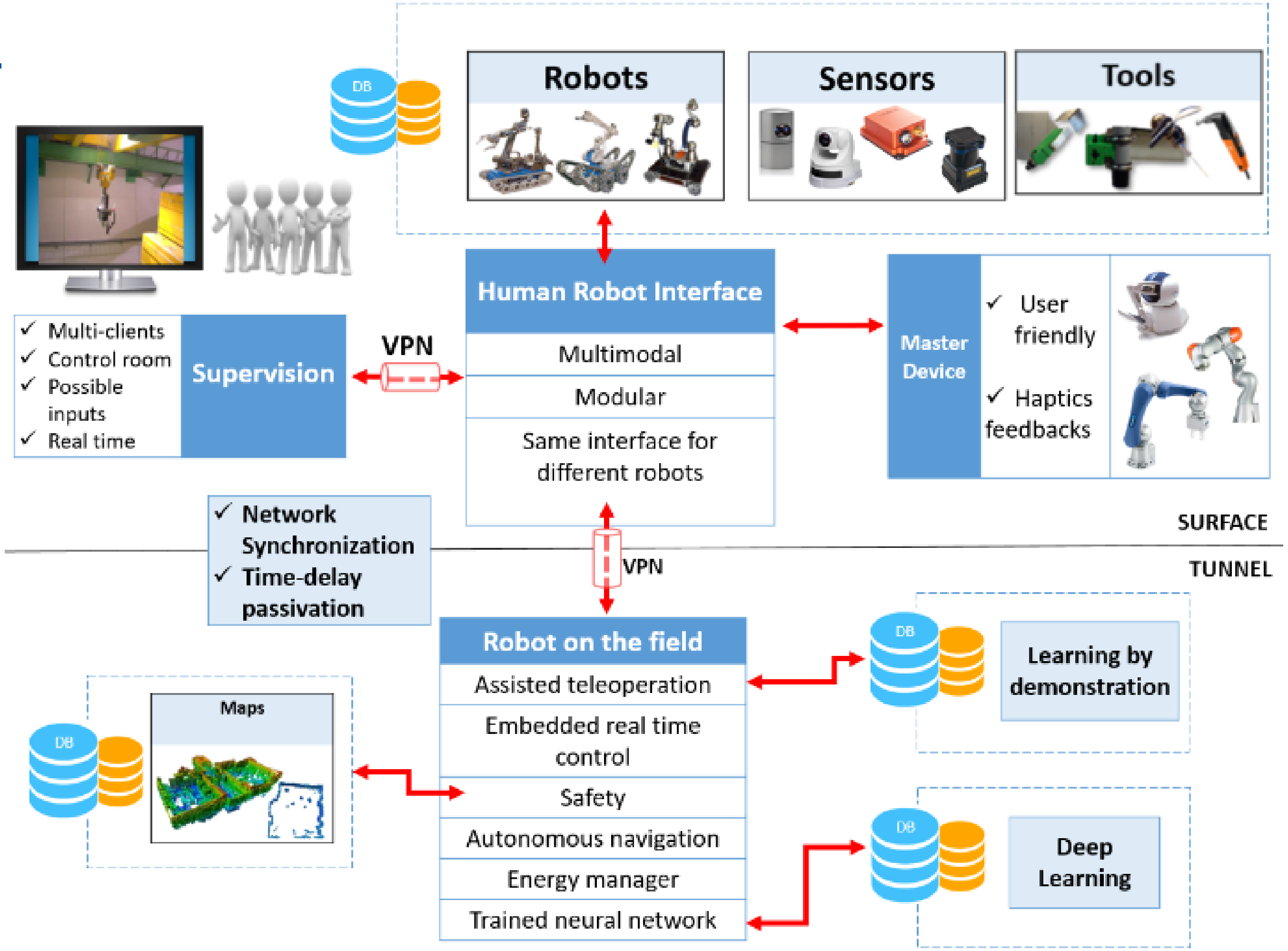


- **New robot and robotic control developed** [9-39]
  - ✓ Human robot interface
- **New user-friendly bilateral tele-manipulation system**
  - ✓ Haptic feedback
  - ✓ Assisted teleoperation
- **Artificial intelligence [30-31-38-40]**
  - ✓ Perception and autonomy
  - ✓ Deep learning
- **Operator and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

CERNTAURO framework

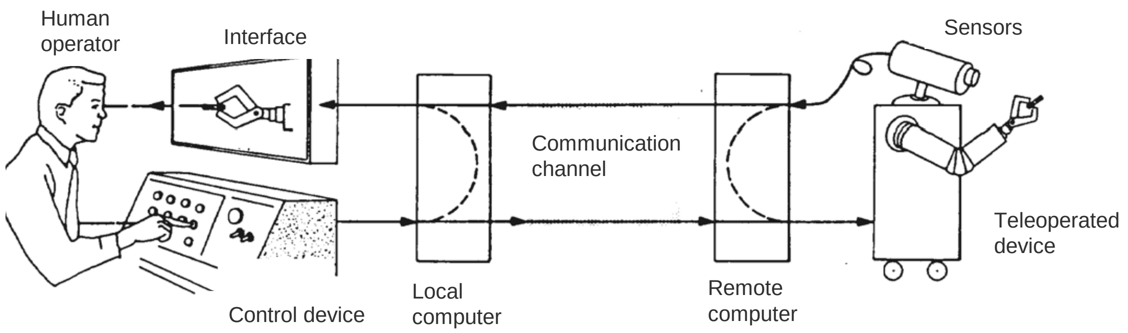
- In house robotic control system [7]
- No use of ROS [8]
- Sensor acquisition, fusion, measurements etc.

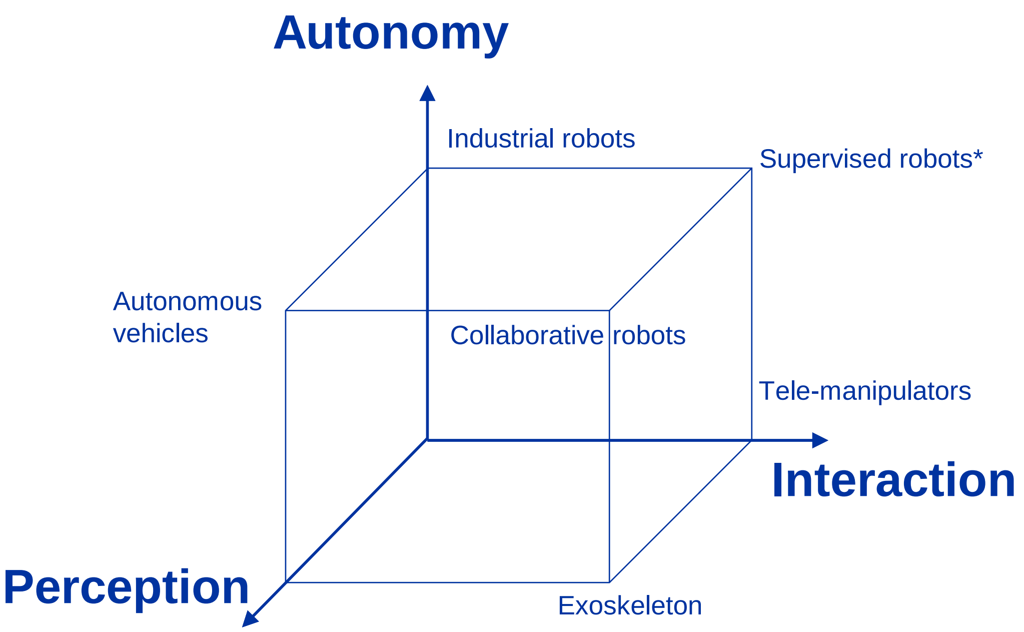




Interaction vs Autonomy vs Proprioception

- **Interaction**
  - ✓ Possibility of human-robot communication
- **Autonomy**
  - ✓ Capacity to decide independently the action to be taken in function of the environmental perception
- **Perception**
  - ✓ Spatial localization of the operator and the robot

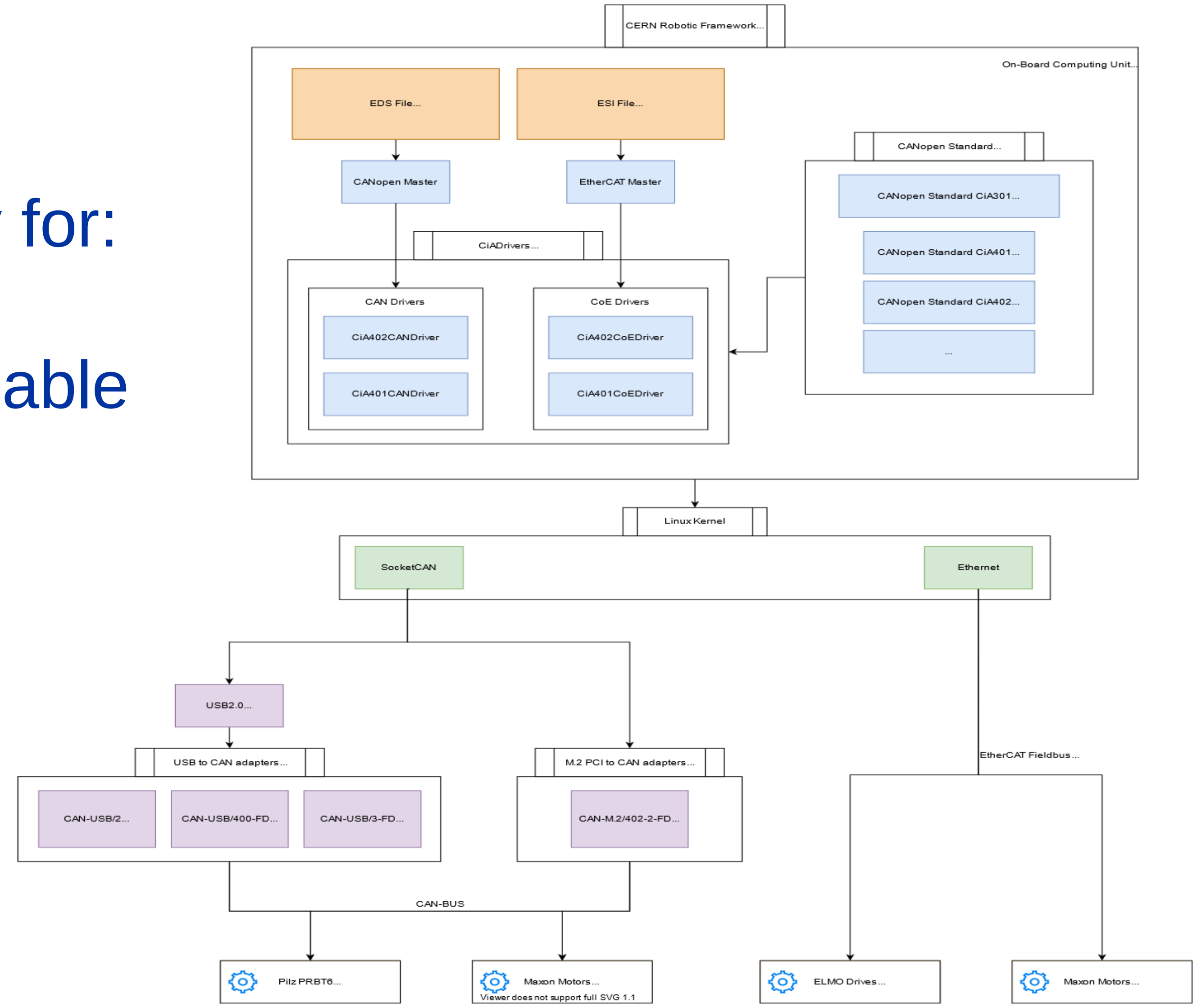




FIELDBUSES

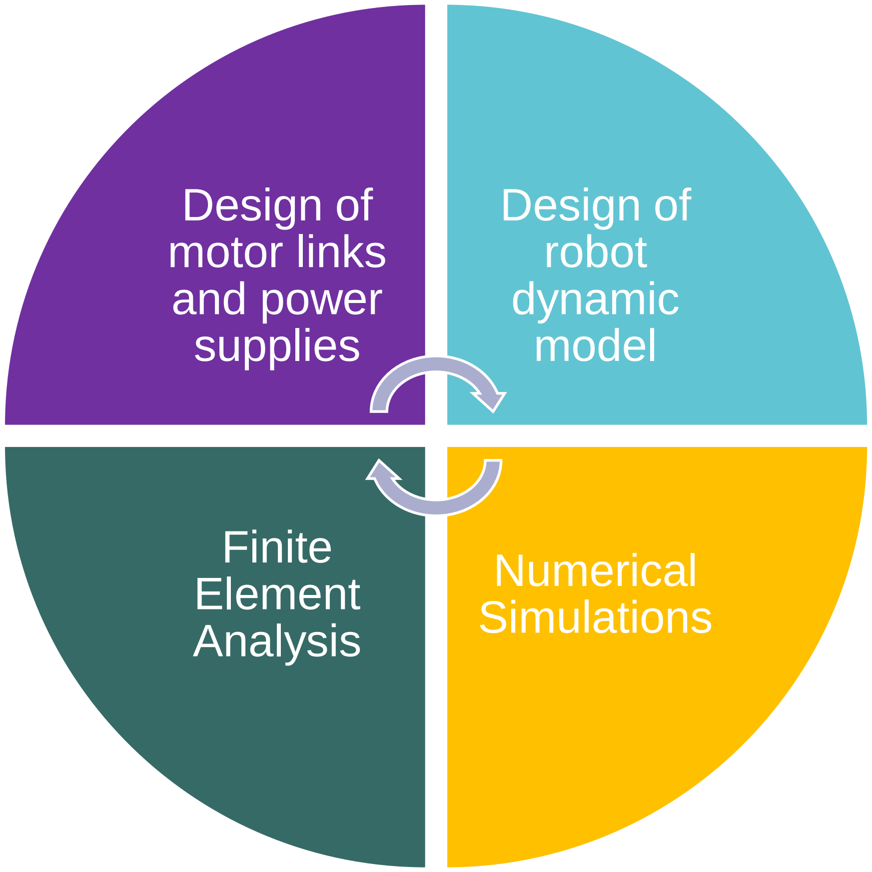
Migrating to EtherCat mainly for:

- ✓ Real-time controls
- ✓ Ethernet based, easy to cable
- ✓ Redundancy



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**

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

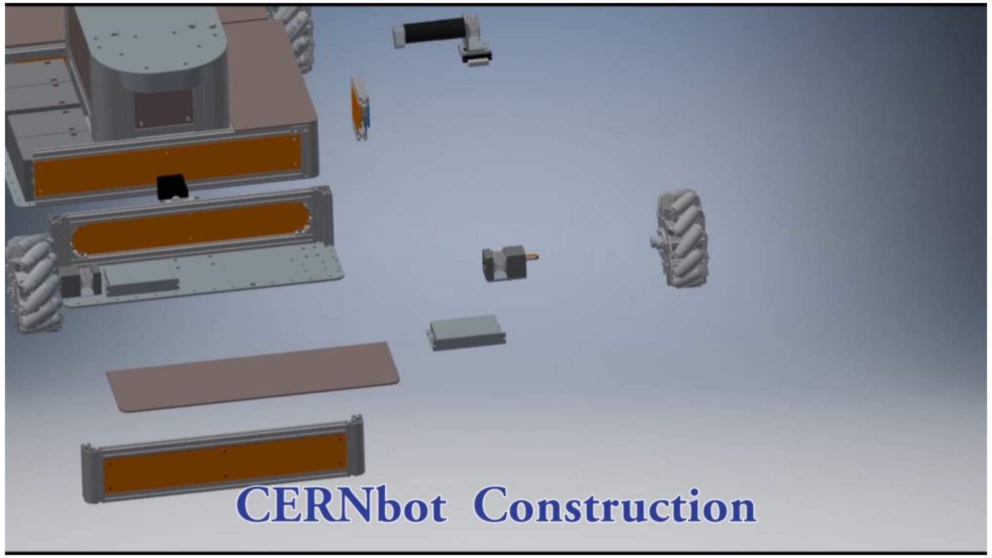
→ Constraint to ensures that the desired end position will be reached

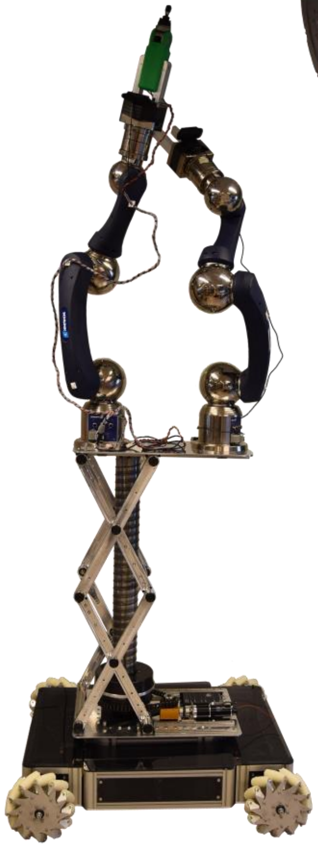
→ Constraint for collision avoidance

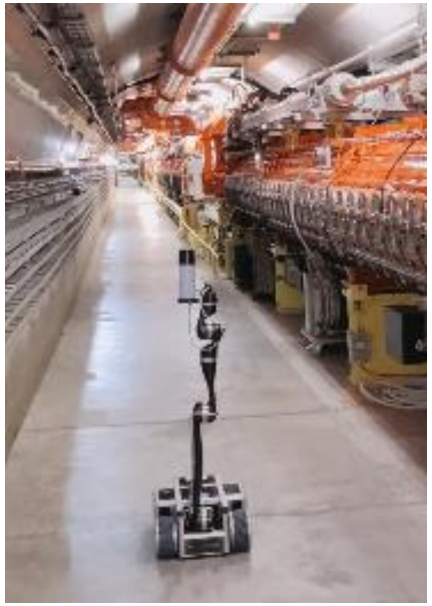
→ Constraints for mechanical joint limits

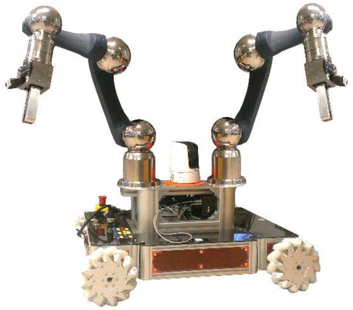
More info on Monday presentation, paper TUMBCMO25, session Feedback Systems & Optimisation MO3A

Modular Robot/Concept (CERNbot)







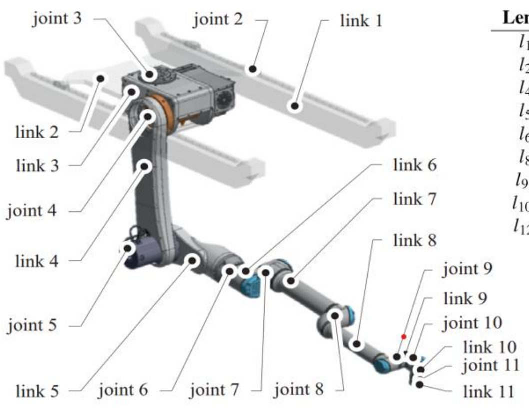


CERNbot, CERNbot2, CHARMbot, MIRA, CRANEbot

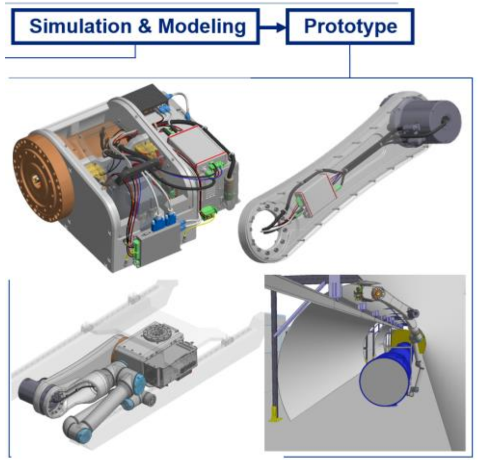
FCC Robot Design

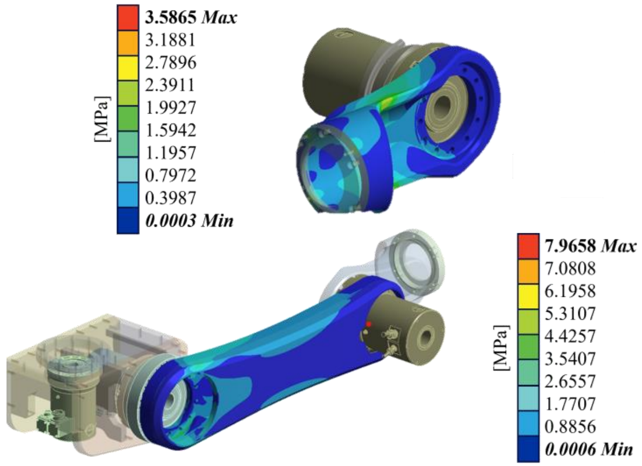
Gamper, H.; Gattringer, H.; Müller, A. and Di Castro, M. (2021). **Design Optimization of a Manipulator for CERN's Future Circular Collider (FCC),** ICINCO 2021

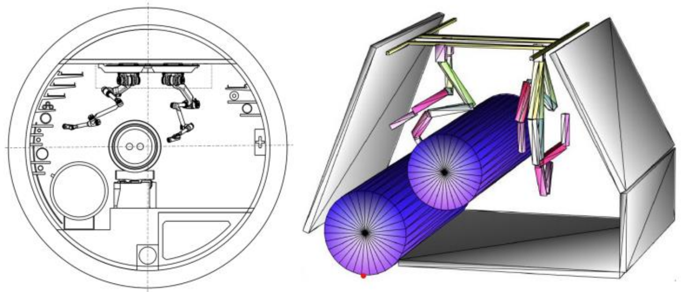
	Requirements
Maintenance	Cover full work space
	Stable movement along tunnel axis
	Pass Fire Doors
	Robust Collision Avoidance
	High Dexterity Manipulator
	Autonomous operation
	Operate in cluttered work space
	Specific Tools
	Tool Changer
	Fast Interventions
	Modularity
	Teleoperation with Haptic Feedback
	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



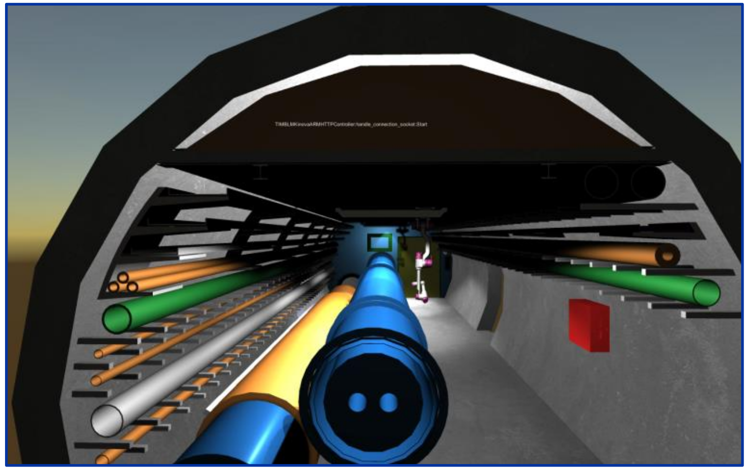
Length	[mm]
$l_{1,2}$	$var.$
$l_{2,4}$	288
$l_{4,5}$	927
$l_{5,6}$	0
$l_{6,8}$	754
$l_{8,9}$	0
$l_{9,10}$	635
$l_{10,12}$	518
$l_{12,E}$	100



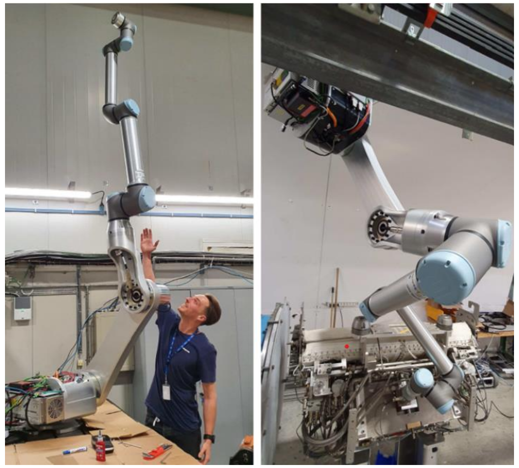




Requirement studies



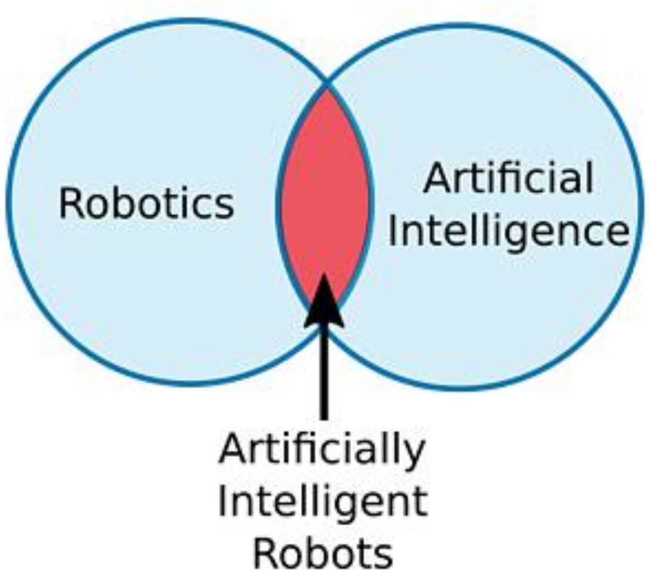
Optimized Geometry and topology



Topology optimization results and device realization

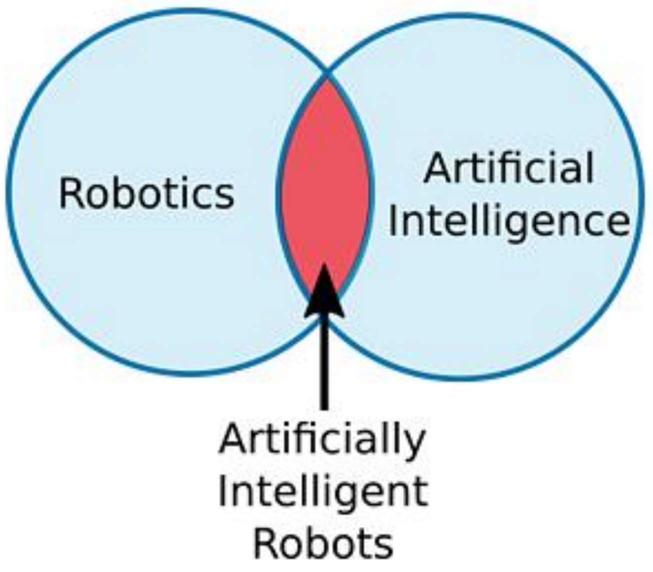
Controls Optimization Are Essential for Physical Interaction

- Main difference between a robot and a computer is a <u>physical action</u>
- 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
  - ✓ <u>Compliant robotics controls</u> (**shared controls**, **haptics, perception, proprioception etc**.)
  - ✓ <u>Compliant mechanics</u>, soft materials etc.



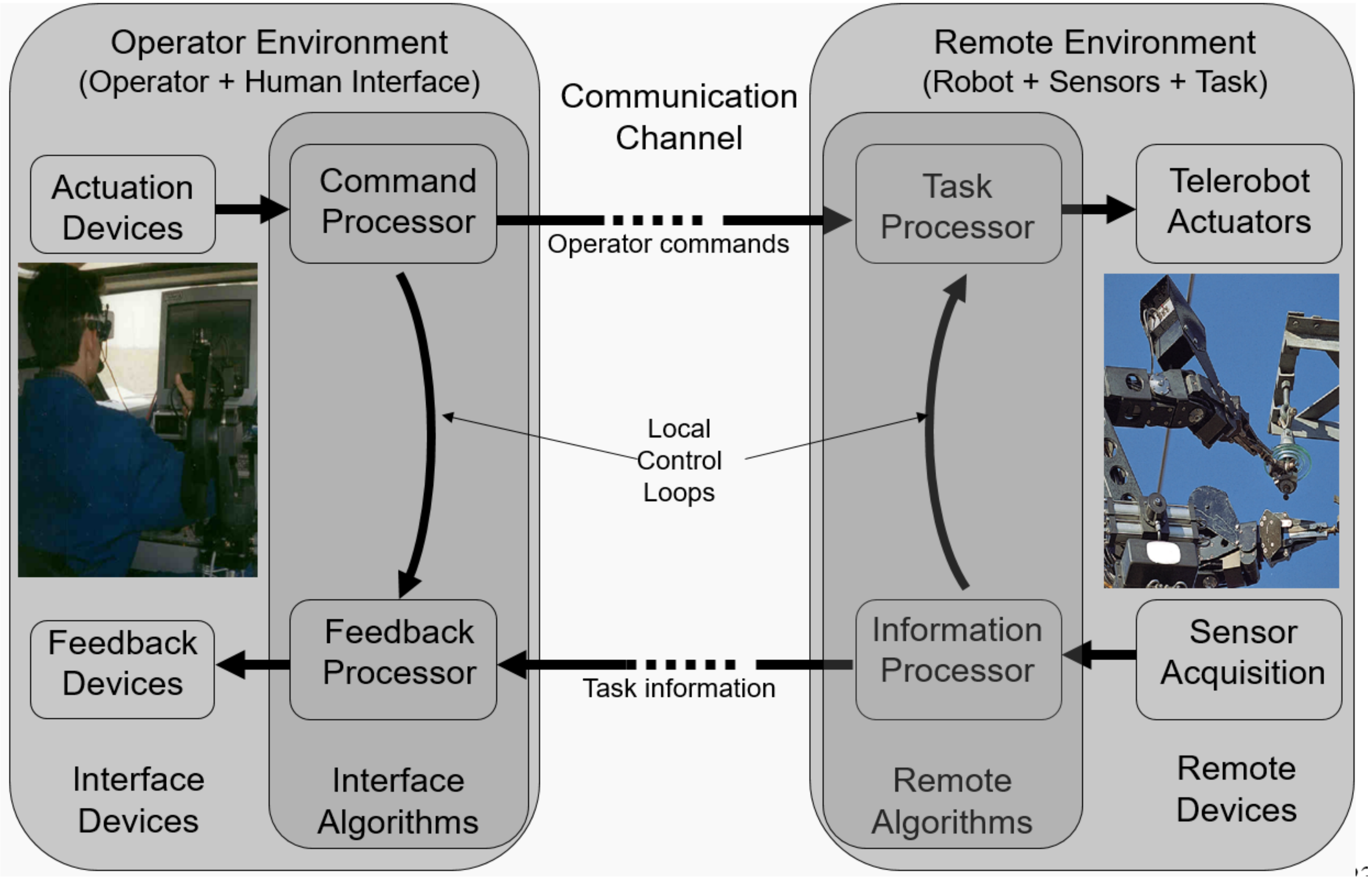
Controls Optimization Are Essential for Physical Interaction

- 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.



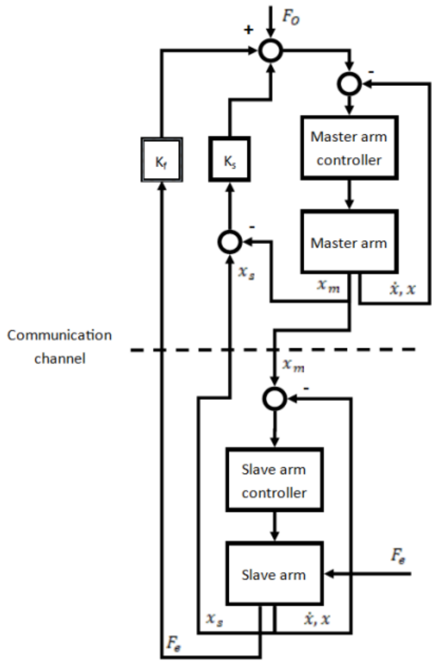
Modern Times, 1936 movie from Charlie Chaplin

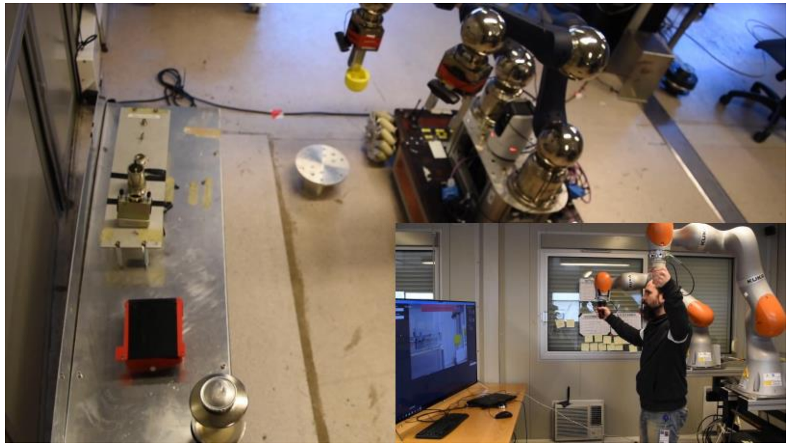
Control Strategies: General Scheme of a Teleoperated System



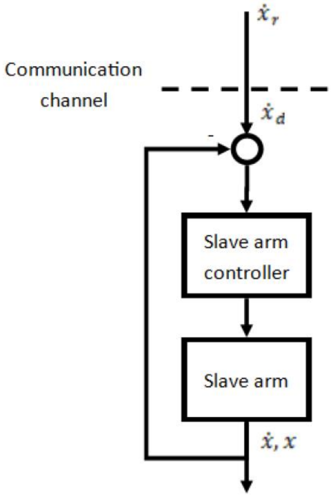
Control Strategies: from standard teleoperation to shared controls

- 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**

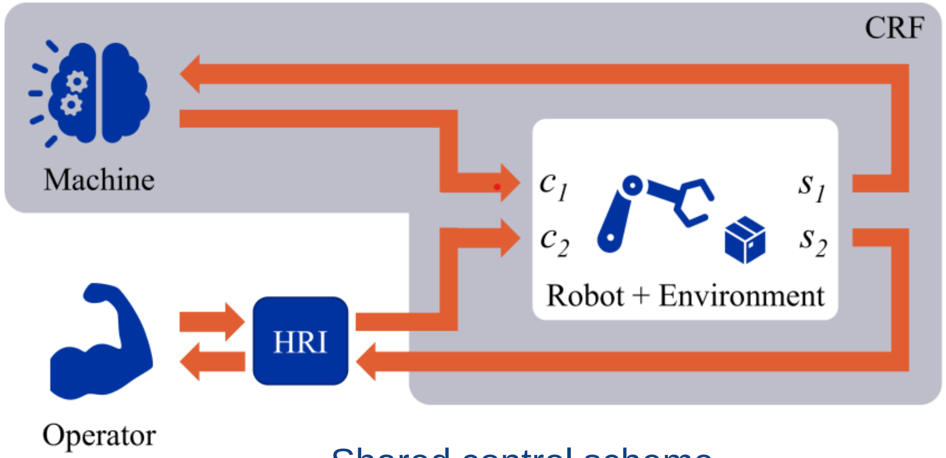




Bilateral teleoperation



Unilateral teleoperation



Shared control scheme

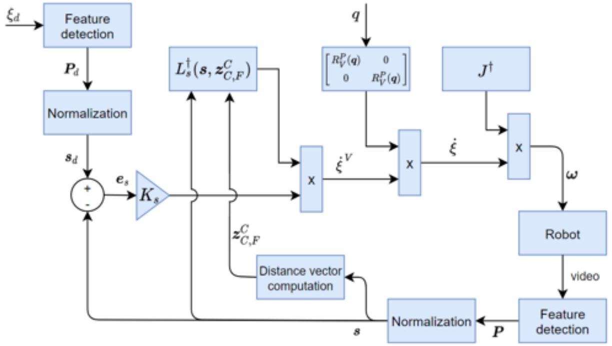
Shared Controls

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

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



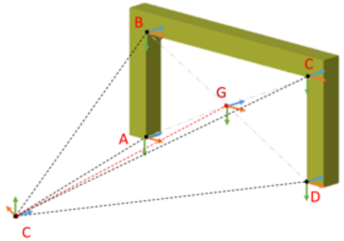


Image-based visual servoing system using ML

SPS robot

Parallel autonomy: Variable Impedance Control

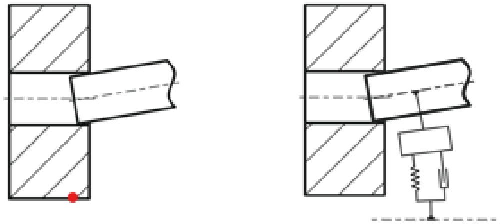
- **Adapts the contact forces to the task characteristics**
  - ✓ Imitation on how we/humans naturally adjust the stiffness of our muscles when we interact with objects that have varying rigidity.

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

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

Parallel autonomy: Variable Impedance Control

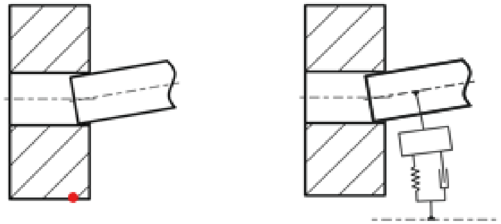
- **Adapts the contact forces to the task characteristics**
  - ✓ Imitation on how we/humans naturally adjust the stiffness of our muscles when we interact with objects that have varying rigidity.

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

Mass-spring dumper model for the variable impedance

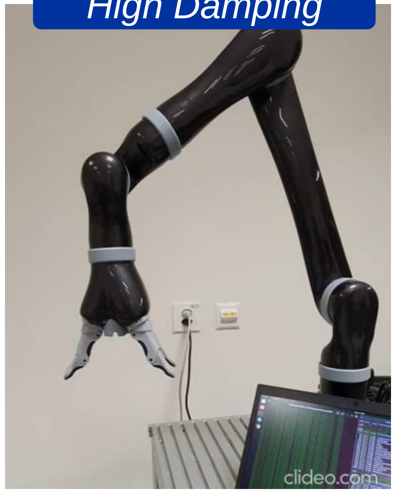
The impedance can be adapted to the task characteristics.

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



Peg-In-Hole

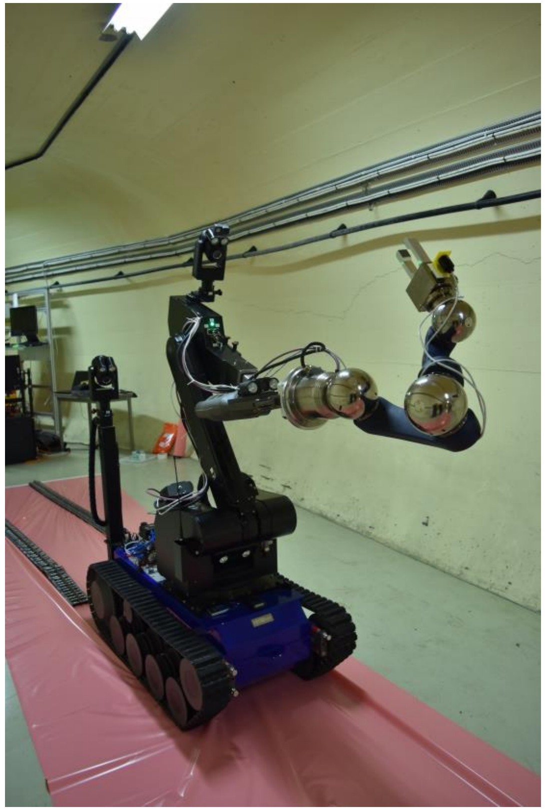
High Damping

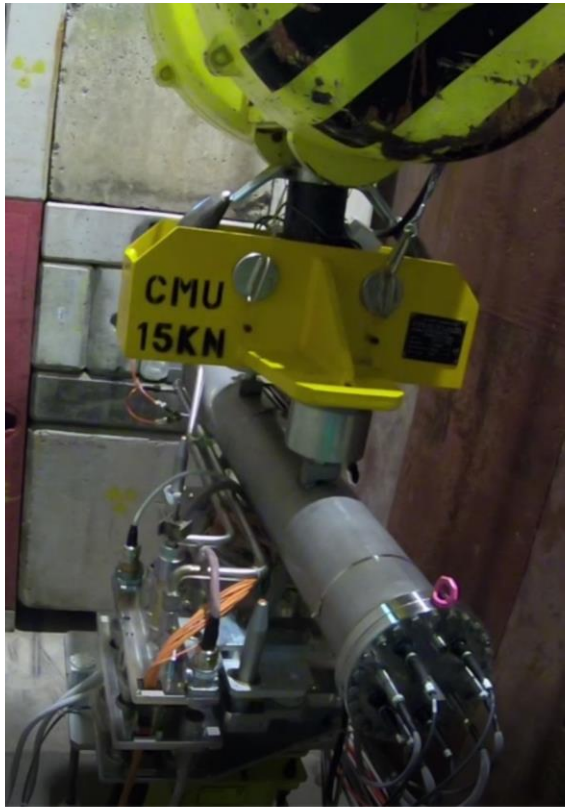


Low Damping

Modular Controls

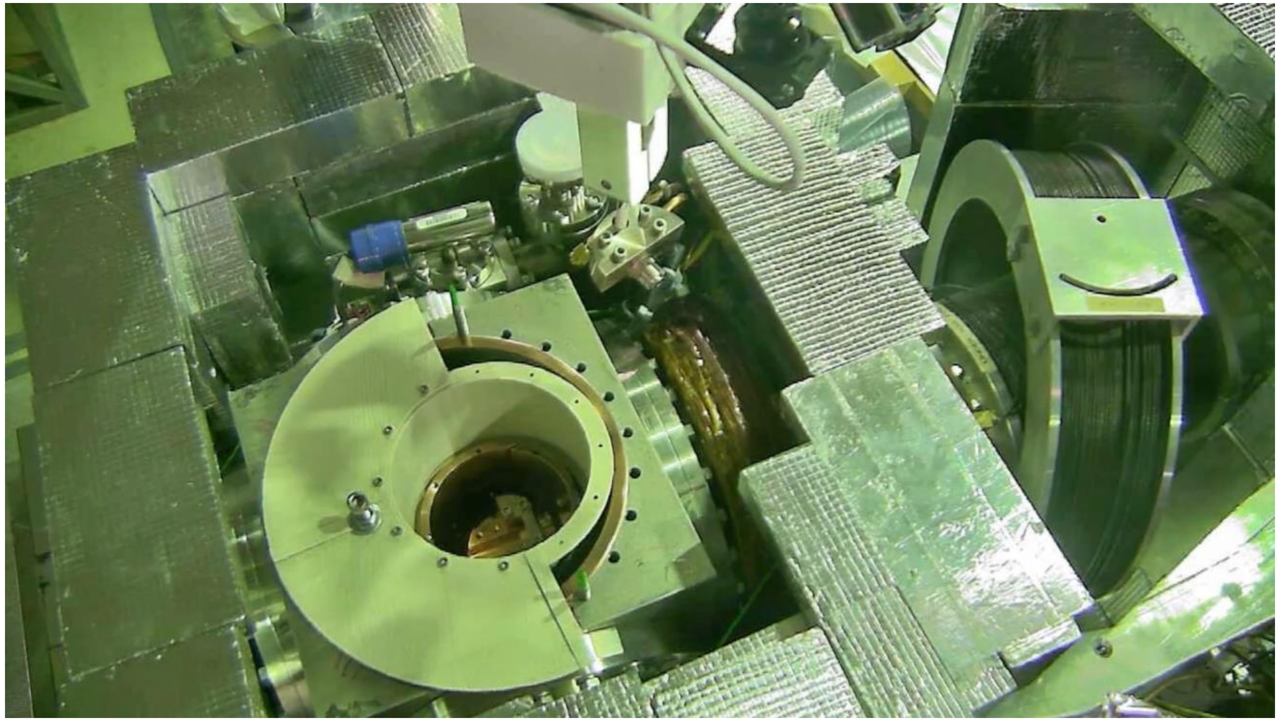
- Particle beam target maintenance, **integration of CERNTAURO on industrial robot**
  - ✓ **CERNTAURO adaptability → seamless control of multi-robots**
  - ✓ Manipulation from unstable support

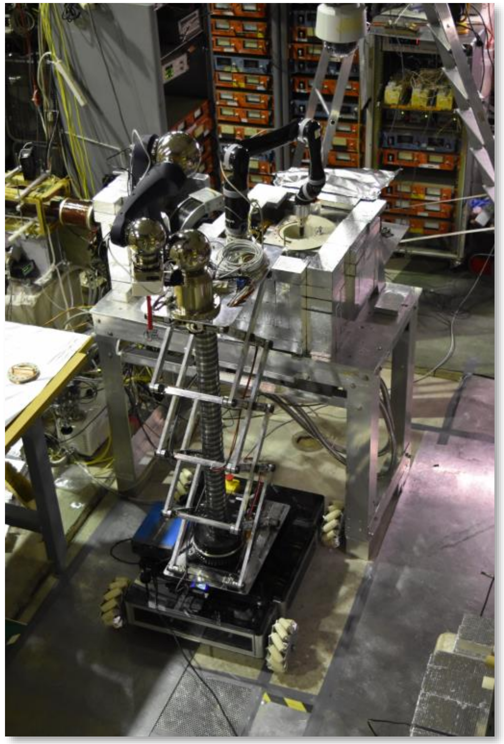


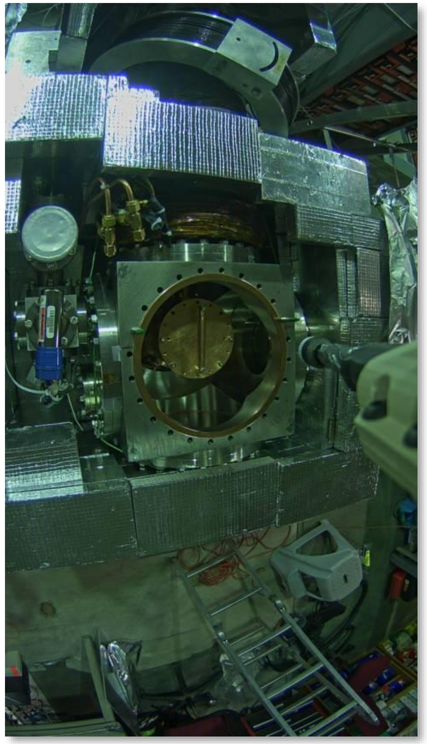


Challenging Teleoperation Example#1

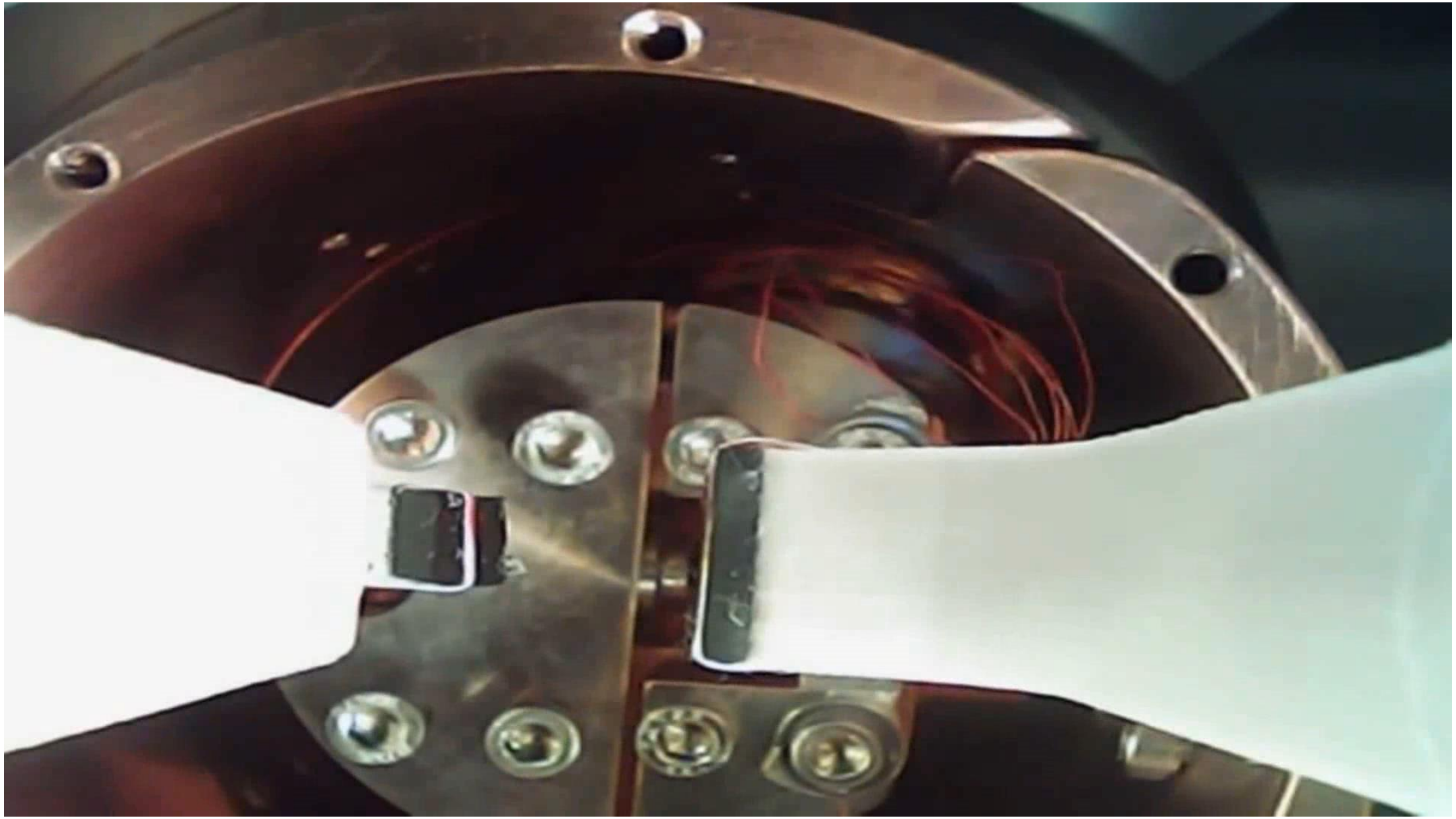
- Radioactive source handling at 2.5 m height using CERNbot 2
  - ✓ **Intervention not possible to be performed by humans**
  - ✓ Bimanual operation, novel procedures and tooling
  - ✓ **CERNTAURO RH procedures and recovery scenarios allowed intervention acceptance by big science facility management**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







Challenging Teleoperation Example#1



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): $\chi_{ee} = \begin{pmatrix} x_{ee} \\ y_{ee} \\ \psi_{ee} \end{pmatrix}$ $\psi_{ee} = \alpha + \beta$

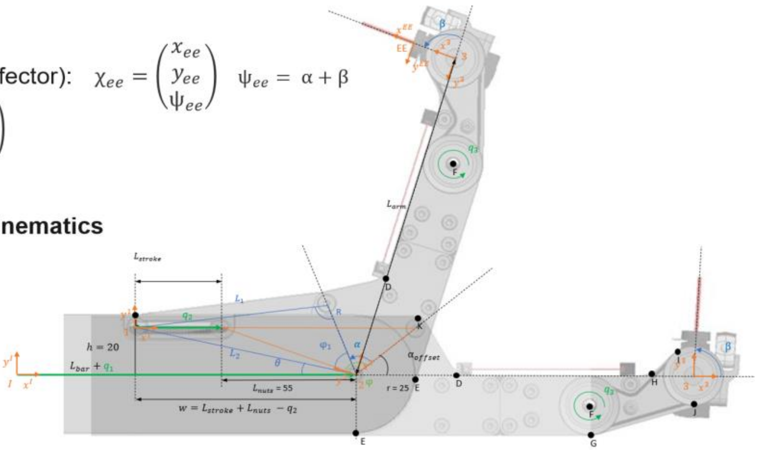
Joints Space: $q_{ee} = \begin{pmatrix} q_1 \\ q_2 \\ q_3 \end{pmatrix}$

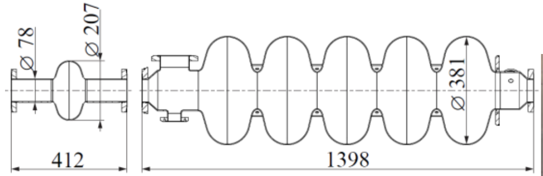
- **Forward & Inverse Kinematics**

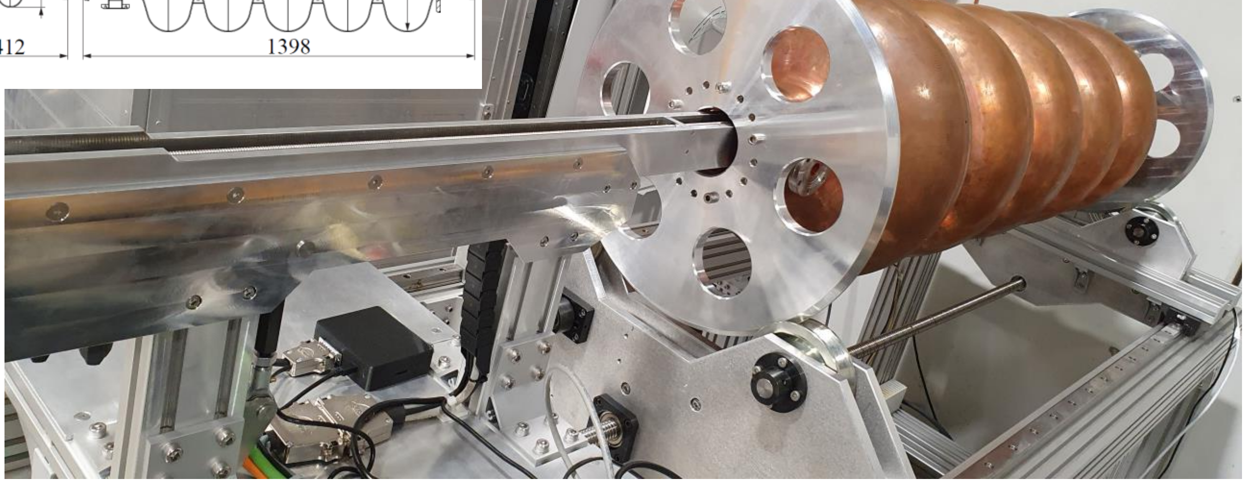
$\dot{\chi}_{ee} = J_A(q)\,\dot{q}$

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

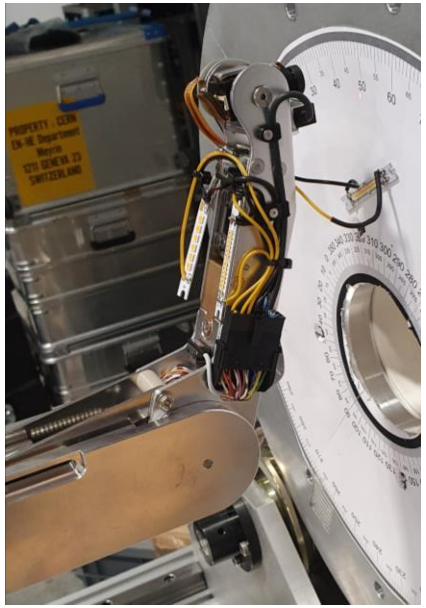
$qNext \cong qActual + \Delta q$

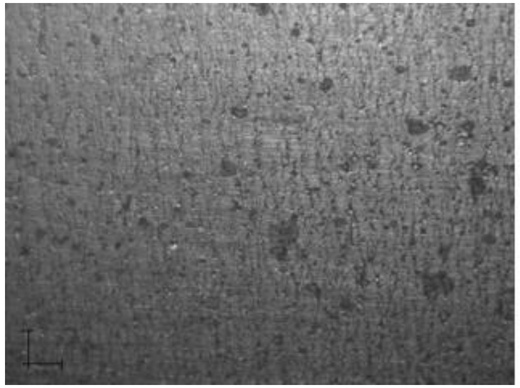






Collaboration with SY-RF, Courtesy of A. Luthi





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

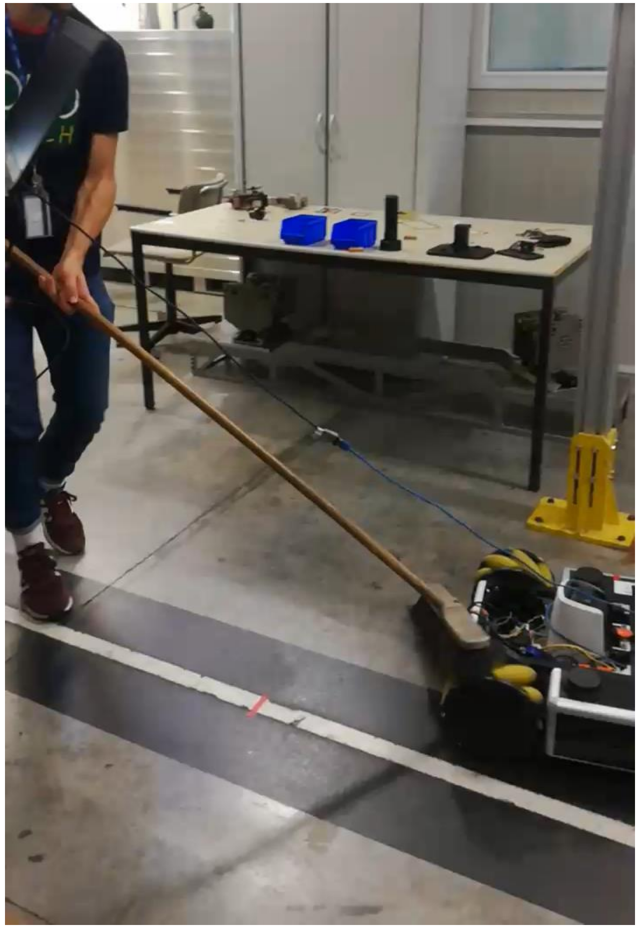
Established partnerships for European Projects

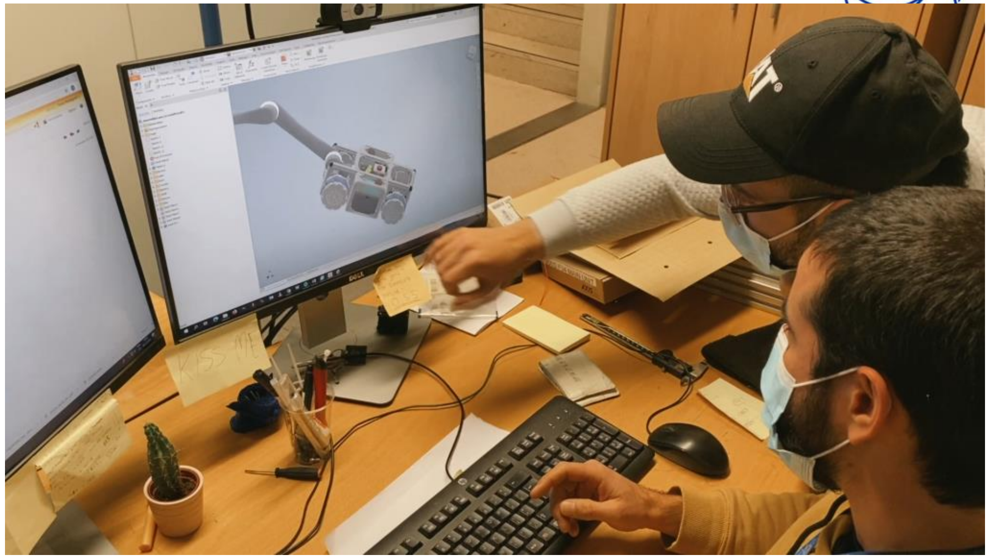
- We are chairing the Teleoperation topic group of the EuRobotics consortium (https://www.eu-robotics.net/)
- Consortiums built for European Projects calls (RECONDITION, BIANCA, HUROSHARE, SCORE, POLE)
- Participation in the European robotic Challenge (EUROC) and Puresafe projects

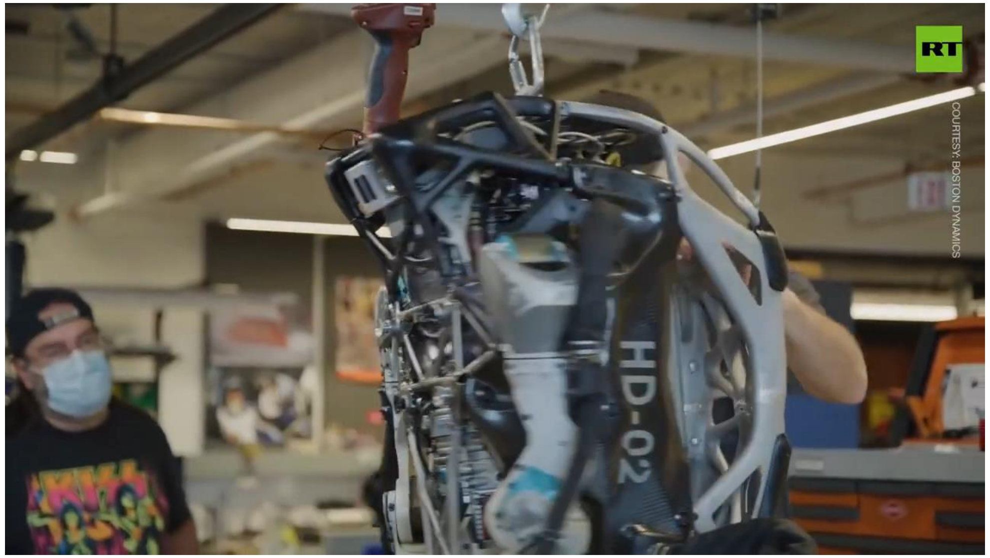
Conclusions

- Particle accelerators devices are normally installed for many years and tasks of dismantling radioactive objects is inherited by the future generation of physicists/technicians/engineers
- Maintenance and dismantling tasks, over a lifetime of a particle accelerator device, must be taken into account at design phase
- Robotic intelligent and robust systems can increase personnel safety and machine availability in performing such tasks
- Ready-to-use industrial solutions do not exist for user friendly remote maintenance and inspection
- We gained an important knowledge and experience in designing, producing and applying robots in harsh and hazardous environment
- External collaboration with Robotics Research Centres and Universities is crucial to take advantage of the cutting edge technology

Are Robot "serving" humans? … or we are serving robots?







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

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
"

www.cern.ch

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

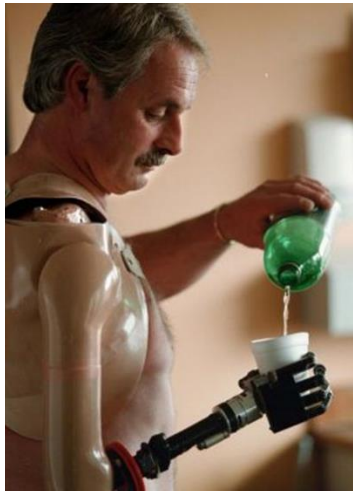
Backup Slides

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?

Robotics for us

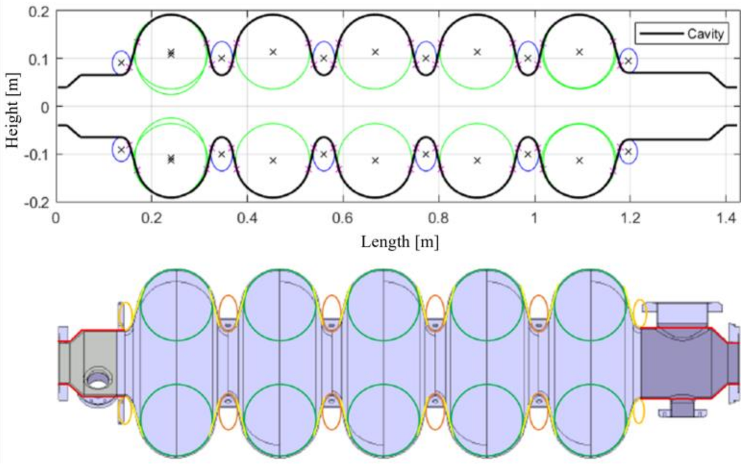
- There is a lot of potential in this technology to be beneficial for people
- Ultimately, everything depends on how we decide to use the technology



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.
<u>ALARA principle followed for each intervention</u>

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): $\chi_{ee} = \begin{pmatrix} x_{ee} \\ y_{ee} \\ \psi_{ee} \end{pmatrix}$ $\psi_{ee} = \alpha + \beta$

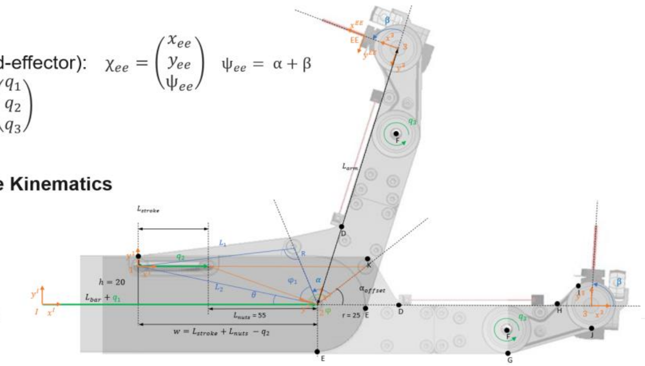
Joints Space: $q_{ee} = \begin{pmatrix} q_1 \\ q_2 \\ q_3 \end{pmatrix}$

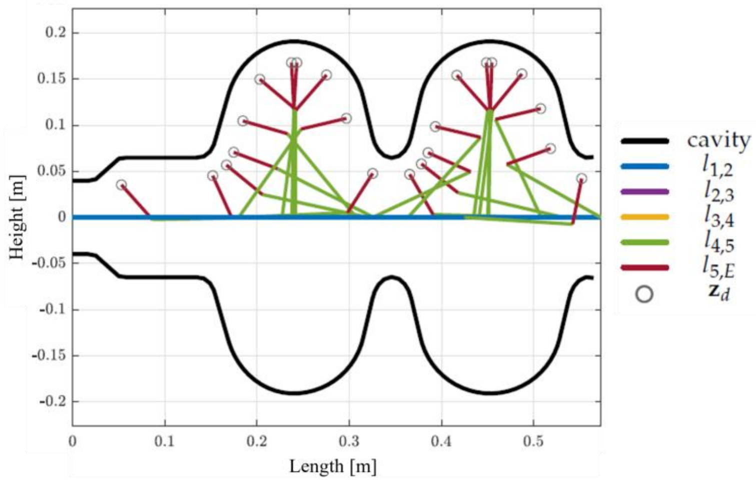
- **Forward & Inverse Kinematics**

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

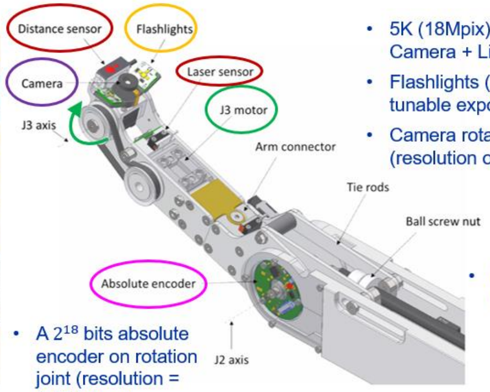
$\Delta q \cong J_A(q)^{-1} \Delta \chi_{ee}$

$qNext \cong qActual + \Delta q$

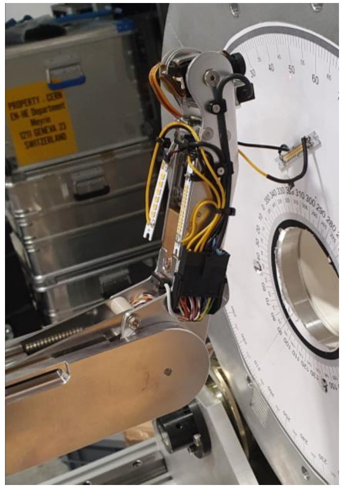




The optimal topology and geometry of the cavity inspection arm after applying the model pruning technique

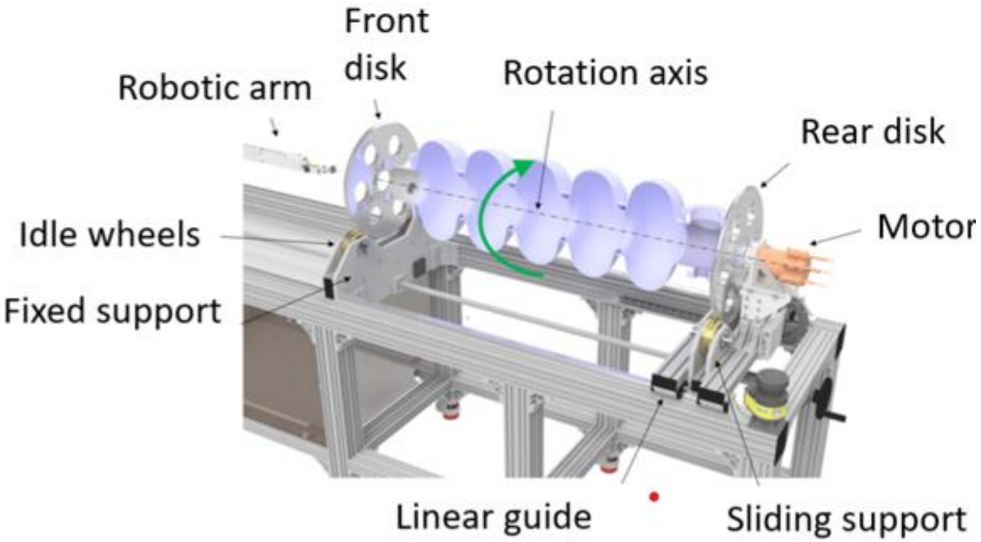


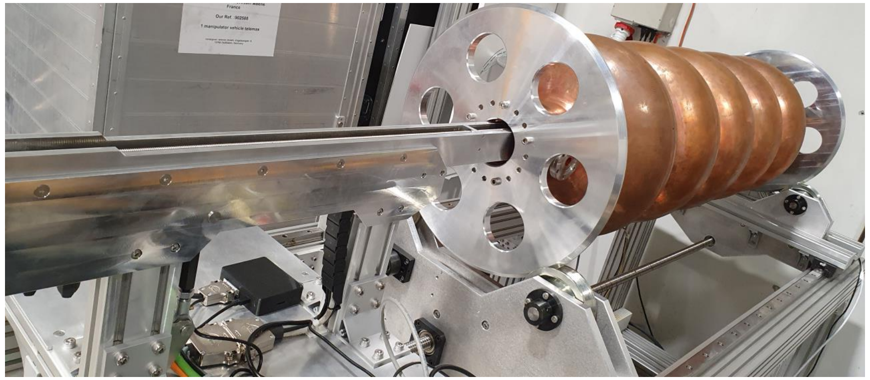
- 5K (18Mpix) miniature Camera + Liquid lens
- Flashlights (2x300 lm) with tunable exposure time (μs)
- Camera rotation – servomotor (resolution of 0.29 deg)
- Avoidance Collision system
- A 2^{18} bits absolute encoder on rotation joint (resolution = 0.0014deg)



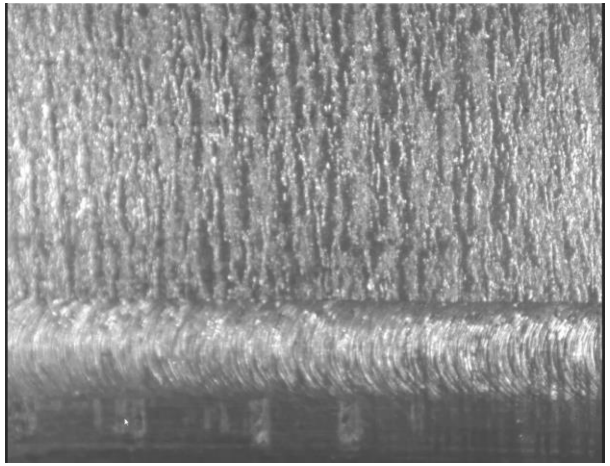
The mechanical design of the robotic arm and its realization based on the optimized design space

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