Industry 4.0 Boosting Reliability in Particle Accelerators

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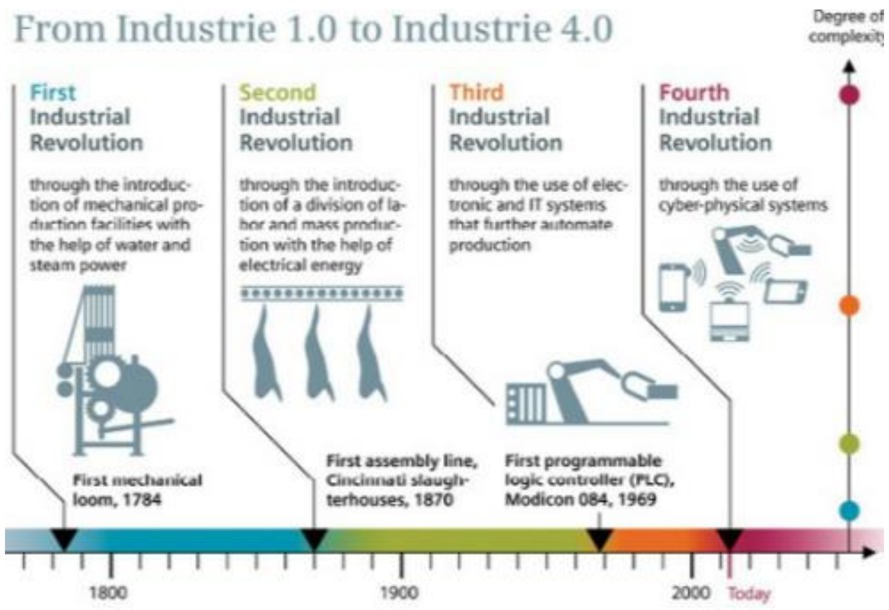
CERN, BE-CEM group

Content

- Industry 4.0 and IoT
- Data driven reliability
- Needs and challenges for remote maintenance
- The robotic service at CERN
- Robotics and AI
- Conclusions

Current industrial revolution

- **Industry 4.0**
  - ✓ Cyber-physical transformation of manufacturing
  - ✓ Internet of things (IoT)
  - ✓ Artificial intelligence
  - ✓ Diffuse signals
  - ✓ Sensor fusion
  - ✓ DATA
  - ✓ Robots
  - ✓ Assisting people and machinery to execute their tasks maximizing efficiency

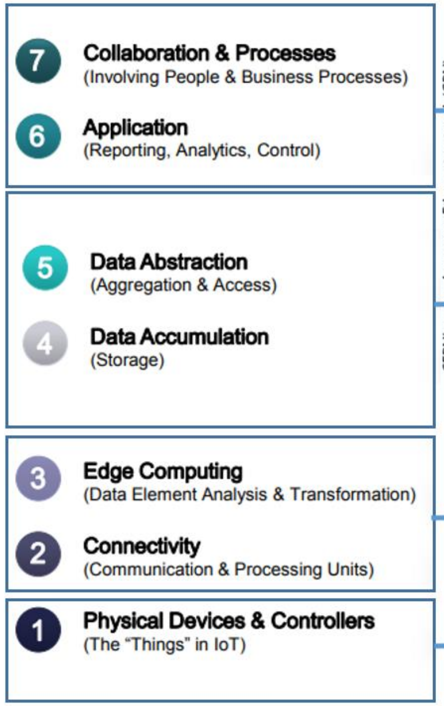


Industry 4.0 making intelligent machines

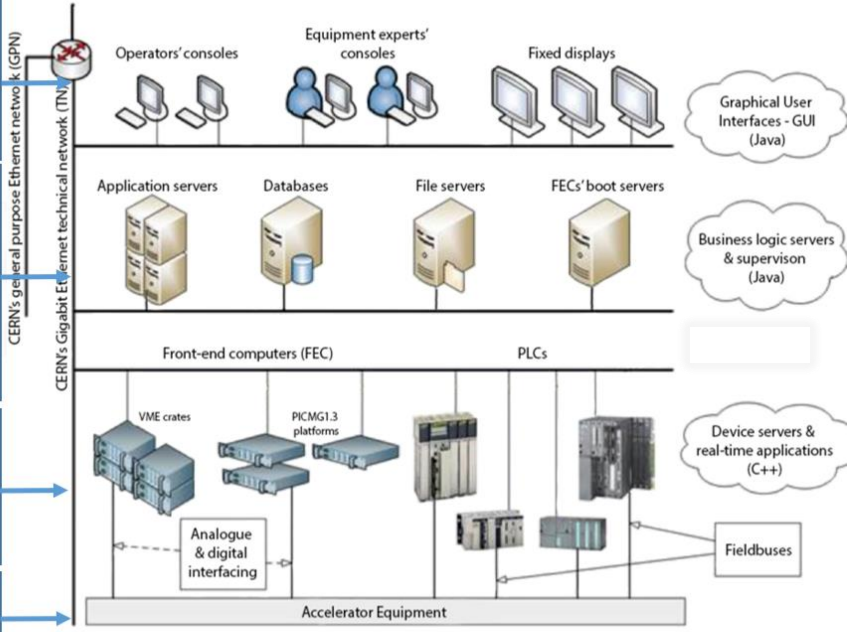
- Many machines nowadays are becoming smart making self decisions based on complex algorithms and environmental interaction
- Machines are programmed to make the best choice possible in deterministic conditions, <u>normally unplanned scenarios should be threated to lead to a fail safe conditions</u>
- These advancements are possible also due to IoT technologies
  - ✓ **Collects/connects data/information** between several devices through the internet and uses machine learning [1-2] to learn, plan, take decisions, perceive, sense etc.
- <u>Humans learn by experience, machines learn with data</u>

IoT reference model and CERN control system

- All the equipment, sensors, devices in a particle accelerator are connected on a **wired based infrastructure**
- IoT gathered great momentum thanks to the wireless technologies
- Industry is moving towards wireless technologies for:
  - ✓ Asset management and tracking
  - ✓ Production and machine monitoring, maintenance and improvement
  - ✓ Interconnected supply chains
- The impact is on:
  - ✓ Costs reduction
  - ✓ Higher efficiency
  - ✓ Data consistency



Cisco IoT reference model



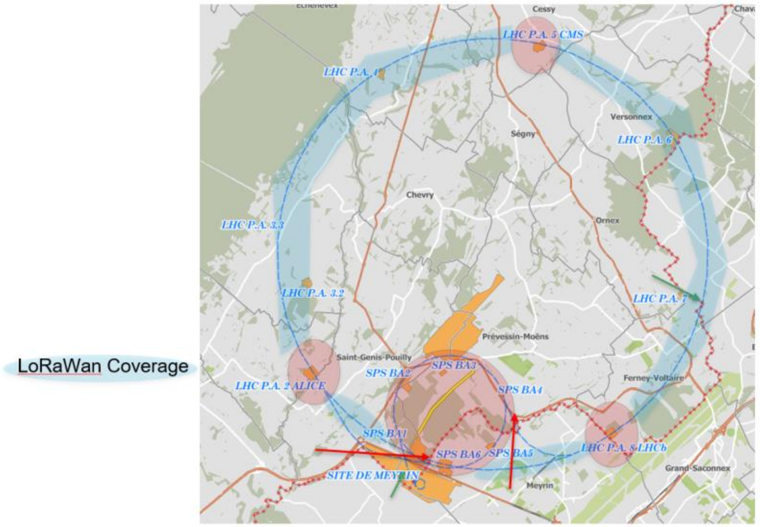
Source [2]

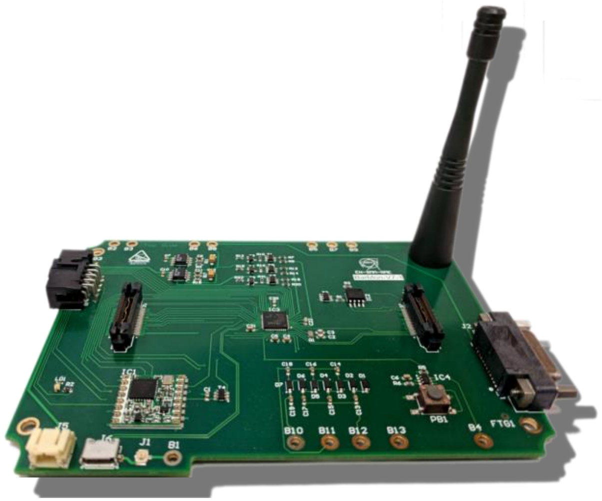
CERN control system

Courtesy of S. Danzeca, CERN

CERN and wireless IoT

- CERN embraced the Wireless IoT for:
  - ✓ Ground application
  - ✓ Underground application -> Radiation areas!
- LoRaWAN wireless network has been deployed in the LHC Underground Tunnel
- A radiation Tolerant IoT hardware platform allow to communicate to the IoT world
- CERN is moving towards a “Smart IoT accelerator”





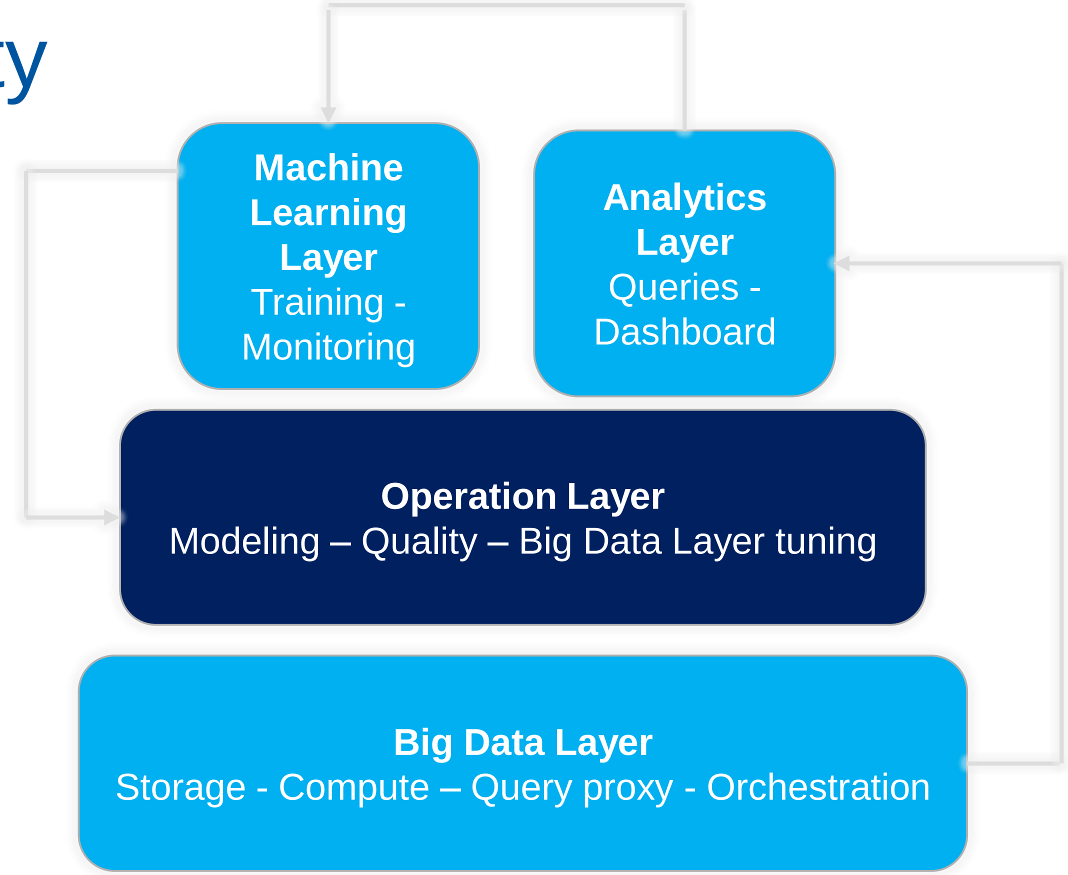
Radiation tolerant IoT hardware platform developed at CERN, courtesy of S. Danzeca

Data driven reliability and data quality

- To understand how to execute, maintain and improve machines, **<u>data are needed</u>**
  - ✓ Key aspect is to put together data scientist, developers and equipment experts → cross functional learning

- Predictive analytic model of machine components could be extrapolated from data
  - ✓ Failures could be anticipated, feedbacks for operation and quality

- Every year, poor/bad data quality costs to organizations an average of $13 millions
  - ✓ Right data / data quality is needed → Data reliability engineering (DRE) approach to data quality is needed. **Treating data quality like an engineering problem**



Data stack based on Bigeye solutions

Question could be: how much money will it cost?

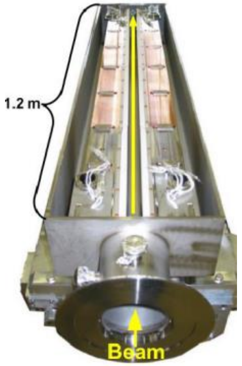
Answer could be: how much money could be saved in prospective?

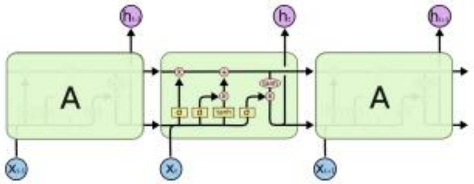
It's not only about money, about SAFETY.

From corrective and preventive to predictive maintenance

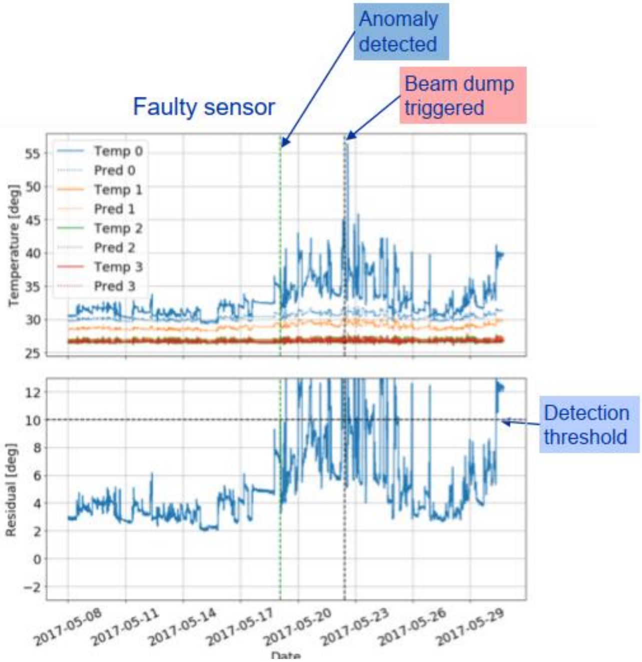
LHC Collimators Jaws temperature Maintenance over the last years

- **Corrective maintenance** during unplanned downtime could have huge impact on accelerators
    - ✓ Unavailability, cost of the operation, needs for backup solutions etc.
- **Preventive maintenance** to improve reliability
    - ✓ High cost
- **Predictive maintenance** could help in reducing the corrective maintenance probability optimizing the preventive maintenance
    - ✓ Example done at CERN for on predictive maintenance algorithms run on interlocked LHC Collimators jaws temperature signals monitored in real time → Anomaly detection
    - ✓ Machine learning LSTM model (RNN)





LHC Collimators and view of inside/jaws

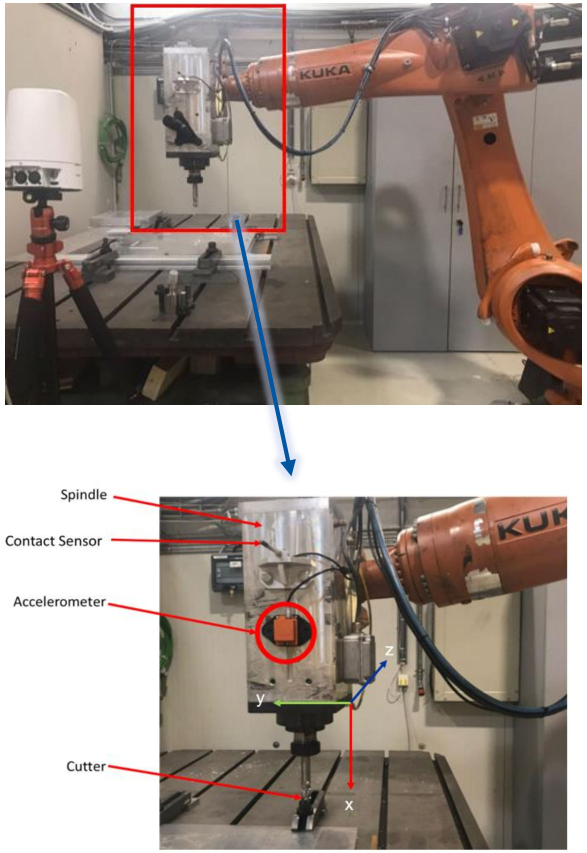


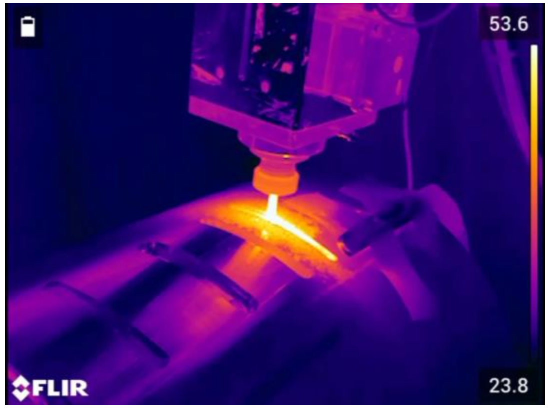
Data Set	tuning	2018
Total Samples	42	**79**
True Positives	21	**23**
True Negatives	20	**52**
False Positives	1	**4**
False Negatives	0	**0**
F-1 Score	0.98	**0.92**
Mean time detection to event [h]	13.73	**3.19**
Accuracy	97.60%	**94.90%**

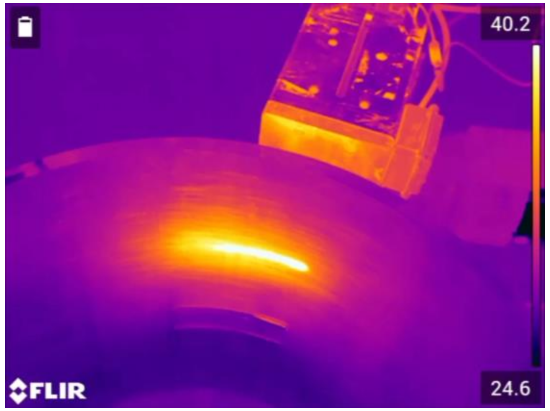
Courtesy of L. Serio, CERN

Use of data to improve process reliability

- **Robotic CNC solution for machining of radioactive objects**
  - ✓ Problem: Robot for fine machining moves in a non ideal way breaking many end effector tools
  - ✓ Solution: real time data collection of several sensors, fusion and analysis with machine learning for anomalies detection
  - ✓ Discovered: problem in online trajectory generation in particular robot poses

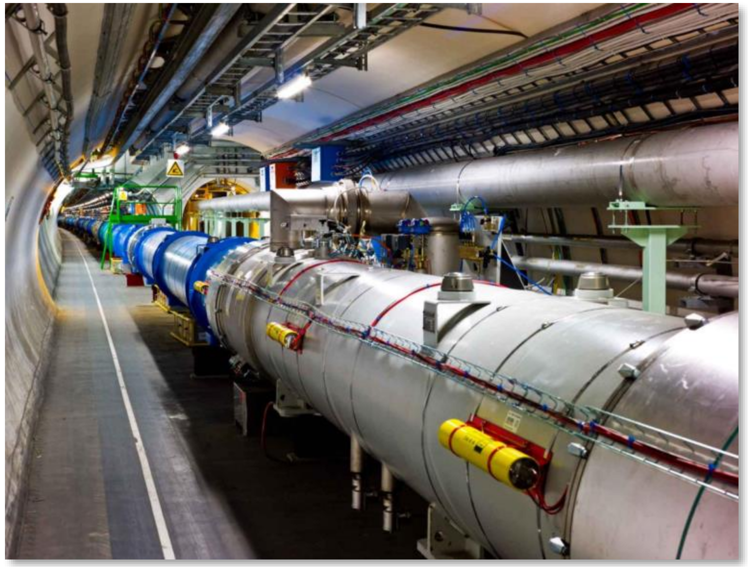






Main needs for robotics at CERN

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



The LHC tunnel

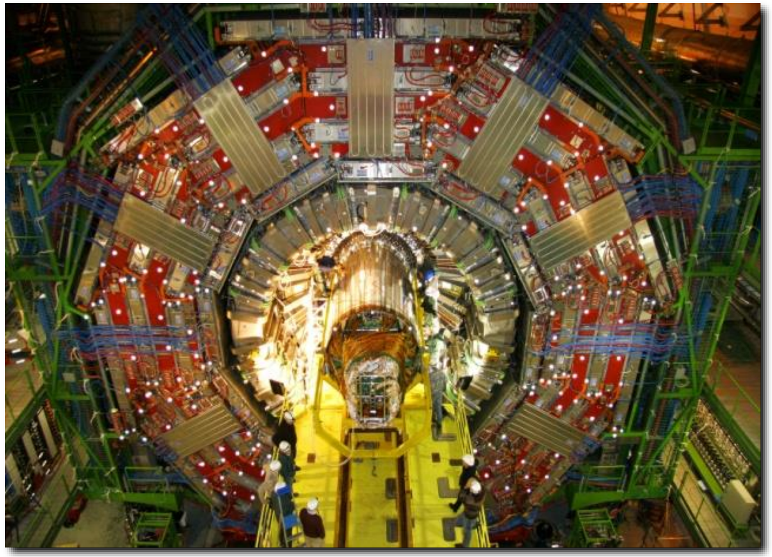
North Area experimental zone

Radioactive sample handled by a robot

Main 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.



CERNTAURO framework [7]

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

- **New robot and robotic control developed** [9-39]
  - ✓ Human robot interface
- **New user-friendly bilateral tele-manipulation system**
  - ✓ Haptic feedback
  - ✓ Assisted teleoperation

Mechatronic System

Intelligence

Perception

Motion

- **Artificial intelligence [30-31-38-40]**
  - ✓ Perception and autonomy
  - ✓ Deep learning
- **Operator and robot training system [41]**
  - ✓ Virtual and augmented reality
  - ✓ Learning by demonstration

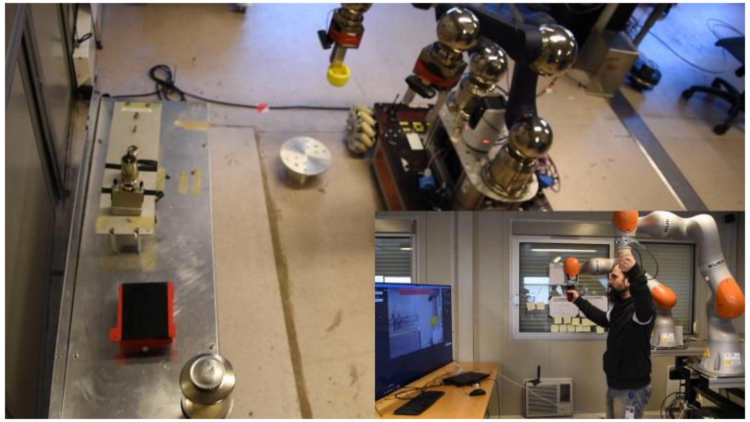
    (data instructed to robots)

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** <u>semi-structured and harsh environments</u>

Main Motivations for Custom Robotic Development #2

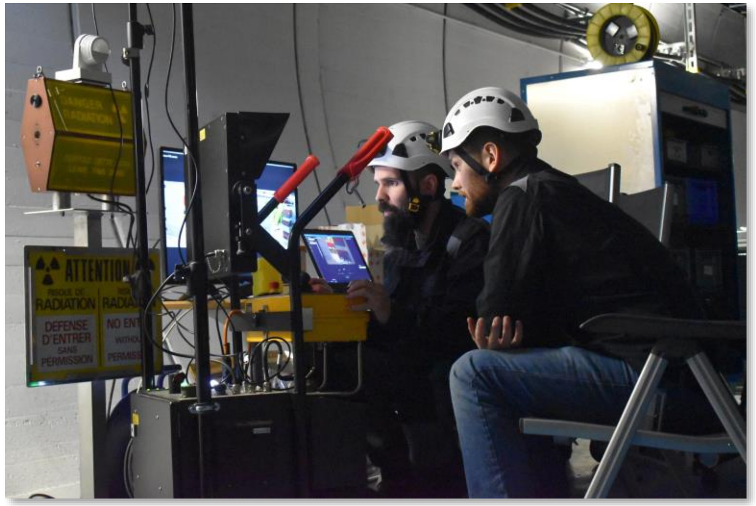
- Industrial robot have **very complicated human-robot interfaces demanding intense operators training**, controls are not open to be integrated in our control system, communication channel is often via radio signal, not built to reduce contamination risks etc.

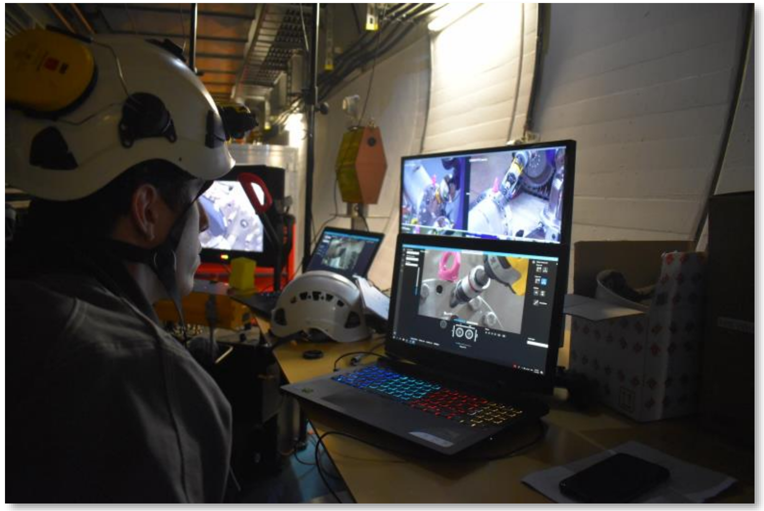


- Necessity of having the human, the machine and the interface working together adopting **user friendly interfaces**
  - ✓ Increase of **proprioception** reducing operators stress

Robotics technologies are mainly used for:

- Remote maintenance for **safety and machine availability increase**
- Environmental measurements, maintenance/tele-operation and inspection in dangerous areas
  - ✓ **Taking data in harsh environment, used also for reliability study!**
- Human intervention procedures preparation
- Quality assurance
- Post-mortem analysis/inspection of radioactive devices
- Reconnaissance, search and rescue
- And others…

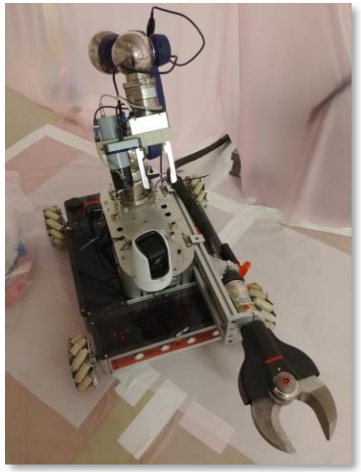


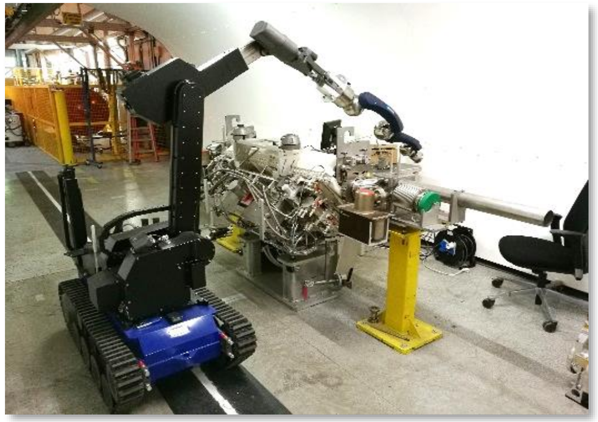


Robotic Support for CERN: Type of Robots Overview

Telemax robot

Train Inspection Monorail [10] (CERN made)

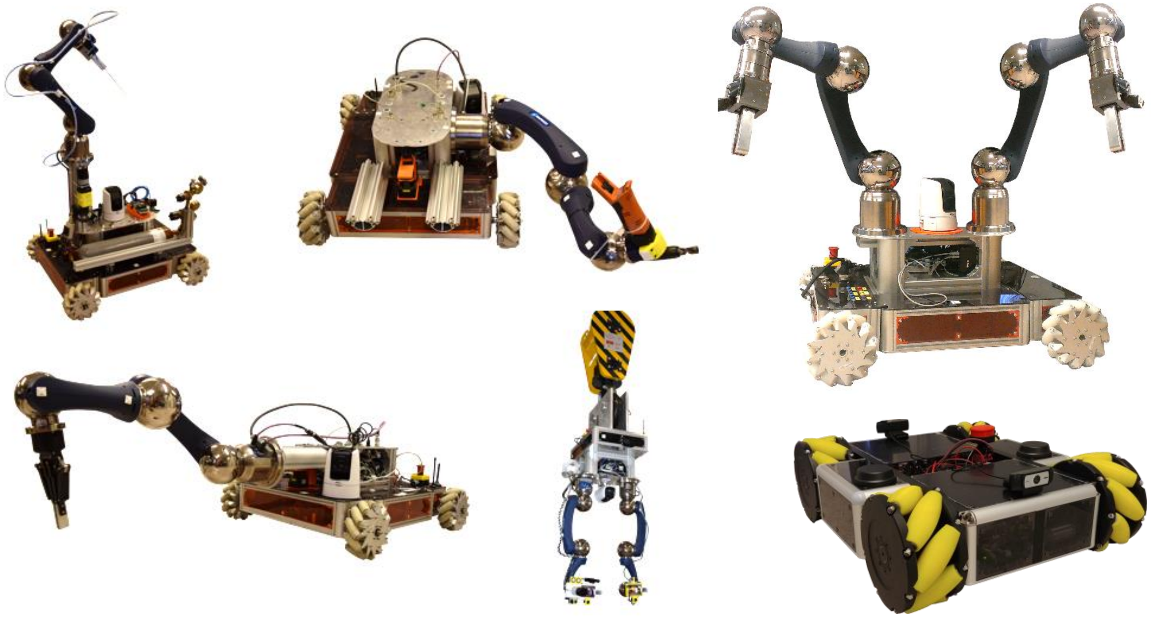




Teodor robot

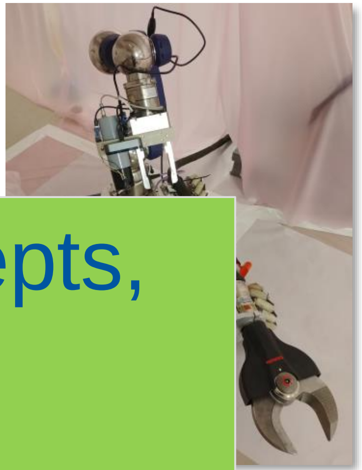
EXTRM robot (CERN controls)

Drone for tele-operation support



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

Robotic Support for CERN: Type of Robots Overview

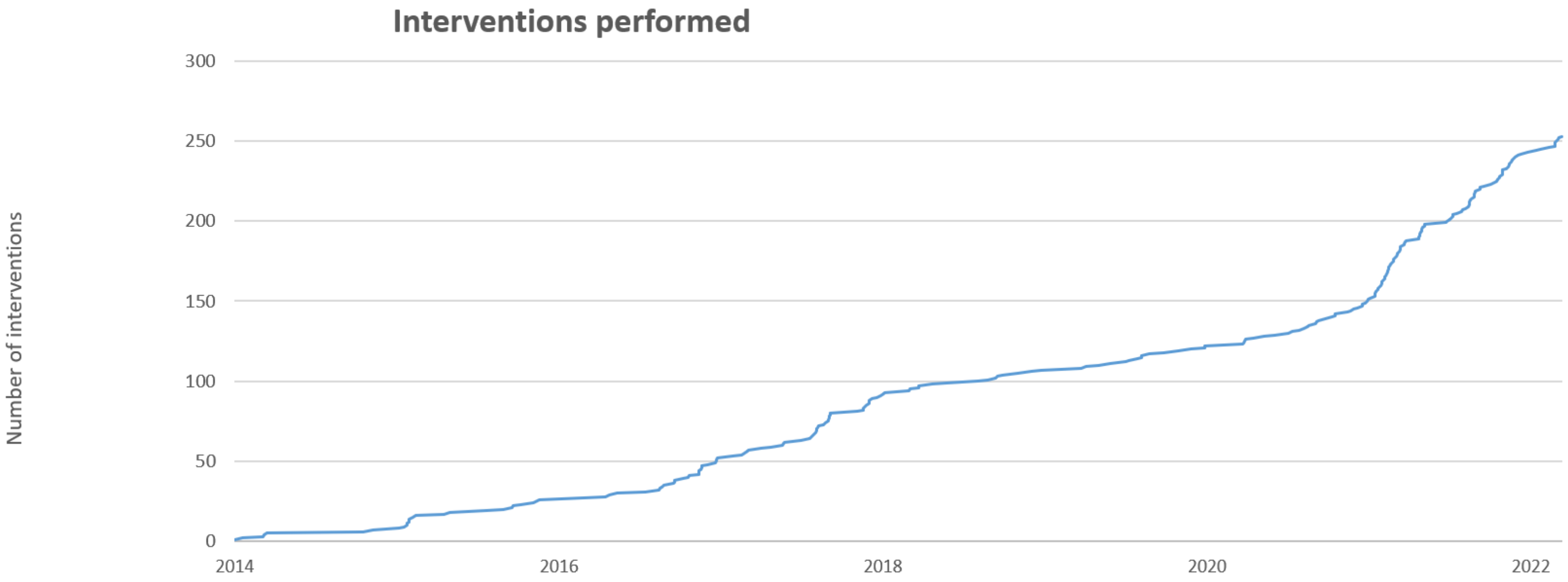


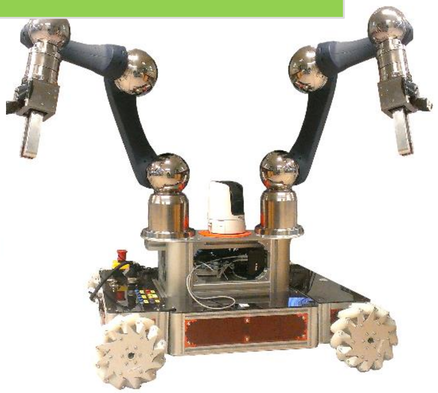
- Mechatronics conceptions, designs, proof of concepts, prototyping, series productions, <u>operations</u>, maintenance, tools and procedures

Telemax rol

Teodor rc

Dror
oper





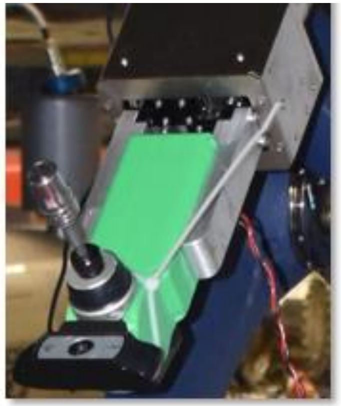
configurations (CERN made)

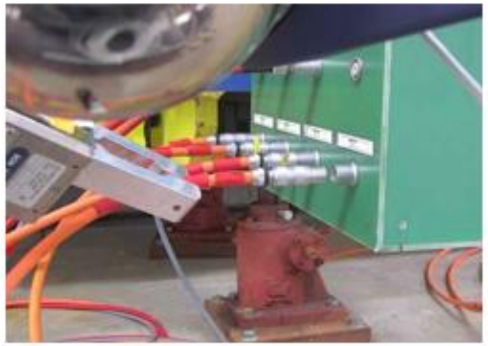
Importance of the design phase, procedures and tools

- 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





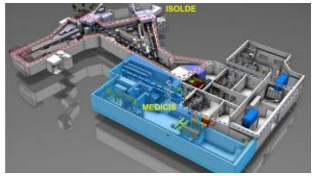



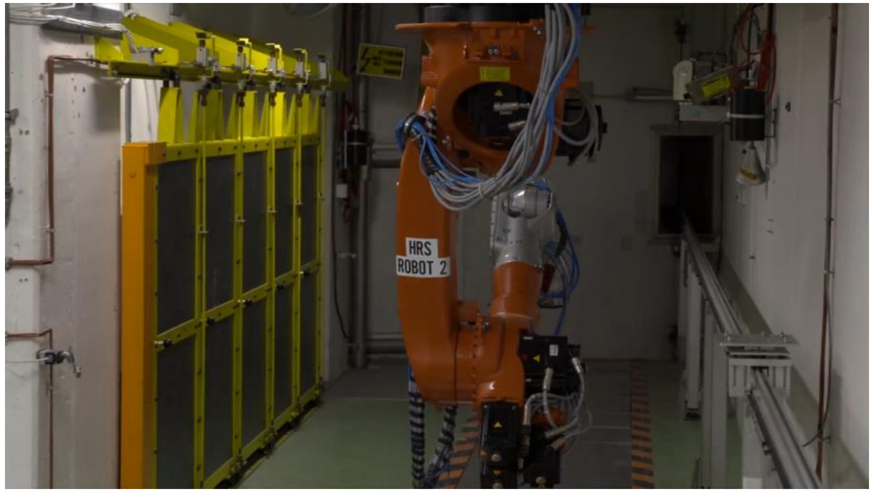


Continuing developing best practice for equipment design and robotic intervention procedures and tools including recovery scenarios

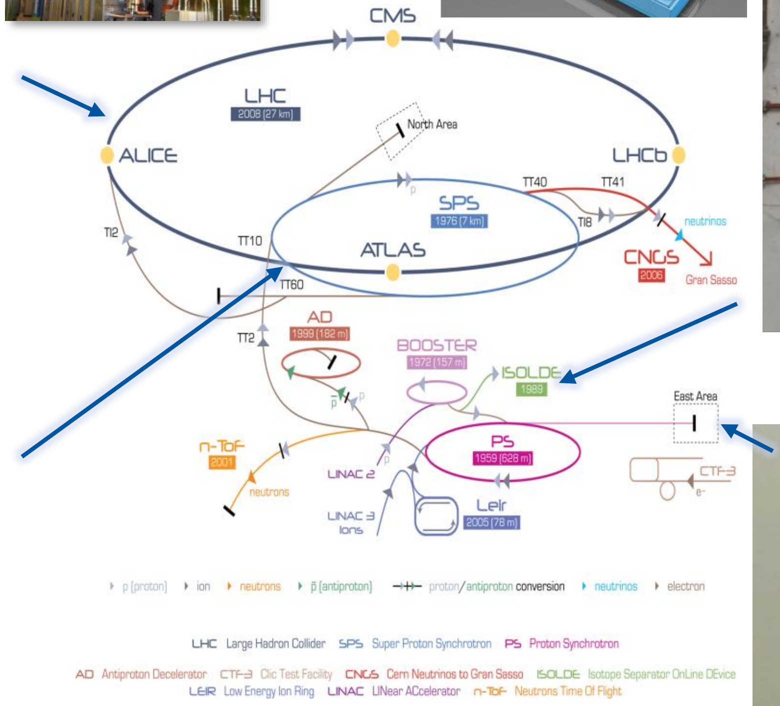
Main Robots integrated/controlled within facilities at CERN

TIM (x4)





Kuka Robots (x3)

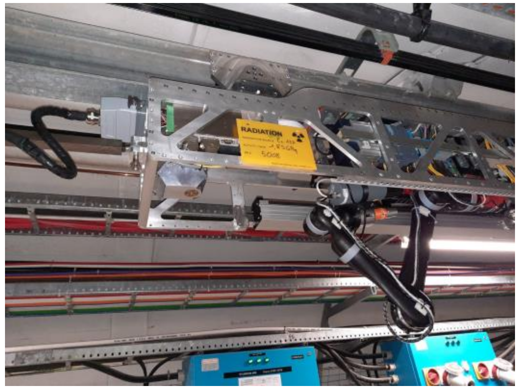


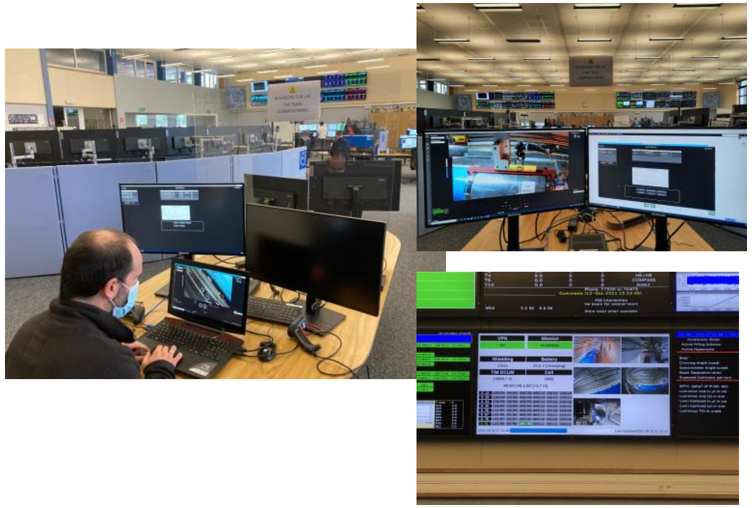
MIRA - CERNbot

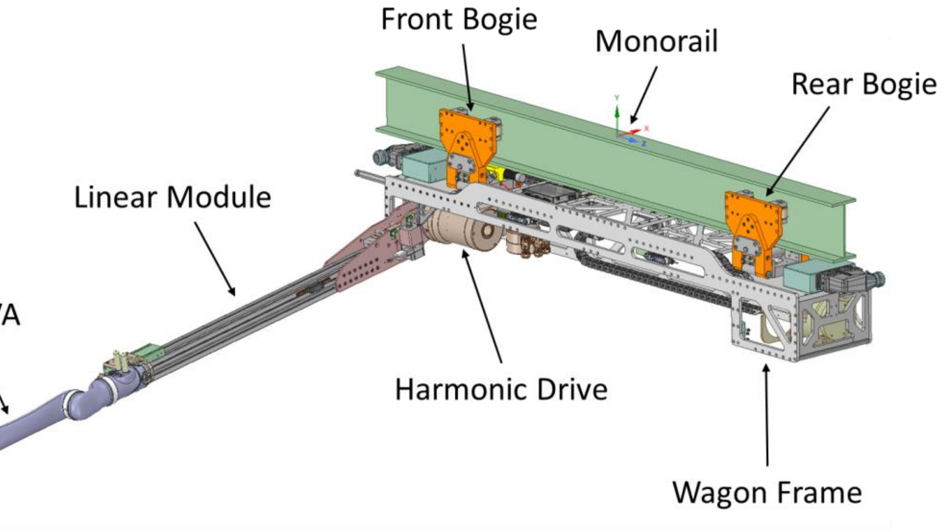
CHARMbot

Novel TIM robotic wagon

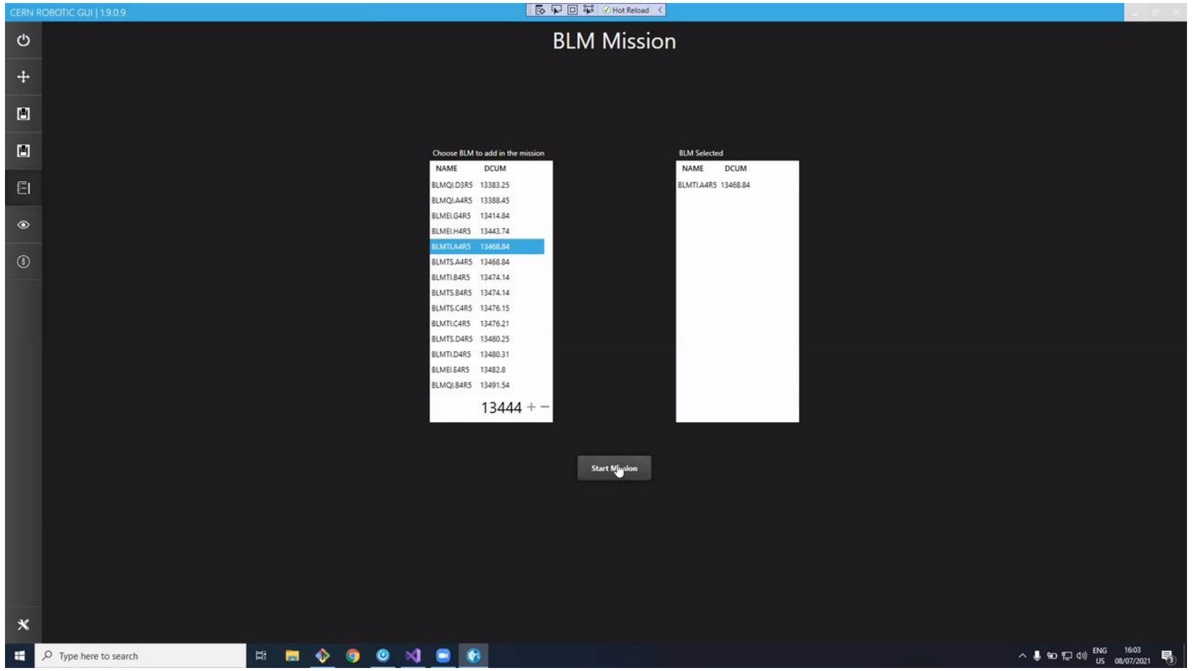
- 6 DoF (rotational axis) + 1DoF (linear axis) for dexterity
- 2 DoF (harmonic drive, backlash-free) for transversal positioning
- 1 stabilization axis
- 5 cameras



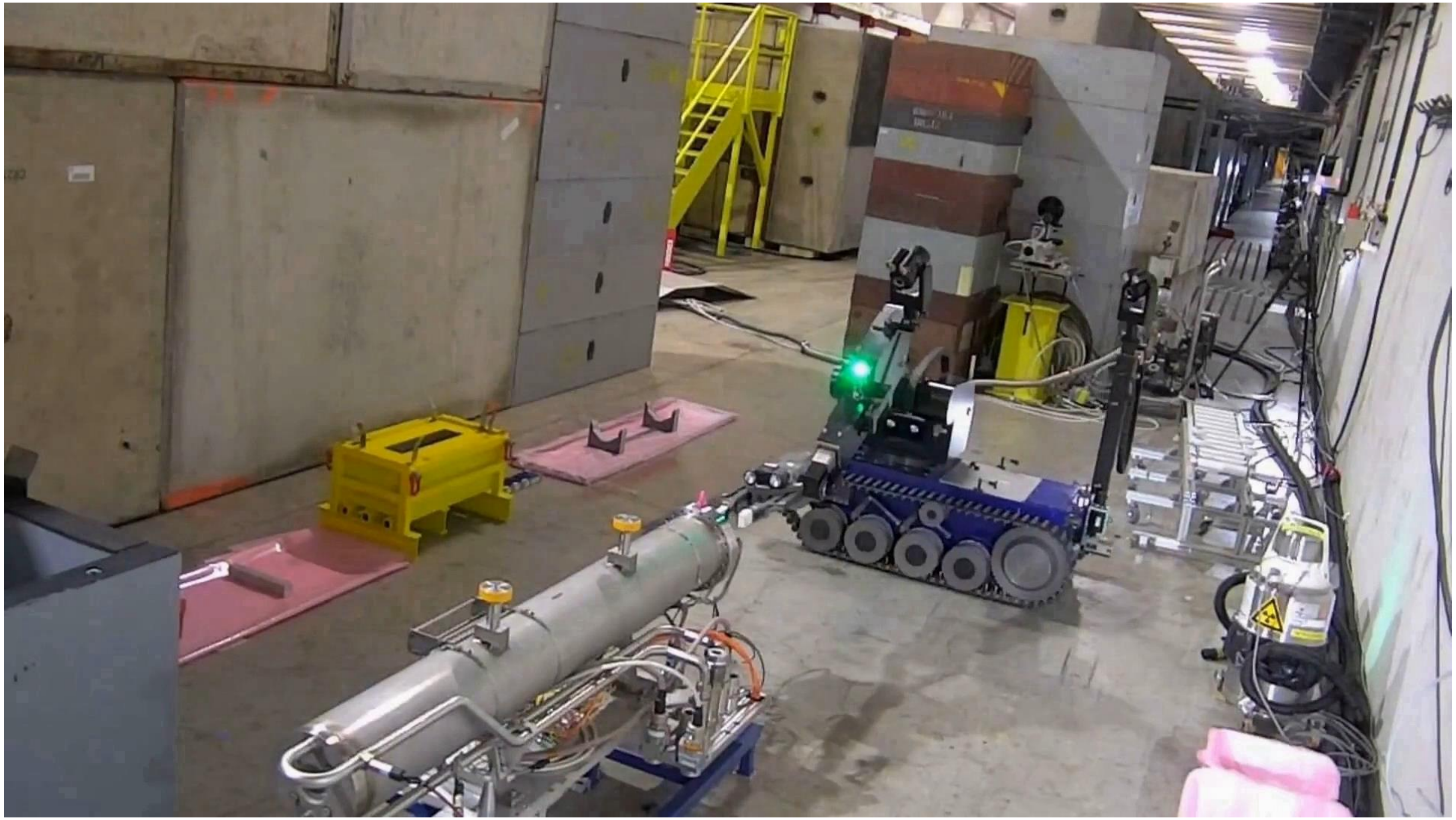




New TIM robotic wagon with extracted arm

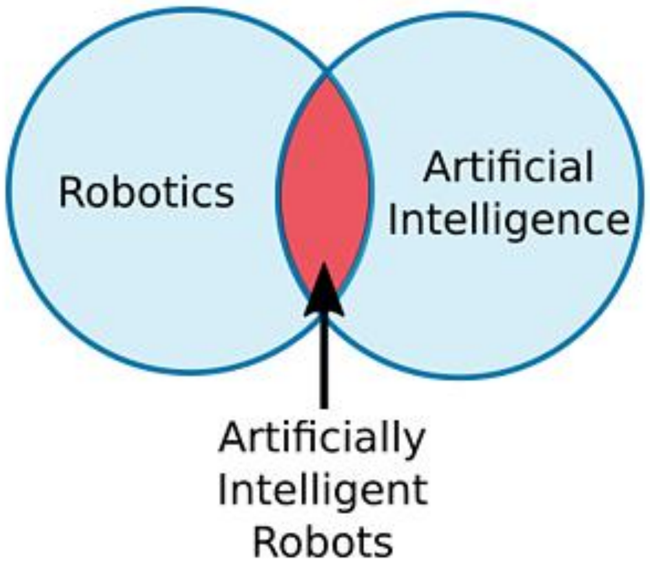


Challenging Teleoperation Example#2



Robotics and AI

- Often robotics is seen as a module of AI (information technology)
- Main difference between a robot and a computer is a physical action
- In robotics, we have not only to deal with information technology but with **“interaction” technology**
  - ✓ Physical interaction (e.g. human-robot interaction) that should be threated with specific robotic controls
- Challenges that are in a physical system must be taken into consideration when apply AI for automated controls
  - ✓ Compliant robotics controls (**haptics, perception, proprioception etc**.)
- Cyber-physical systems



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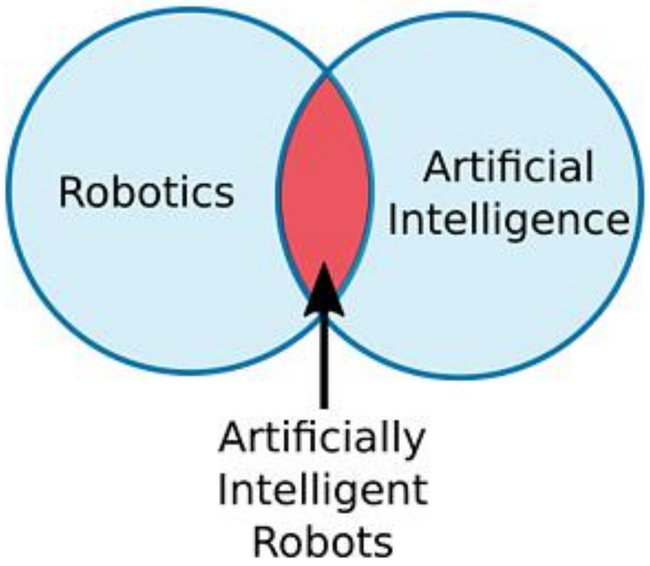


Modern Times, 1936 movie from Charlie Chaplin

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

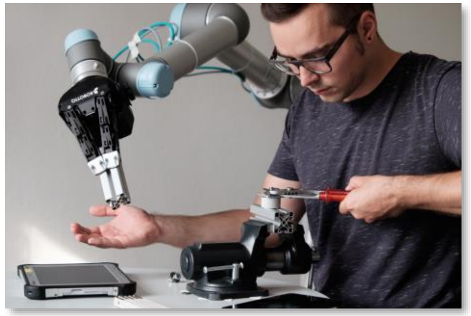
- Control of closed chains kinematic robots
  - Still an open issue, Long short-term memory (LSTM) networks for system dynamic learning

- 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]

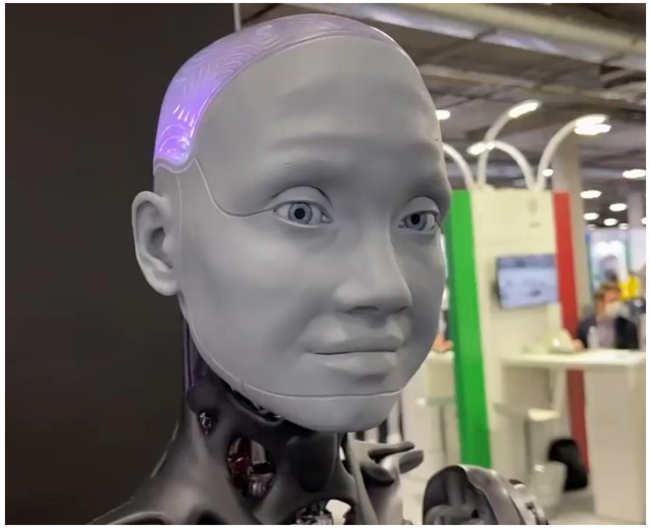

Human Robot collaboration for mechanical assembly

Machine learning in Robotics #2

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

Jia Jia

Sofia



Ameka

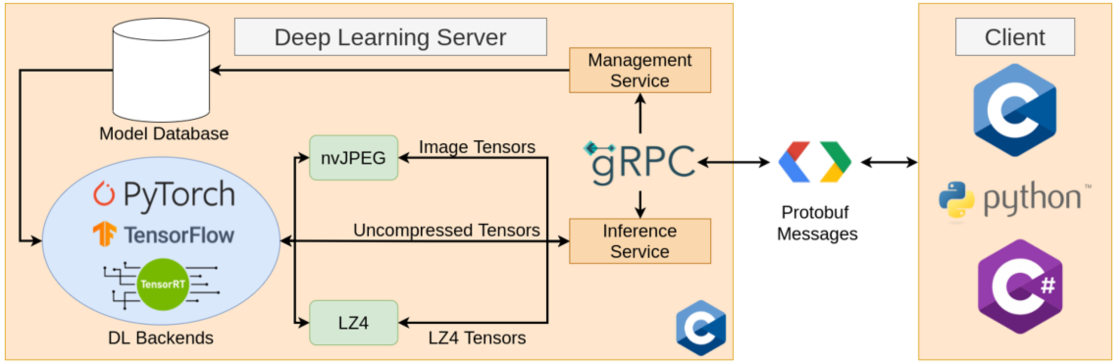
Current state of collaborative robots

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

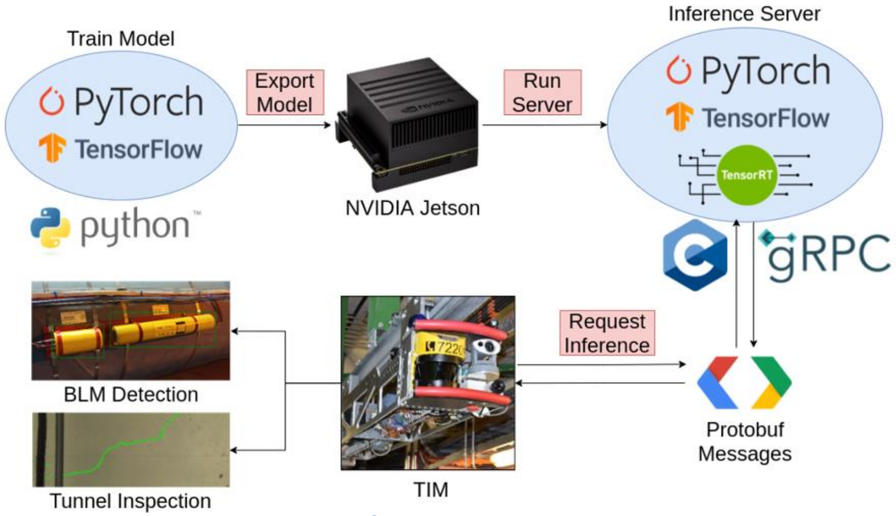
Robot still don’t appear fast enough [4]

Framework for Deep Learning Inference

- Developed in C++
- Python, C++ and C# Clients.
- TensorFlow, Pytorch and TensorRT frameworks as back-end.
- Support model formats:
  - Keras SavedModel,
  - TensorFlow SavedModel
  - TorchScript
  - ONNX
- Optional compression of data.
- Multi-model inference
- High performance network protocols.



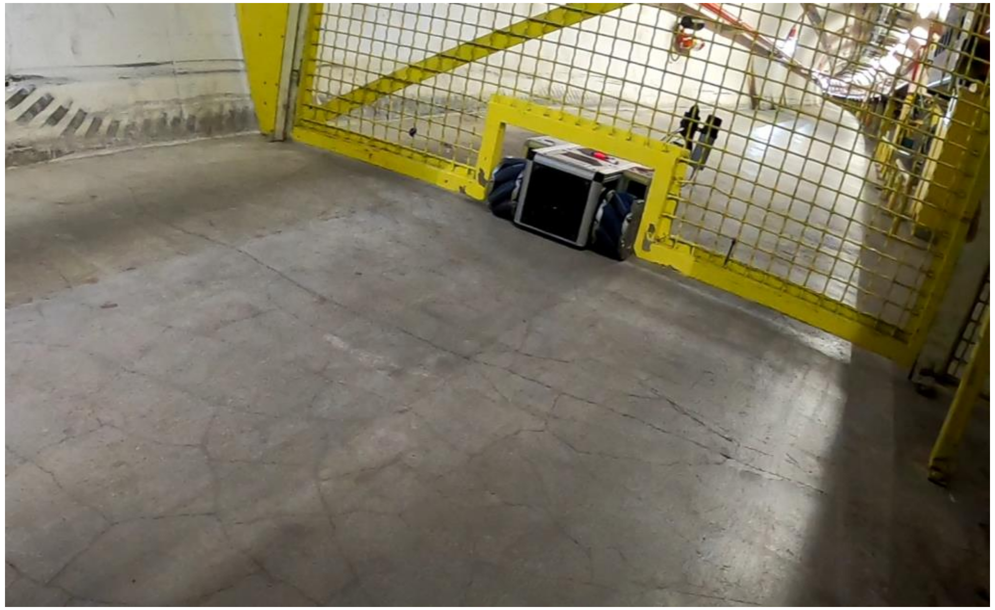
Workflow overview

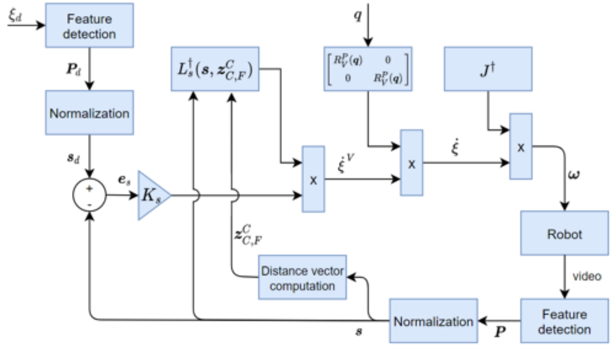


Workflow example

Framework for Deep Learning Inference: application

- SPS section doors autonomous recognition and passage –> heavily relies on vision
- Narrow passage through 200x400 mm door aperture (clearance 10 mm each side)
- Optical flow and deep learning to detect and perform pose estimation of the section door aperture – CNN-based dense pixel correspondence estimation





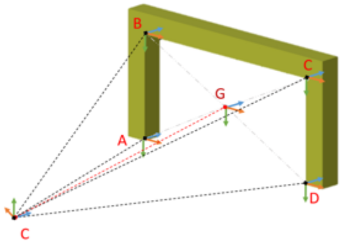
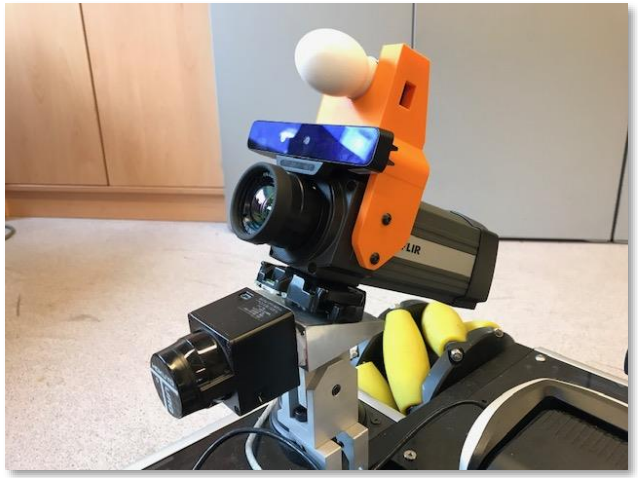


Image-based visual servoing system using ML

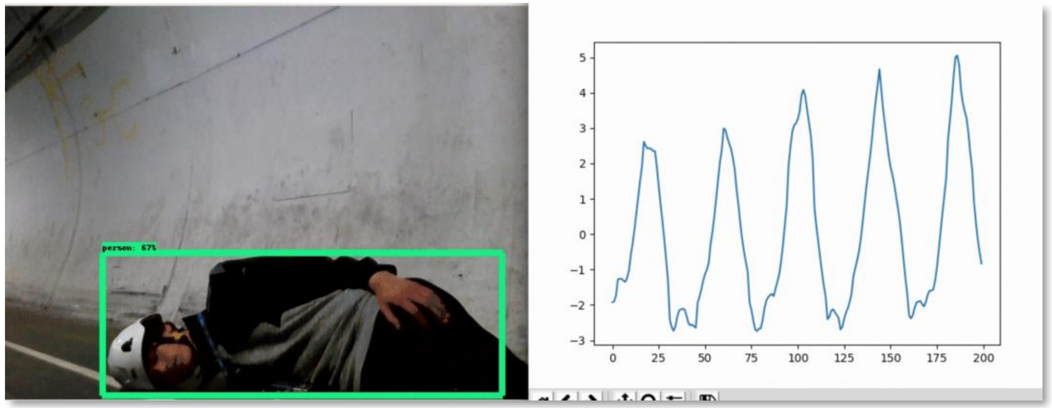
Morra, D., Cervera, E., Buonocore, L. R., Cacace, J., Ruggiero, F., Lippiello, V., & Di Castro, M. (2022, June). Visual control through narrow passages for an omnidirectional wheeled robot. In *2022 30th Mediterranean Conference on Control and Automation (MED)* (pp. 551-556). IEEE.

People recognition and vital monitoring

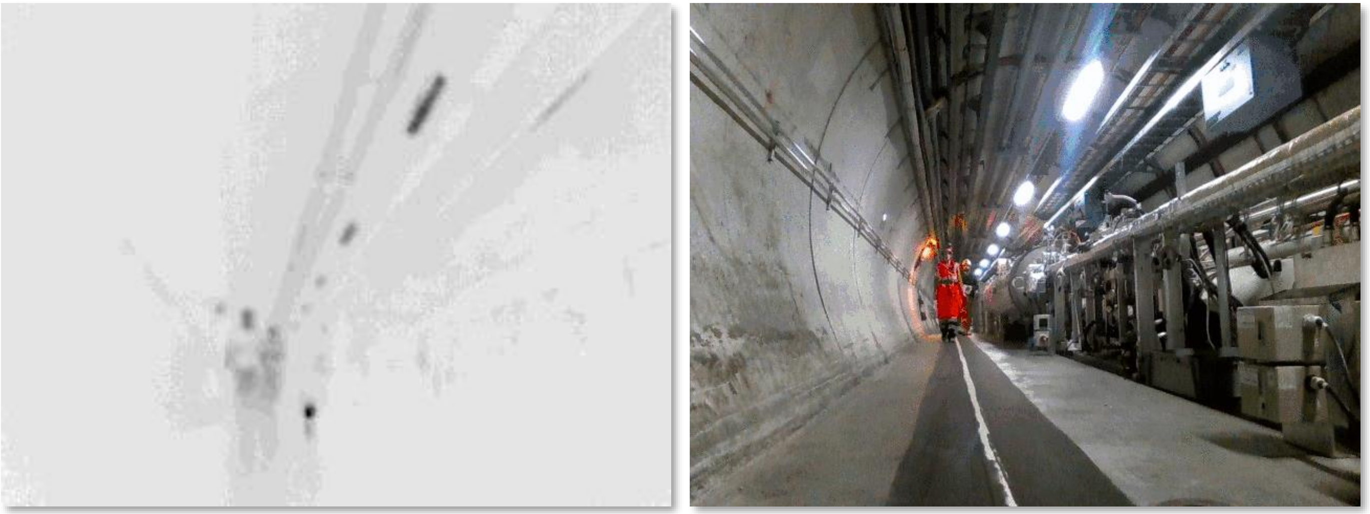
- Machine learning techniques enhance people detection and vital signals monitoring at distance
- People search and rescue is of primary interest in disaster scenarios
- People monitoring during rehabilitation



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

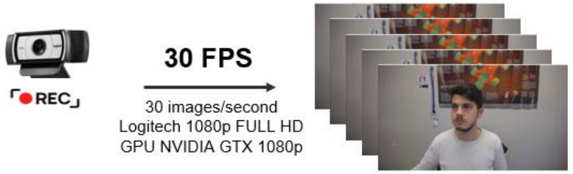


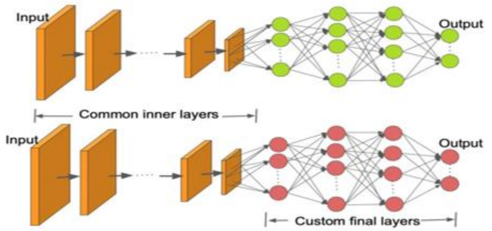
Online respiration monitoring

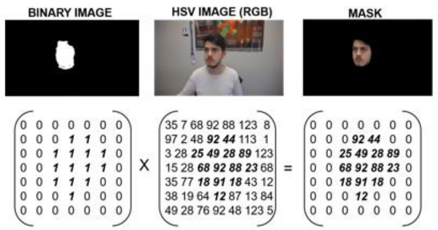


Online people recognition and tracking

MARCHESE project: Health Contactless Monitoring







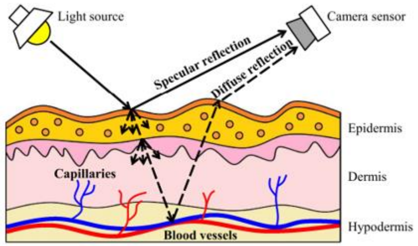
SKIN PIXELS
NO-SKIN PIXELS

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

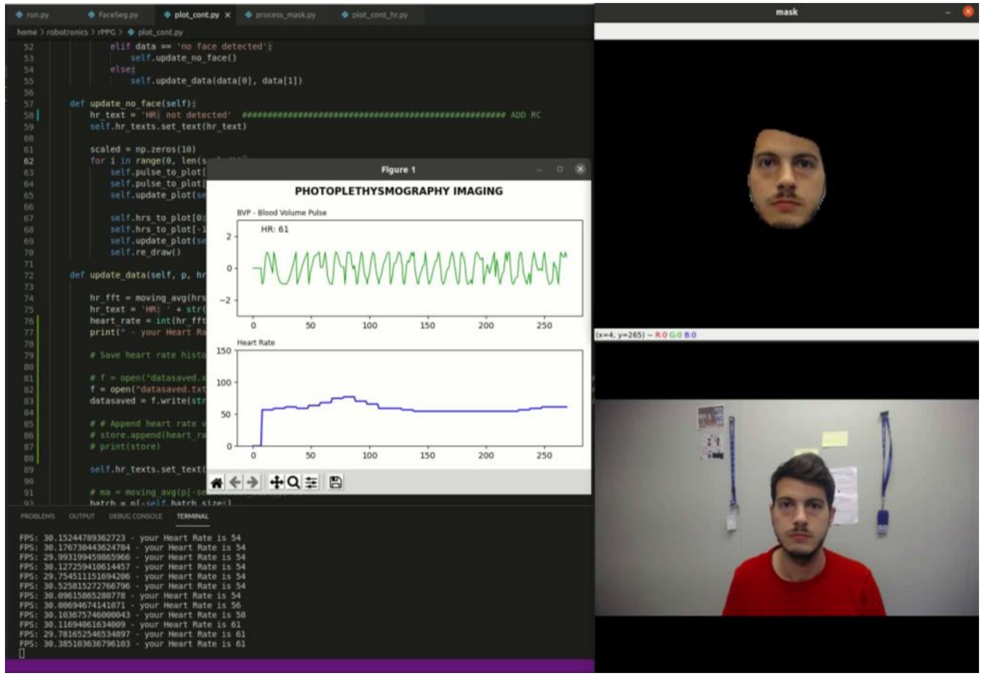
Reflection of each skin pixel in an image sequence in RGB channels

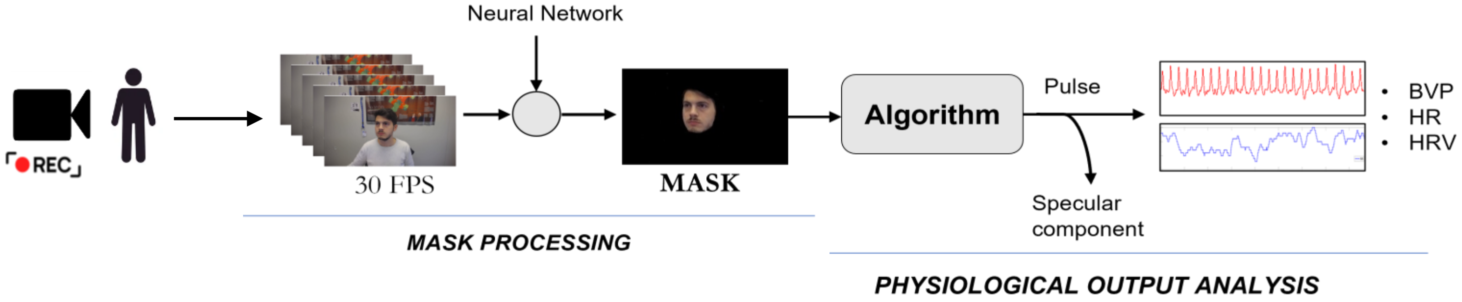
SPECULAR REFLECTION is a mirror-like light reflection from the skin surface (not contain any pulsatile information). Time dependent: body motion influence.

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 $\rightarrow$ $C_k(t) \sim I_0(1 + i(t)) \cdot [\underbrace{\cancel{u_c \cdot c_0}}_{\text{Constant}} + \underbrace{\cancel{u_s \cdot s(t)}}_{\text{Specular}} + \underbrace{u_p \cdot p(t)}_{\text{Pulse}}]$

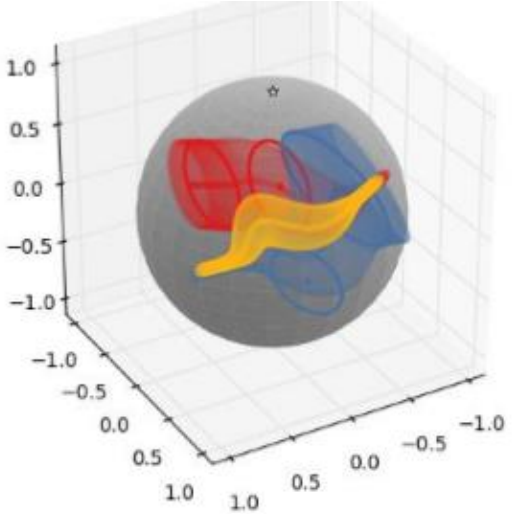




→ Robotic operators monitoring to benchmark interfaces and future developments

Learning by Demonstration Using GMM and DMP

- **Machine imitation learning**
  - ✓ Generate movement trajectories using Gaussian Mixture Model (GMM) on a Riemannian manifold from several human demos and Dynamic Movement Primitives (DMP)
- **Learning Benefits**
  - ✓ Robots adapted to the tasks and the environment
  - ✓ Fully autonomous task implementation possible
  - ✓ Assistive robotic technology supporting remote operators



Blue: robot moves in its base frame
Red: robot moves in target's frame
Orange: generated/reproduced movement for rob

Learning by Demonstration Using GMM and DMP

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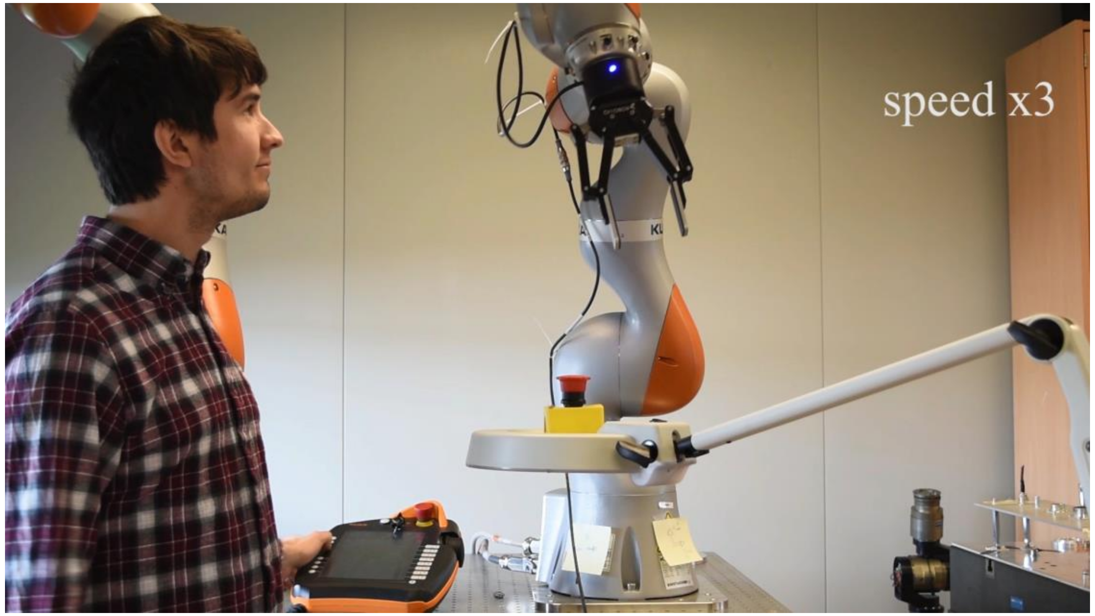
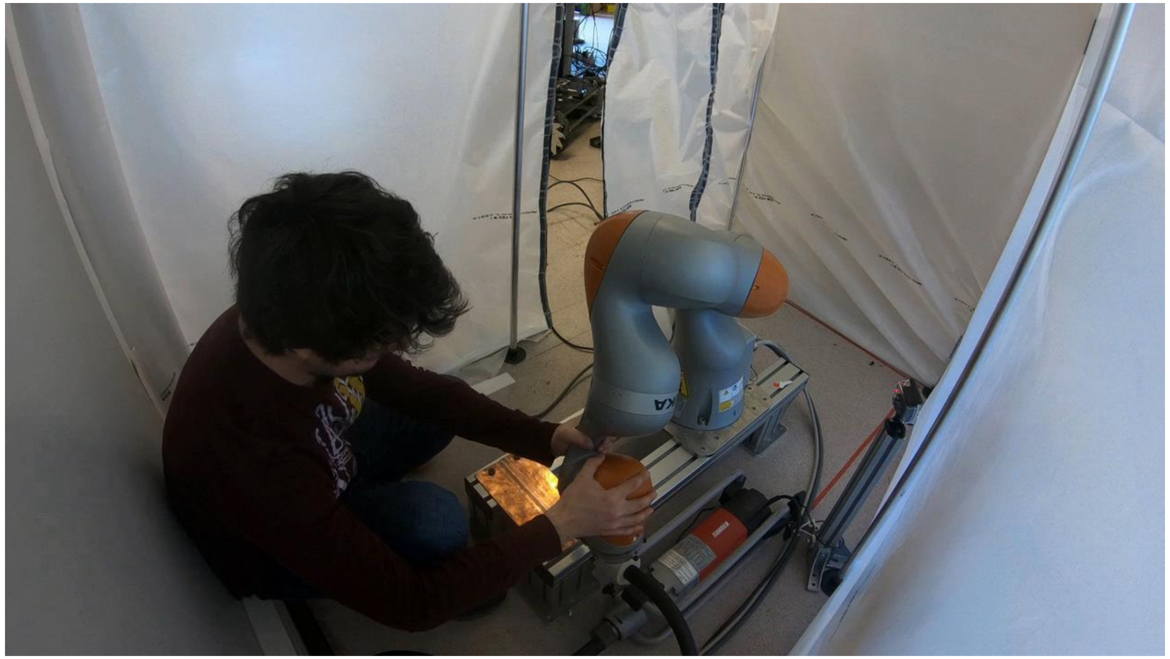
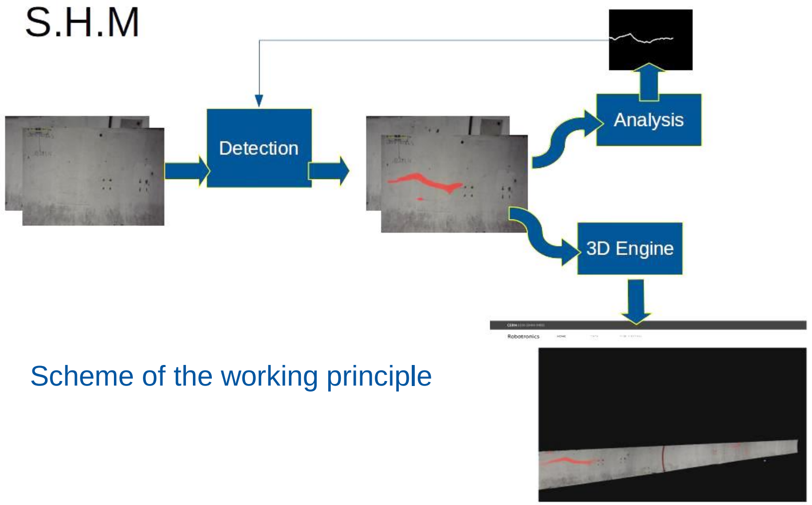


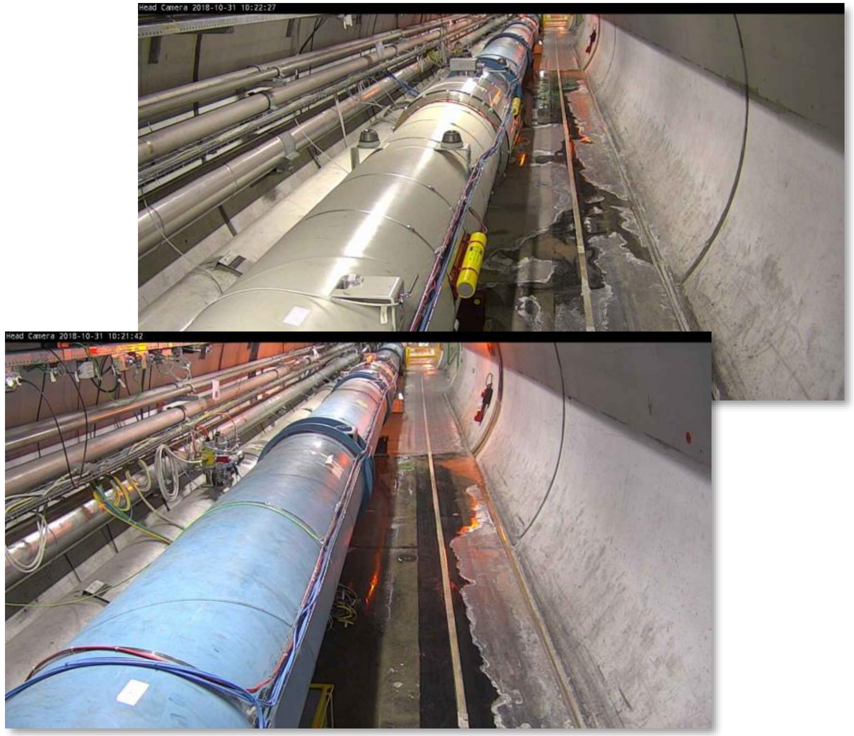


Tunnel Structural Monitoring

- Automating detection of anomalies and classification of walls' cracks using **machine and learning (RCNN)**

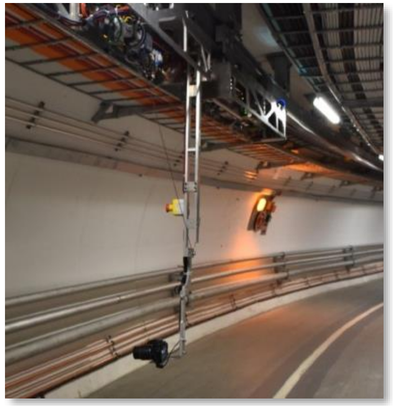


Scheme of the working principle

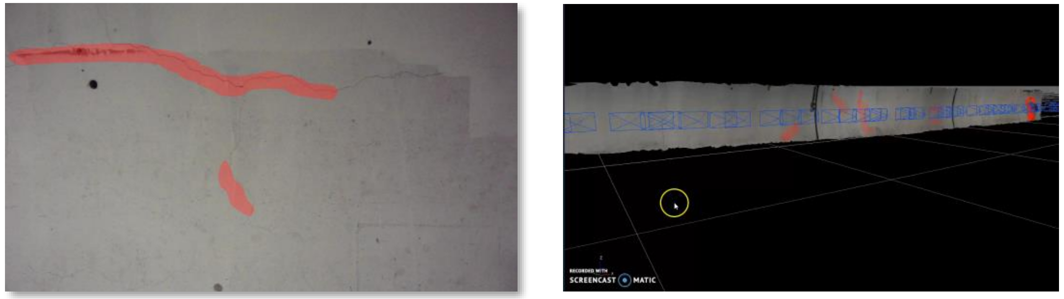


Example of water leak found by TIM2 during TS3 2018

more on this topic in [30] [31]



HD cameras mounted on TIM



Example of crack found using vision based machine learning techniques and visualization in VR

RF cavity visual inner inspection: ML for surface quality assurance

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

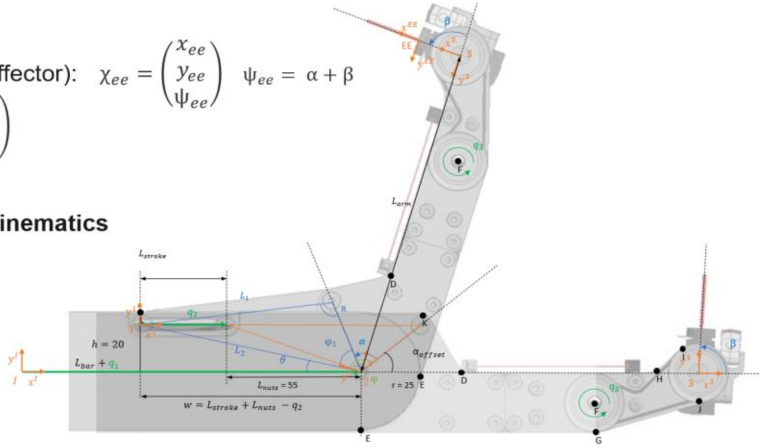
Joints Space: $q_{ee} = \begin{pmatrix} q_1 \\ q_2 \\ q_3 \end{pmatrix}$

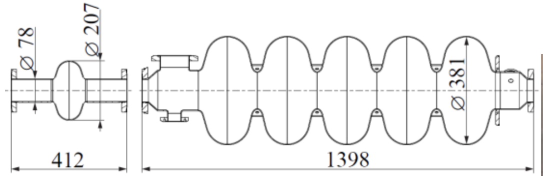
- **Forward & Inverse Kinematics**

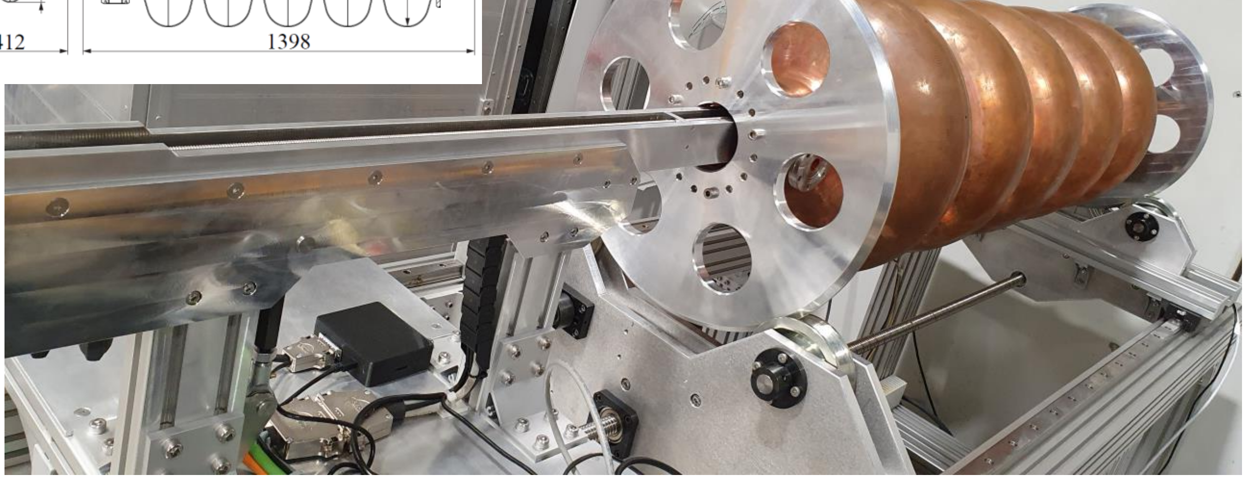
$\dot{\chi}_{ee} = J_A(q)\,\dot{q}$

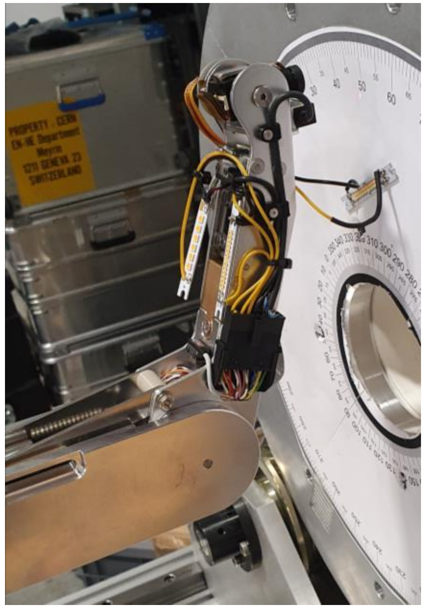
$\Delta q \cong J_A(q)^{-1} \Delta\chi_{ee}$

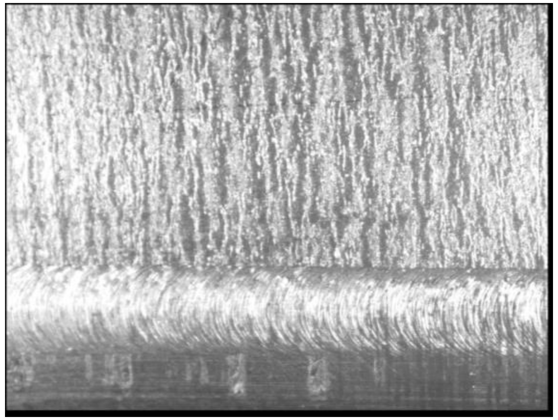
$qNext \cong qActual + \Delta q$









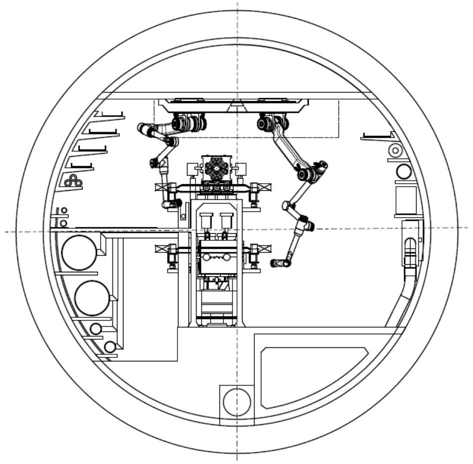


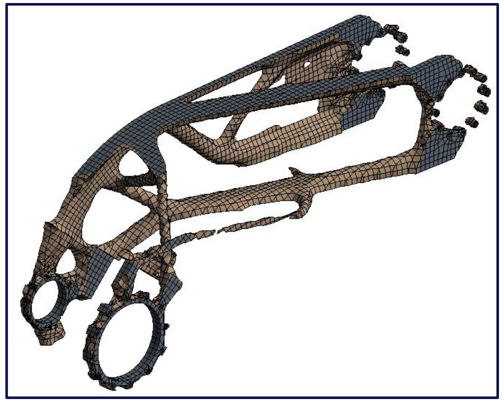
Autofocus on images size: 1 x 1 cm taken at 23 mm distance

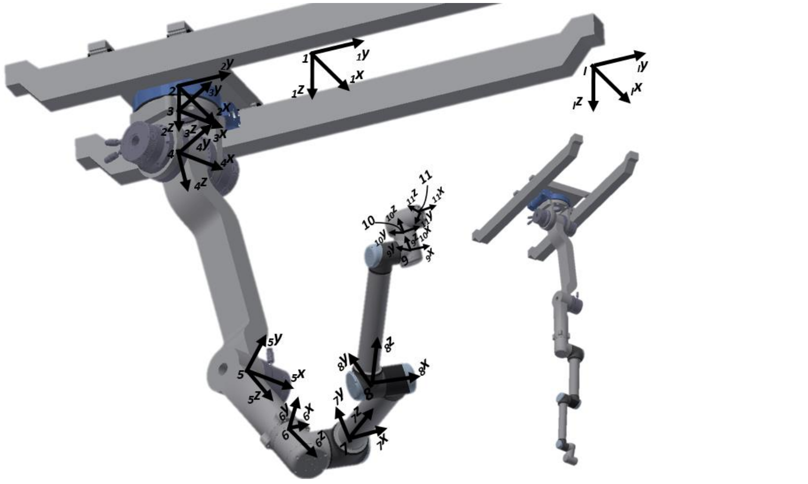
Robots for Future Accelerators (FCC)

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

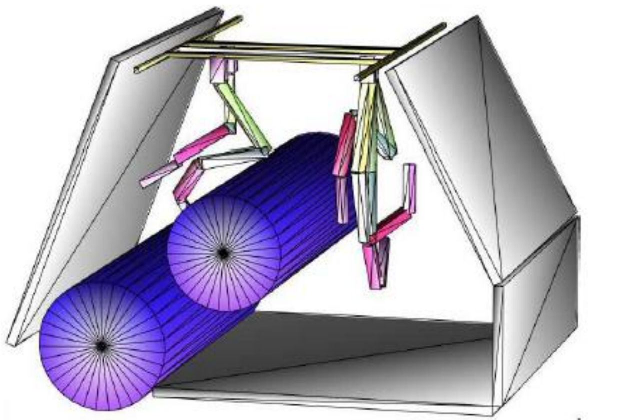
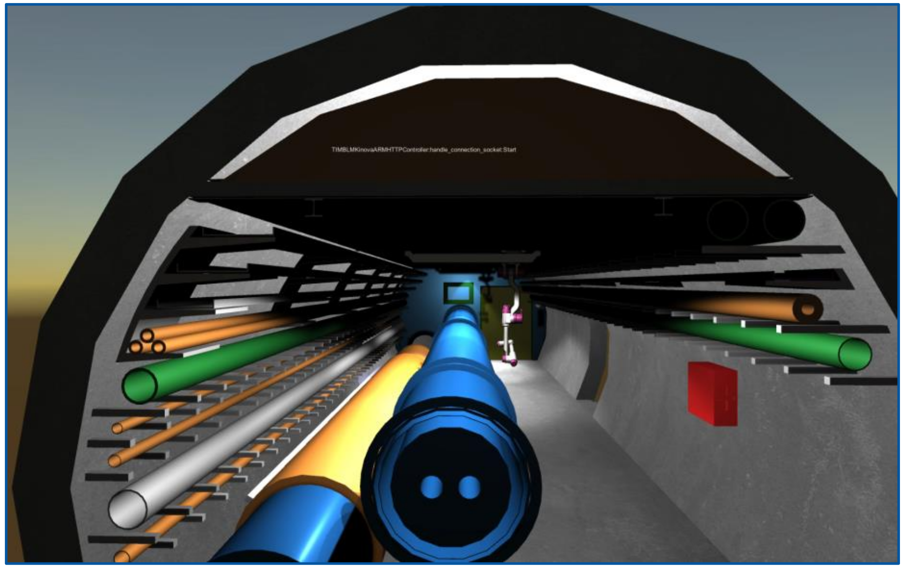


Figure 11: Optimization results FCC-hh (collision objects)



Lessons Learned and Conclusions

- Industry 4.0 is built for <u>industry</u> and is boosting its efficiency. Particle accelerators are complex machines with specific needs, hazards and risks, that are not always in line with industrial plants.

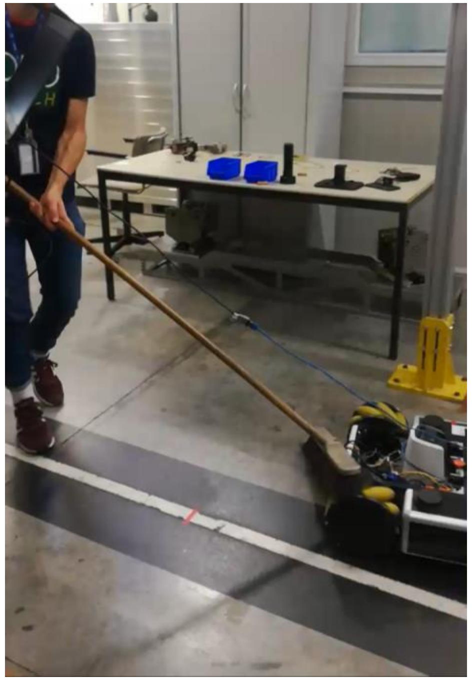
- Toolboxes of Industry 4.0 can improve particle accelerators machines availability increasing components reliability, preventing failures and boosting maintenance efficiency.

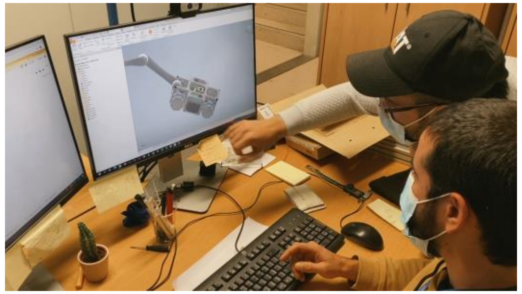
- Reliable Data are fundamental to make tools of Industry 4.0 usable. <u>Start to collect data even if these tools are not yet available in your toolbox. Time is mature to share data between accelerators towards standardization?</u>

- 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

- Artificial intelligent and robust remote systems can increase personnel safety, machine availability and quality assurance.

- The user-friendliness of robotic interfaces could allow equipment owners and expert technician to maintain facilities using teleoperation





“Behind” a robot there are many human brilliant brains
Robots and robotic instrumentation, including SW, need a crew to use them and maintain and experts in-house to be effective

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"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

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

Mario.Di.Castro@cern.ch

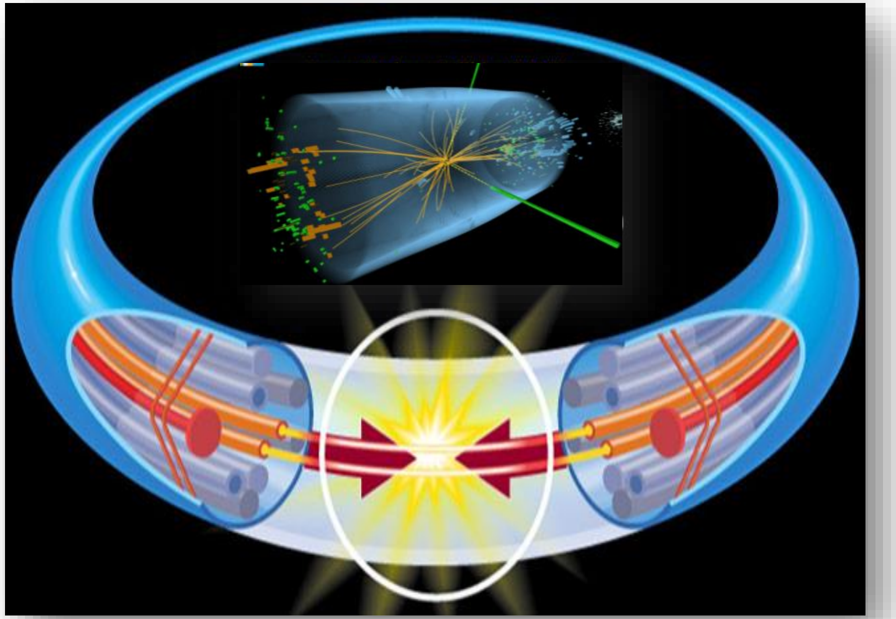
Backup Slides

Robotics mandate at CERN

- The “mission” of tele-robotics at CERN may be resumed in the following:

Ensuring safety of Personnel

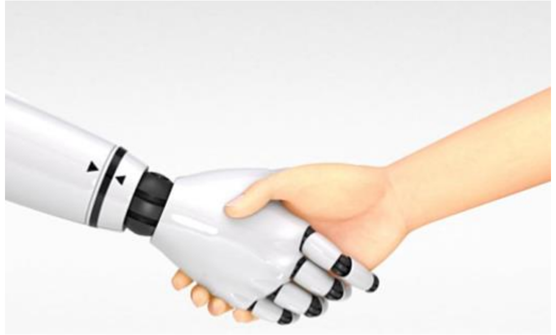
improving availability of CERN’s accelerators



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



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

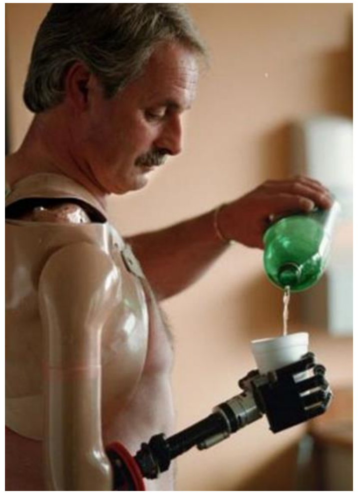
Not human, but cause to worry

SEATTLE

Experts at conference explore questions about artificial intelligence

Robotics for us

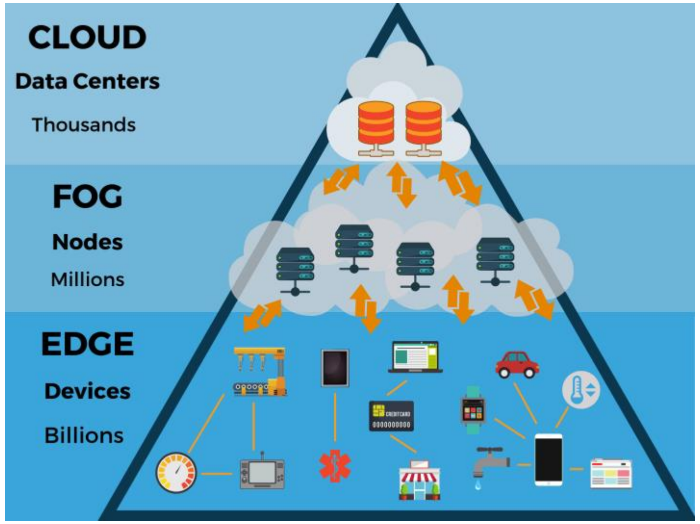
- ➢ **There is a lot of potential in this technology to be beneficial for people**
- ➢ **Ultimately, everything depends on how we decide to use the technology**

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

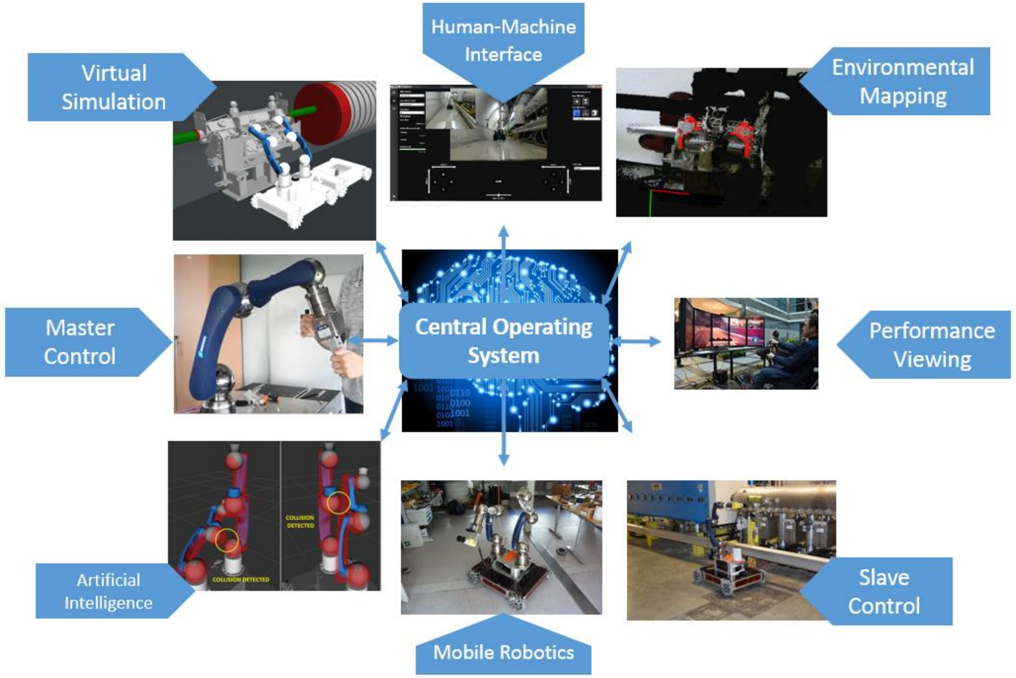
Big Data in IoT

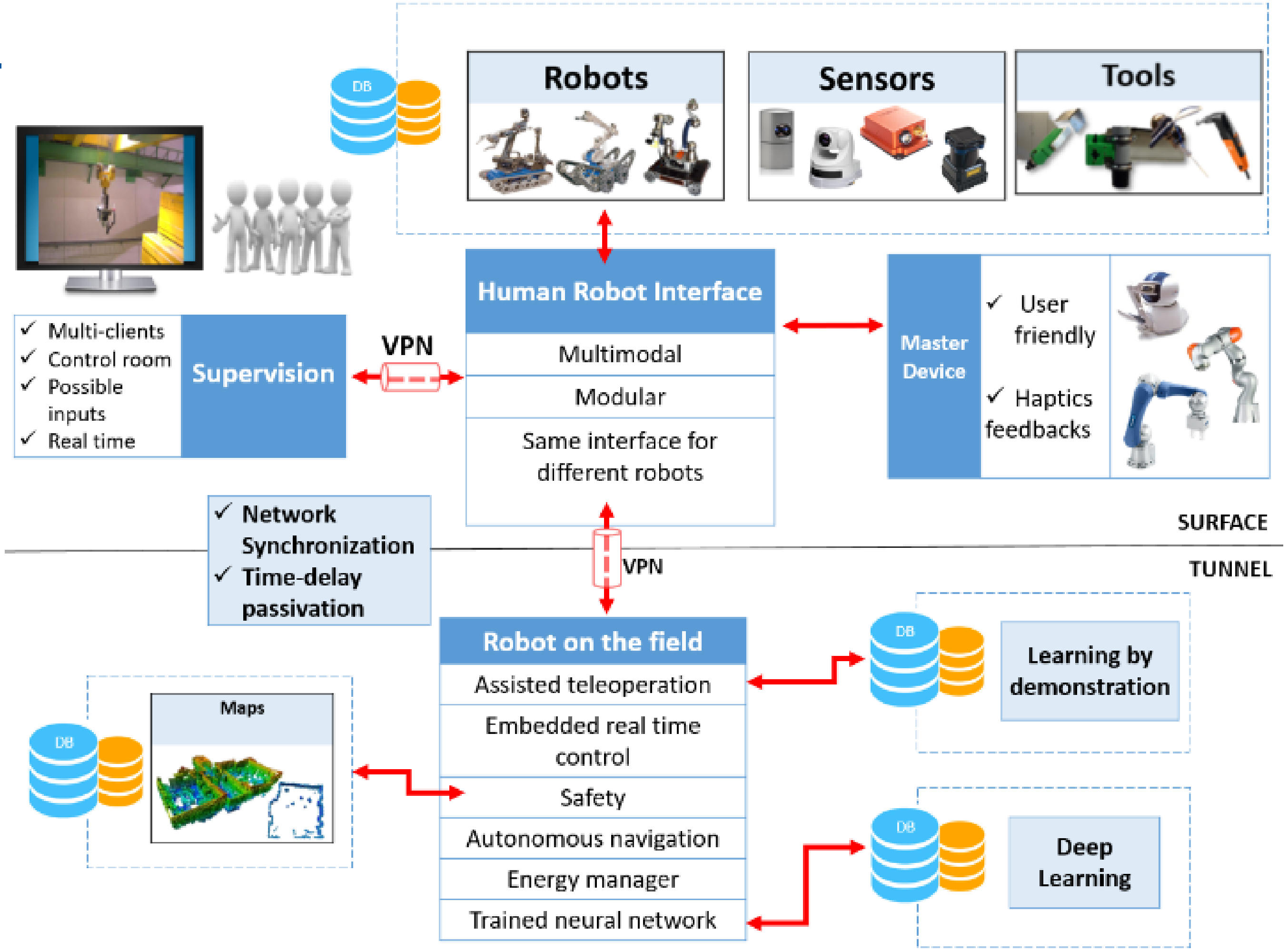
- Distributed and highly digitized sensors produce an enormous quantity of data
- Data collected by IoT devices are normally in unstructured form
- Big data processes the collected data in real time form and store them using several storage technology
- Big Data developments increase IoT efficiency and vice-versa
  - ✓ Edge computation
- **Sharing of data between accelerators could lead to better efficiency and cost reduction →** a digitized version of what we do nowadays with conferences, meetings etc.



CERNTAURO framework

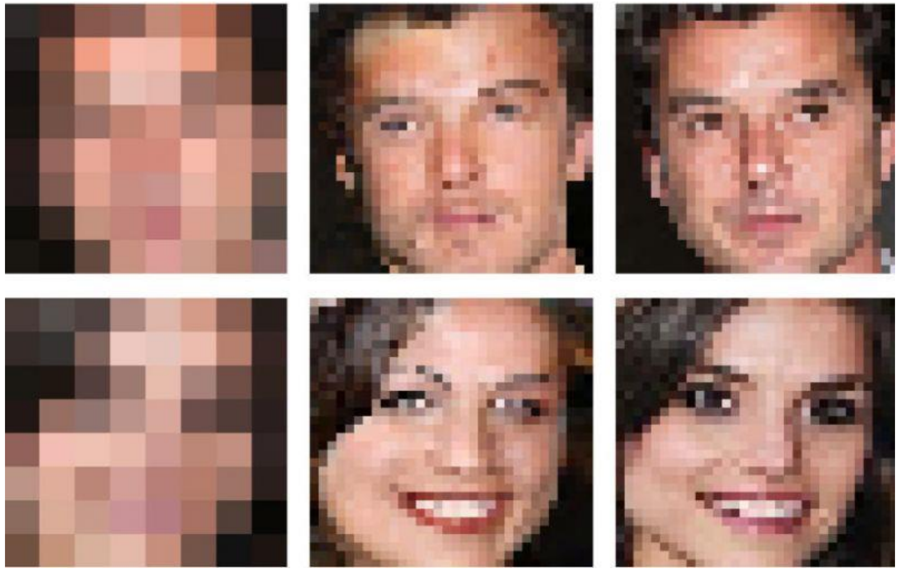
- In house robotic control system [7]
- No use of ROS [8]
- Sensor acquisition, fusion, measurements etc.

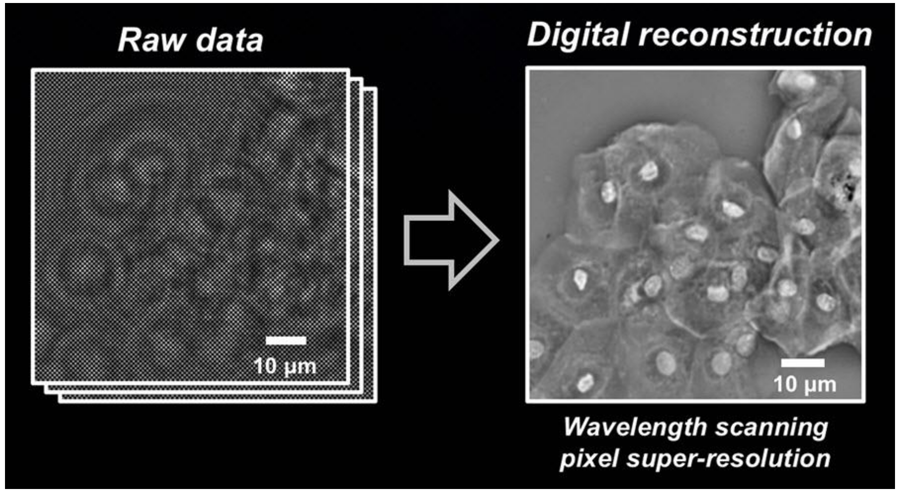


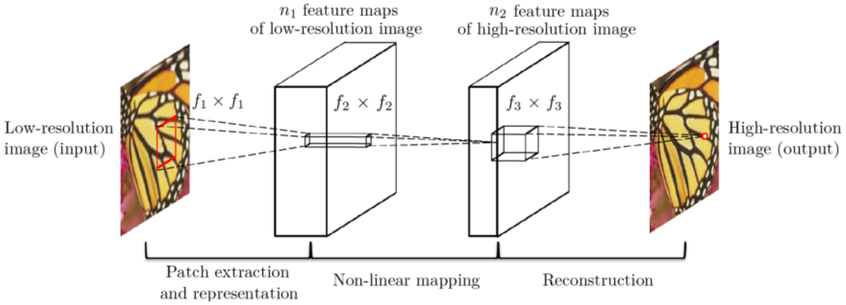


Super resolution for visual online monitoring #1

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

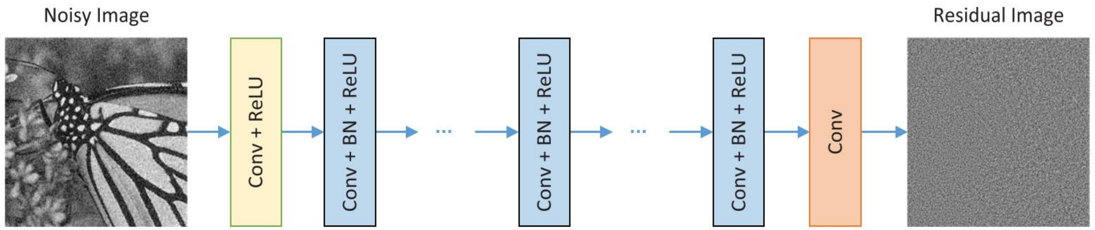


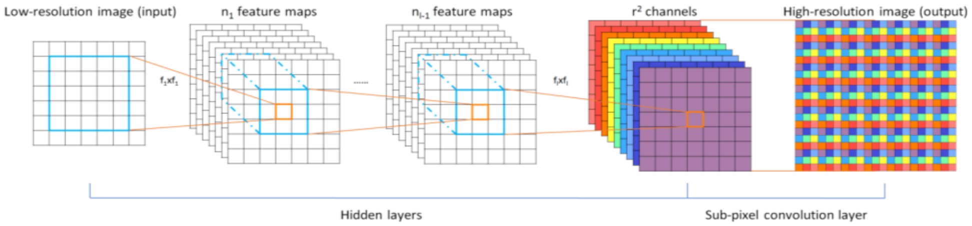




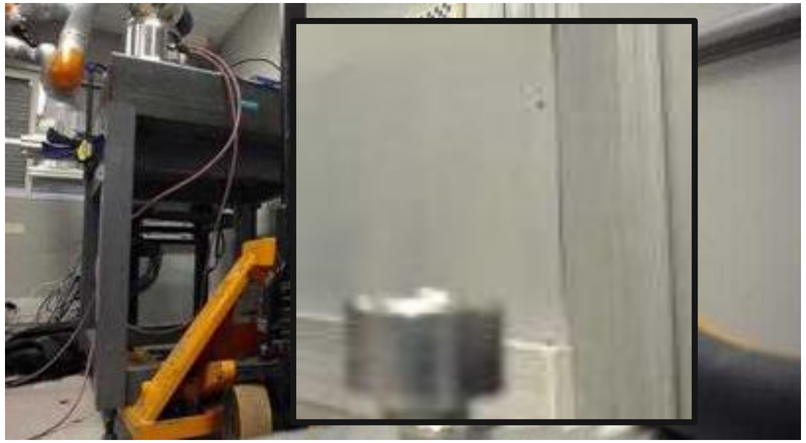
Super resolution for visual online monitoring #2

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

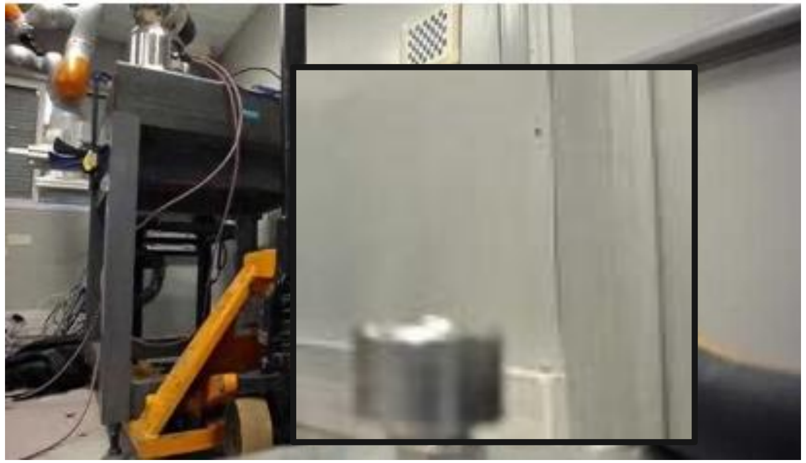




PYTORCH



50% jpeg compression; 14 kb

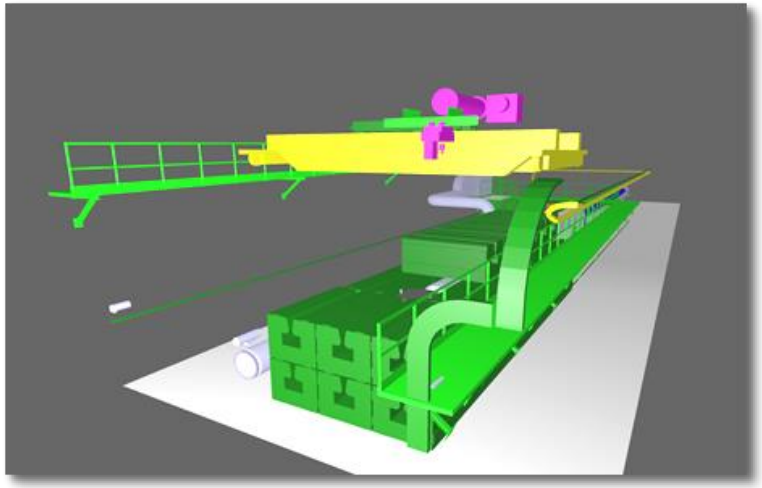
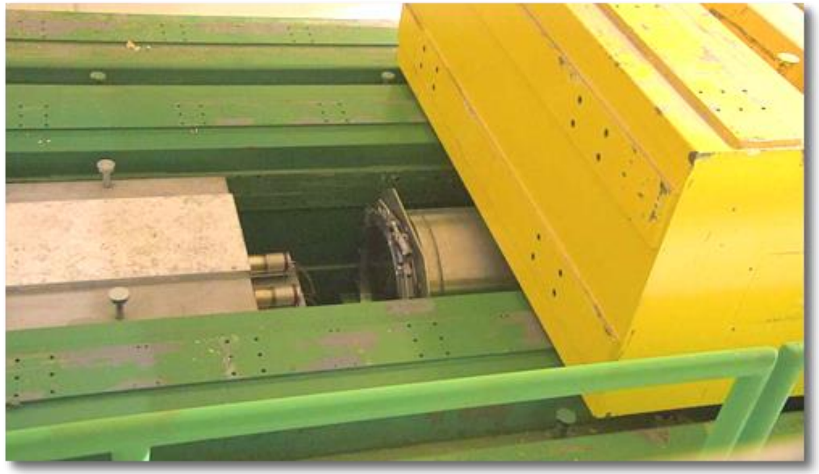


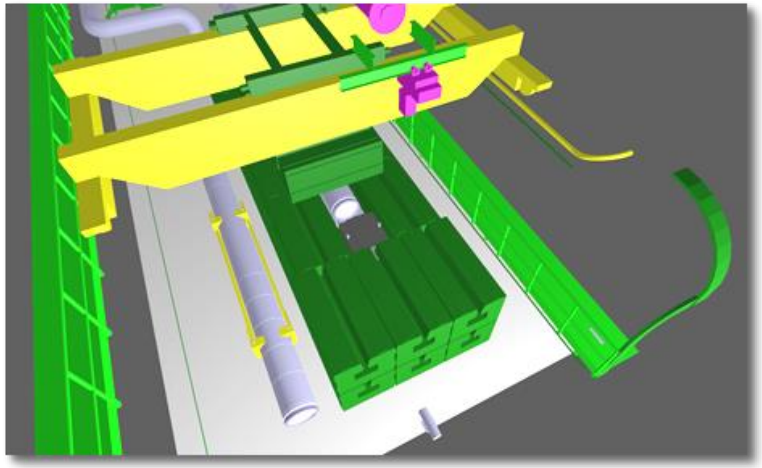
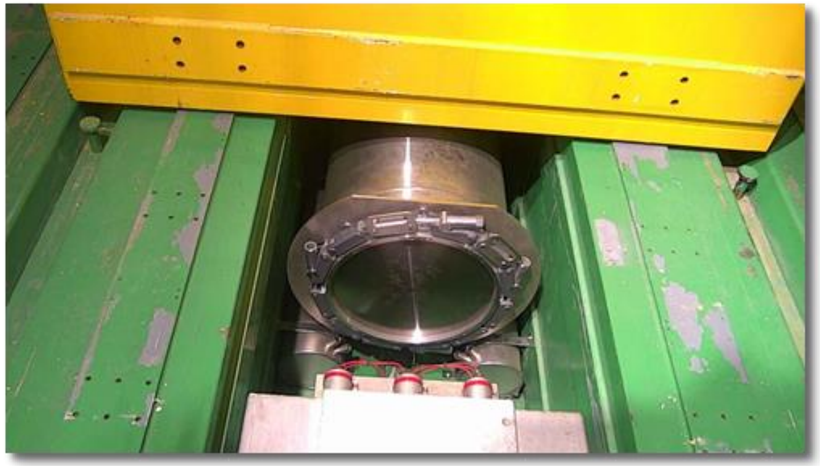
4X resolution enhancement + noise reduction; 282 kb; computation time 4 ms

Challenging Teleoperation Example#2

- LHC TDE inspection

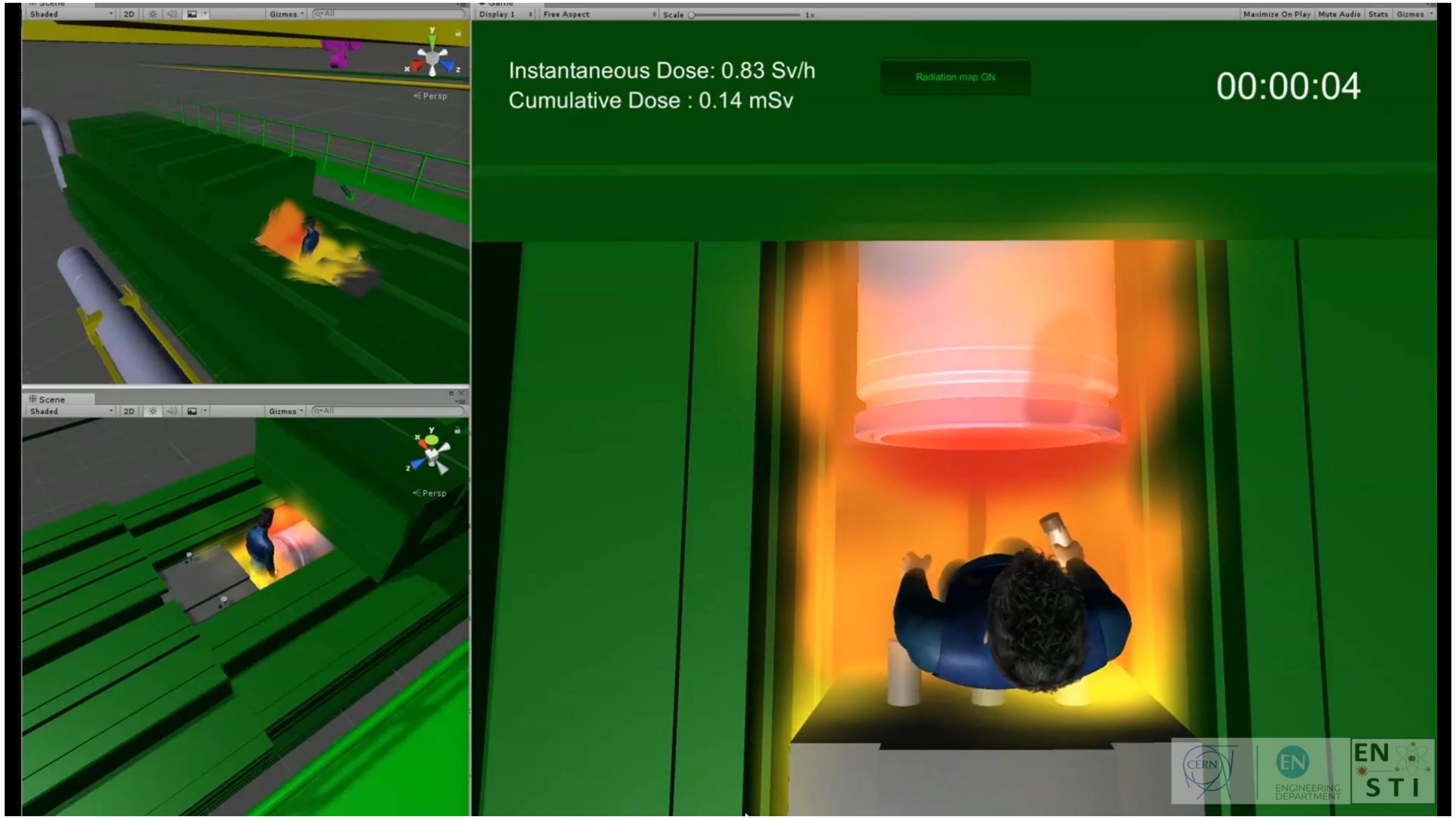
CERNbot v1.0 core

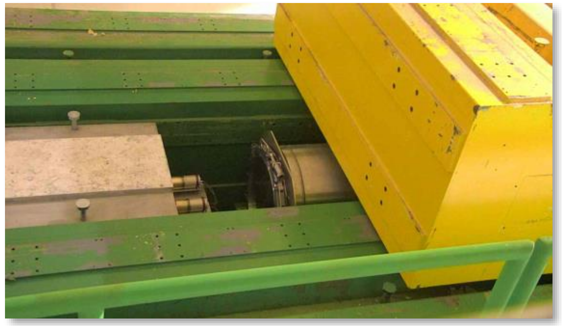



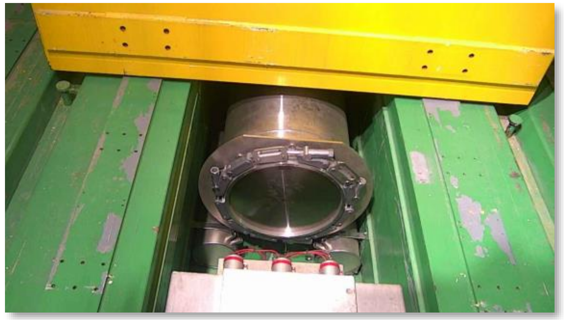



Challenging Teleoperation Example#2

- LHC TDE inspection



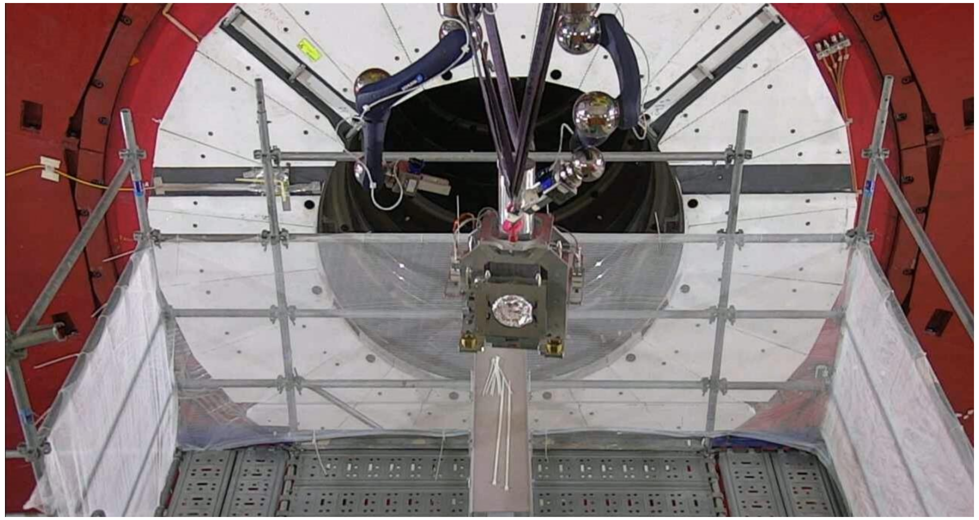
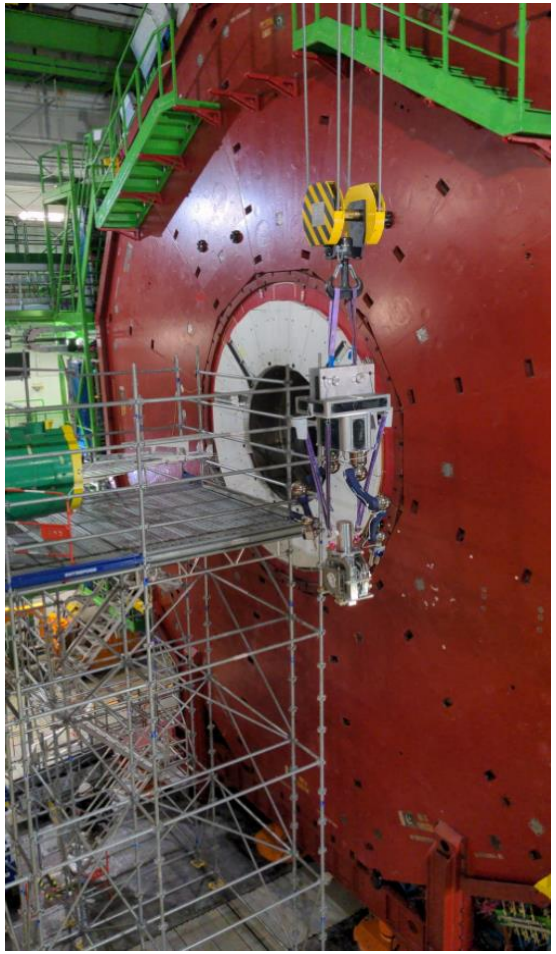
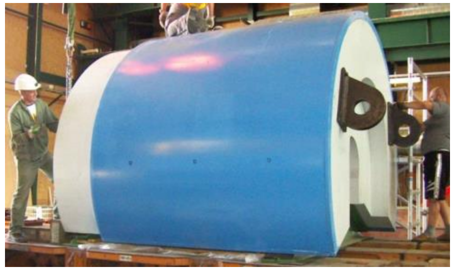




Future main missions and developments

- ➢ New CMS VAX maintenance with CRANEbot, ATLAS shielding doors robotic milling



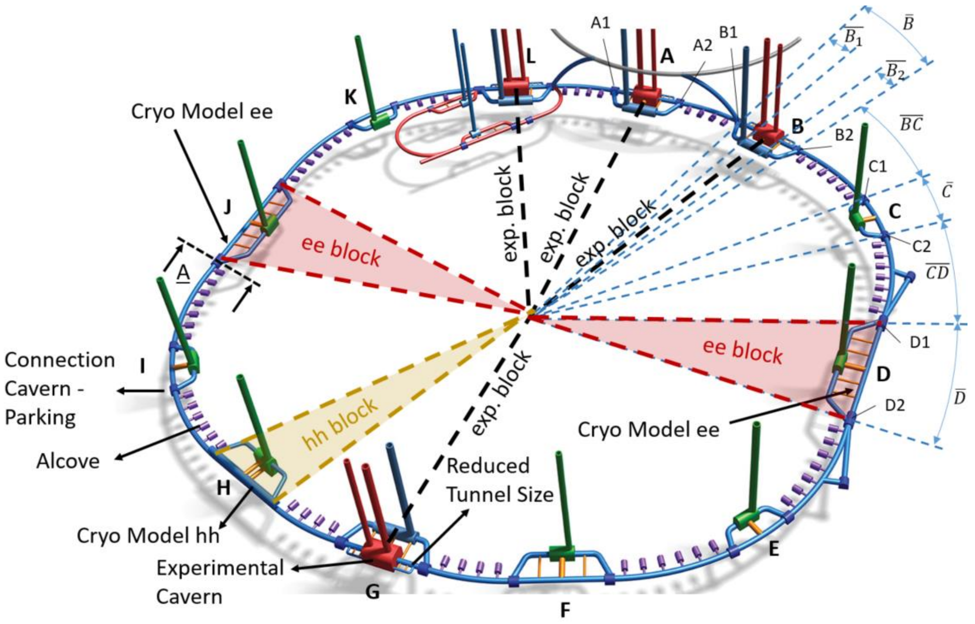





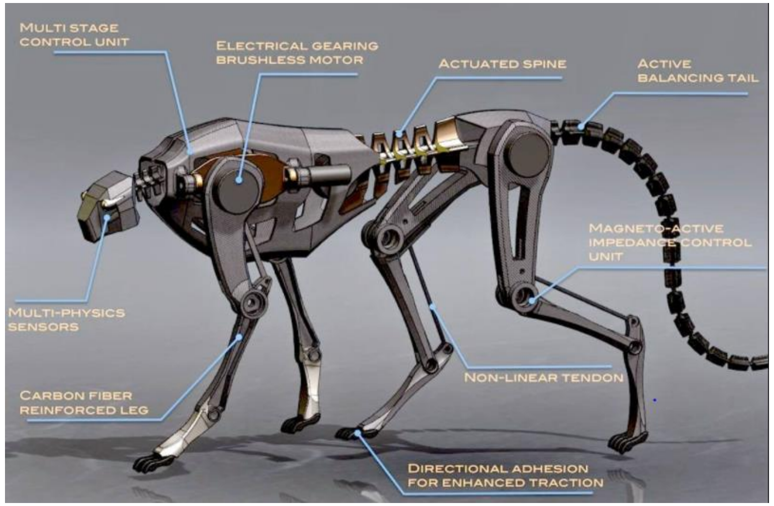

- ➢ **ATLAS shielings modification using robotic CNC techniques developed in-house**


- ➢ **Future main developments →** User friendly human robot interfaces and snake robots

Robots for Future Accelerators (FCC)

- ➢Novel robotics platforms and controls for remote maintenance and interventions



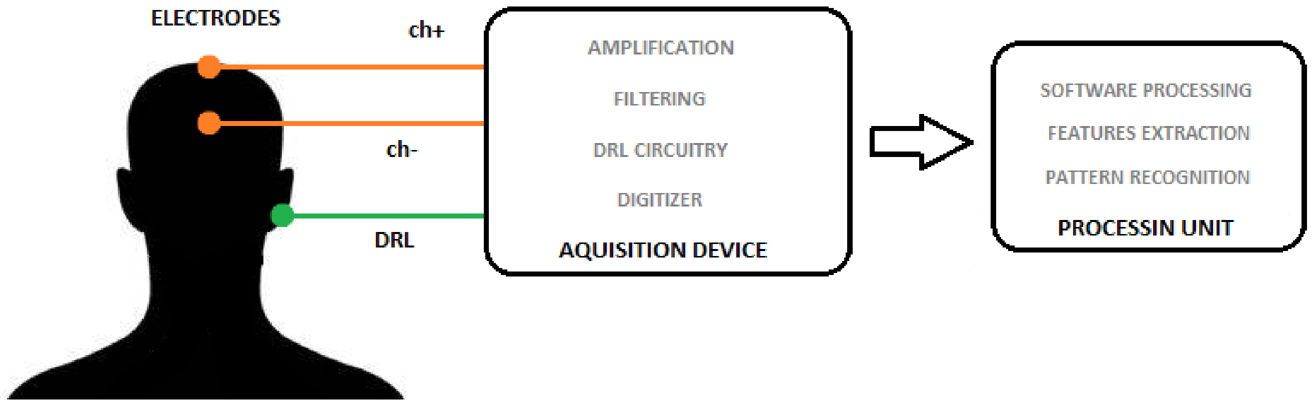


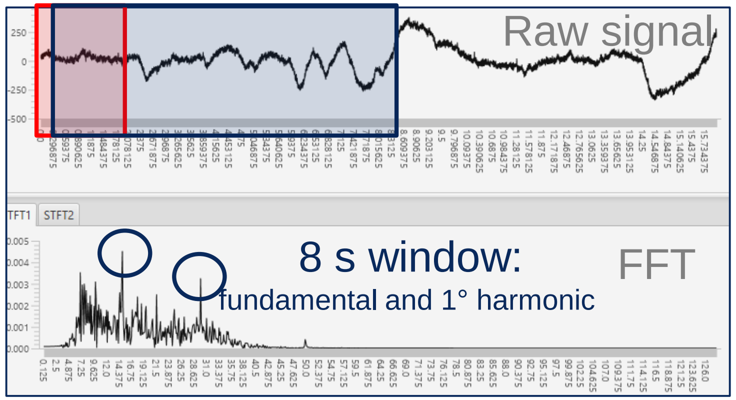
More on H. Gamper lecture

Brain-Robot Interface for robot arm control

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

Hardware used for the brain monitoring





Example of brain activity monitoring

Brain-Robot Interface for robot arm control