Controls Electronics & Mechatronics

CERN

ROBOTICS FOR MACHINE AVAILABILITY AND OPERATIONAL SAFETY

Content

CERN

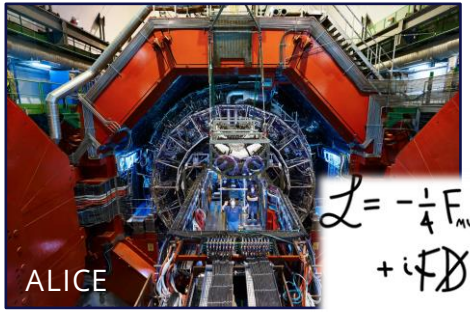
"European Organization of Nuclear Research"

- Trying to model the universe
- Colliding Particles at 99.9999% the speed of light
- Building Particle Accelerators: PS -> SPS -> LHC
- Best model so far: The Standard Model of Particle Physics

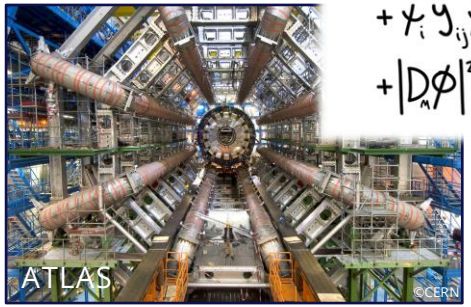
CERN in Numbers

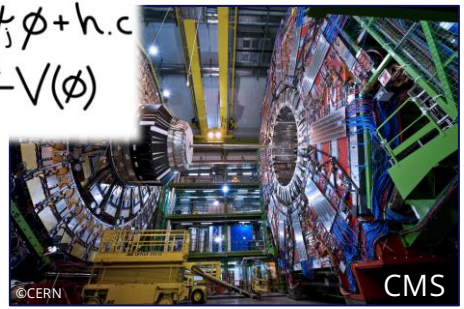
16,950 member of personnel
700+ buildings
3 Nobel prizes
23 member states
1.2 GCHF/year budget

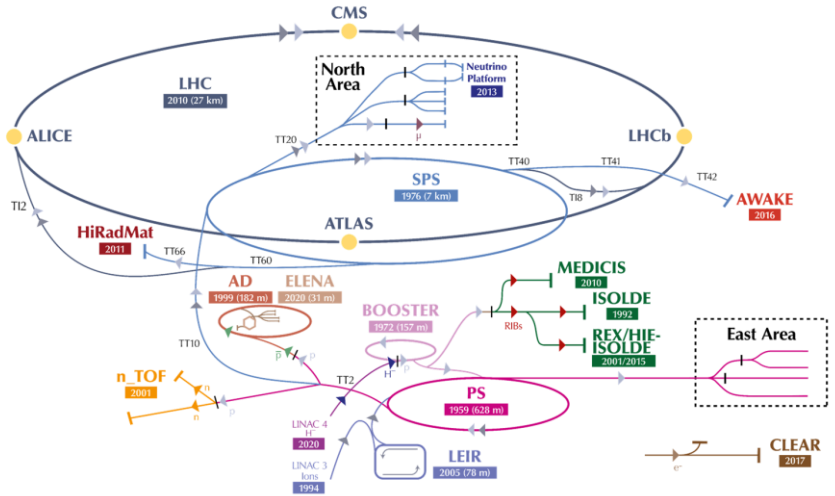
Director General F. Gianotti



$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c + y_i y_{ij} \psi_j \phi + h.c + |D_\mu \phi|^2 - V(\phi)$$





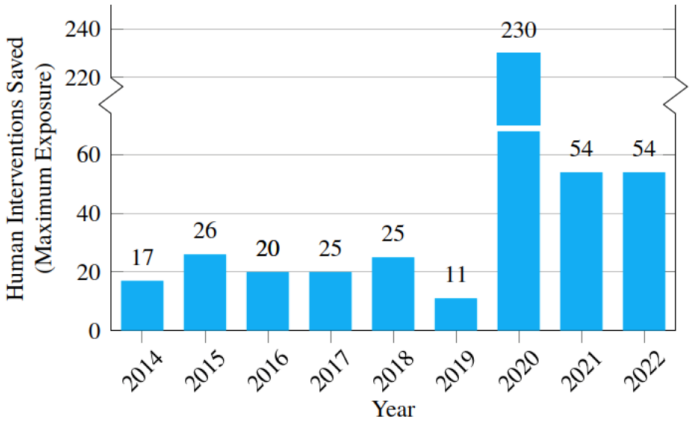


Robotic Service at CERN

That's why we started using robotics

Main Objectives of the current Robotic Service:

1. Increase Operational Safety by …
   - Protecting workers from dangerous interventions
2. Increase Availability by …
   - Corrective & preventive maintenance increasing maintainability
3. Quality Assurance
4. Postmortem Analysis improving new design



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

Availability: $A = \frac{Up\ Time}{Total\ Time} = \frac{MTBF}{MTTR + MTBF}$

Reliability and Availability Working Group: https://indico.cern.ch/category/9071/

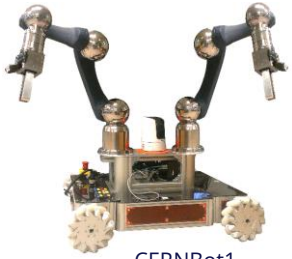
Academic Training Lectures on Robotics: https://indico.cern.ch/event/1055745/

Robotic Service at CERN

- Infrastructure not designed to host robotics
- Need to adapt robots to environment
- Highly versatile systems / relatively low efficiency
- > 20 robotic systems operational in different configurations

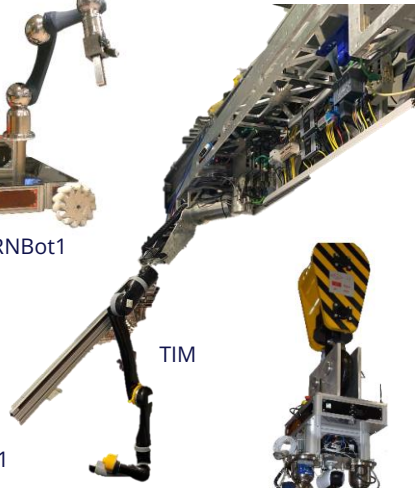

KUKA


Telemax


CERNBot1


Teodor

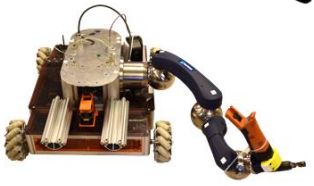

Unitree Go1


TIM

CERNBotCrane

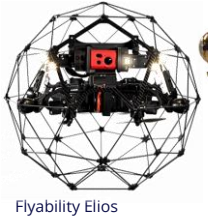

Unitree Go1


Train Inspection Monorail - TIM




Telerob Teodor X Schunk Arm


CERNBot1


Flyability Elios


CERNBot1


CERNBotSPS


CERNBot2

Additional information on the service in academic training lectures: https://indico.cern.ch/event/1055745/

Robotic Service at CERN – Application Categories

Universal Systems


Tesla Optimus


Flyability Elios

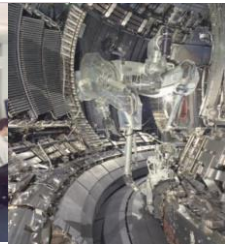

Telerob Telemax


Unitree Go1

Task Specific Systems

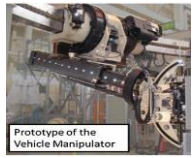

SNS – Oakland National Laboratory


JET – Primary (RACE)


JET – Secondary (RACE)


CERN - TIM

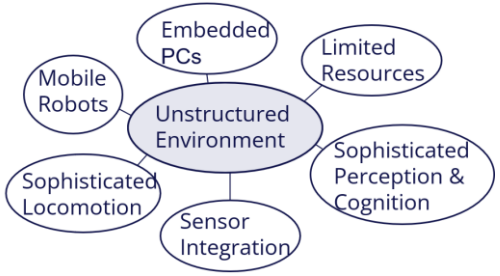

ISS – Canada Arm



ITER – RACE

Industrial Automation S.

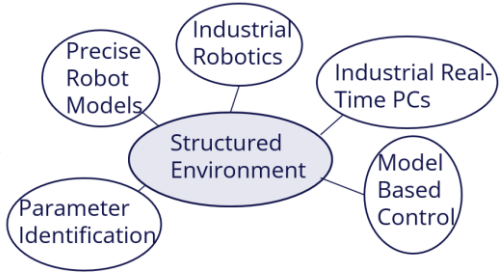

KUKA W8 center



High Versatility / Low Efficiency

LHC
SPS
NA
...

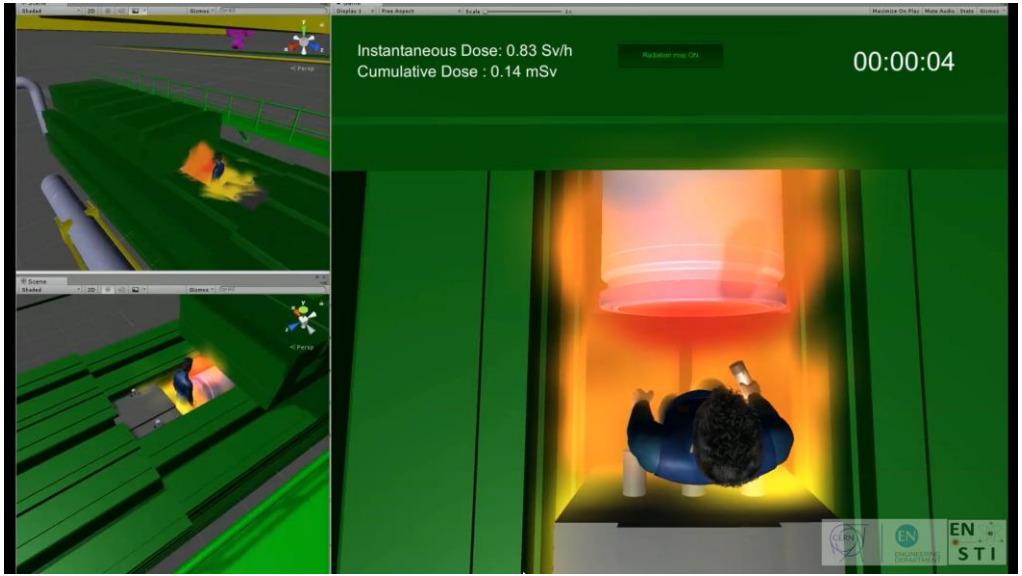
Future Systems
FCC

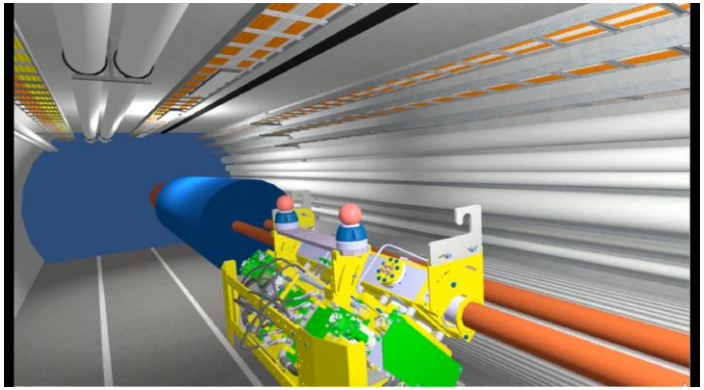


Low Versatility / High Efficiency

Deployed Systems

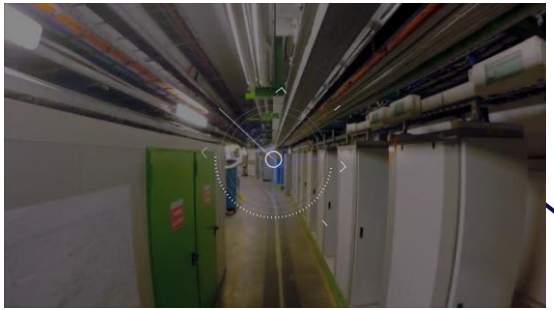
- When do we deploy robots?
- Based on ALARA principal
- Supported by simulation tools (digital twins)
- Human risk evaluation
- Example: LHC Target Dump External (TDE) Inspection



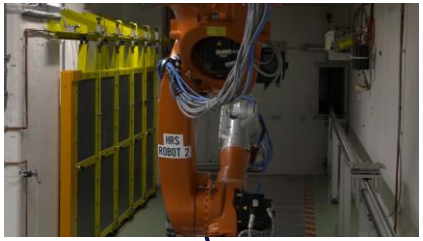


Deployed Systems

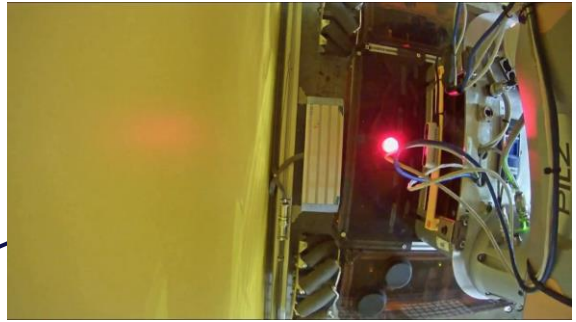
- 12 permanently installed systems: 1 milling robot, 2 SPS, 4 LHC train inspection monorail (TIM), CHARM, North Area (NA), 3 ISOLDE target changing robots
- Efforts to increase robotic efficiency in the current facilities by adapting the environment => Machine Availability Boost



4x TIM operated by TI

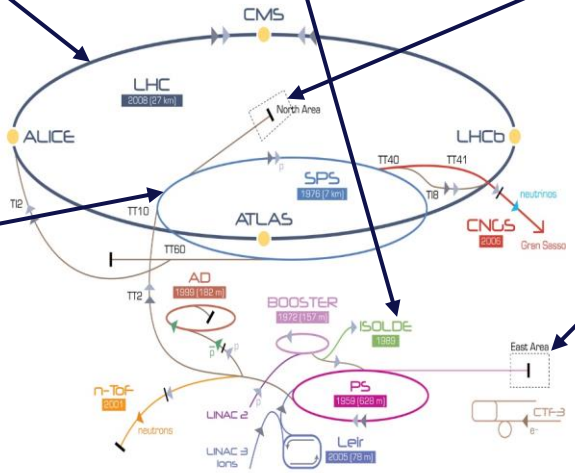


3x Kuka Robots in ISOLDE-Medicis



NA80 Robot (Intervention time reduced from 4 h to 5 min!)

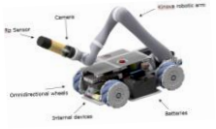
2x SPS robot

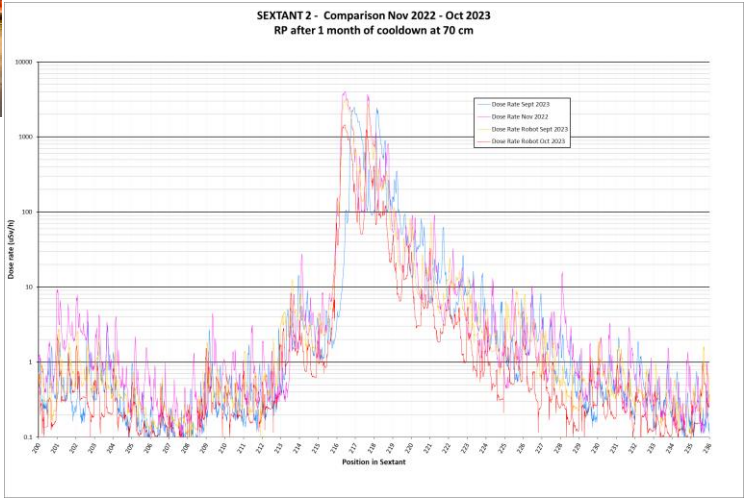


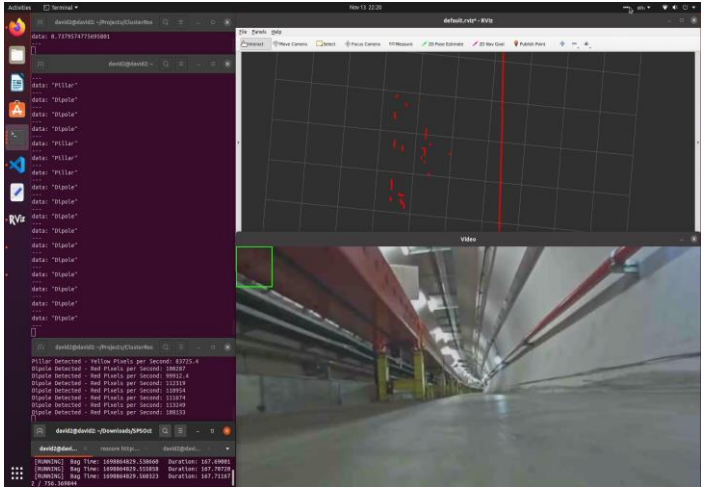
CHARM robot

Deployed Systems

- SPS robot x 2 successfully commissioned for RP measurements and anomalies detections (e.g. water leaks)
- Two robots used for the RP survey in parallel: Autonomous wall following combined with manual teleoperation at access points. 3 sectors completed each, followed by a swap of the charging station location at BA3 and BA6
- 7 km of RP survey performed in 1.5 h



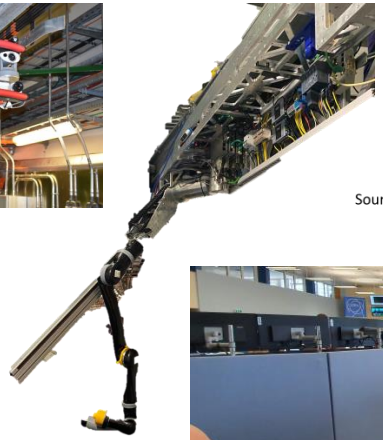


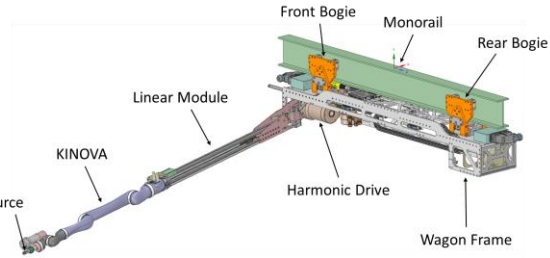


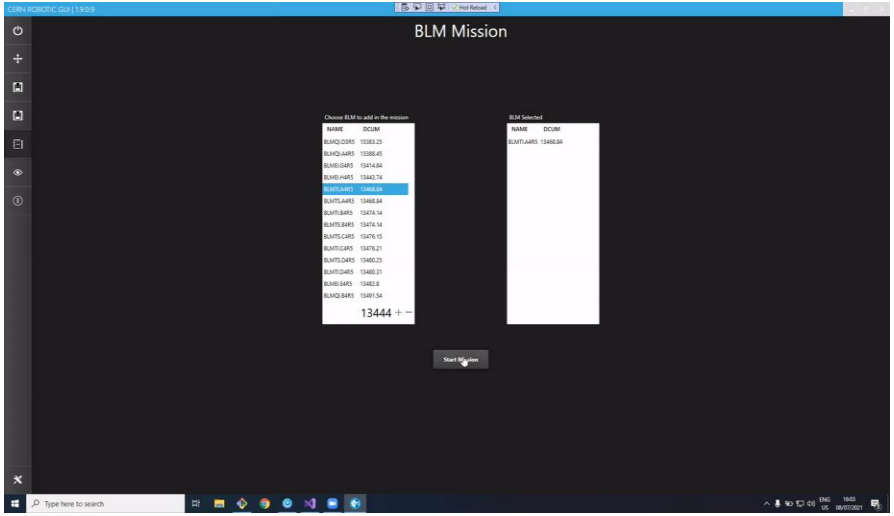
Deployed Systems

- Beam Loss Monitor (BLM) Sensor validation
- Train Inspection Monorail (TIM)

- Reliability increase by performing hazardous task that are too dangerous for workers (radiation exposure, …)
- 900 BLM during Long Shutdown 2
- Foreseen ~4000 BLM validations in 2028

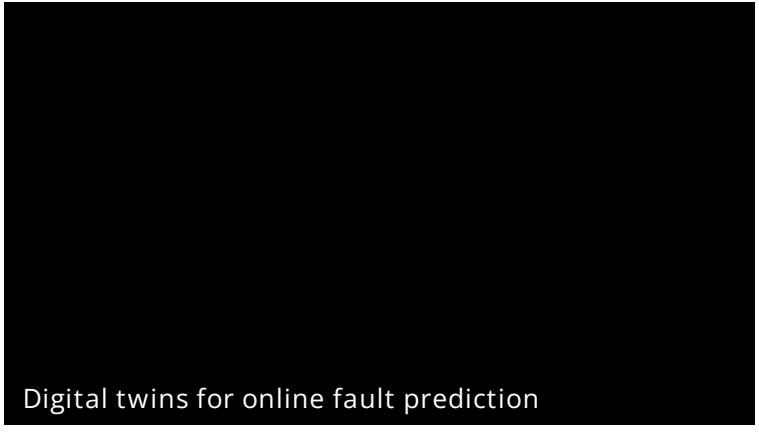






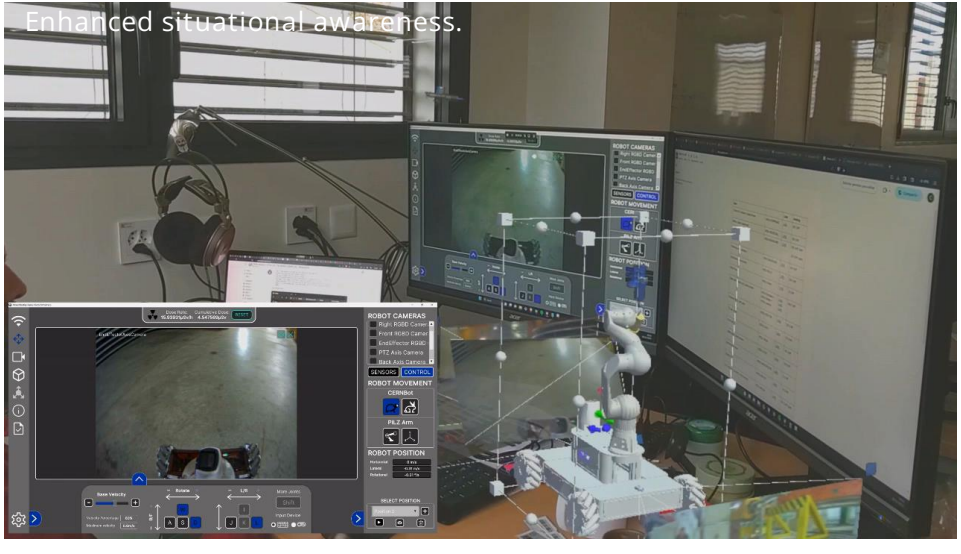
Deployed Systems – Operator Interfaces

- Some operations require human cognition and perception => must be teleoperated
- In confined environments, situational awareness through intuitive interfaces is key:
  - Decreases Operator Stress
  - Increases robot reliability by “online” fault prediction



Digital twins for online fault prediction

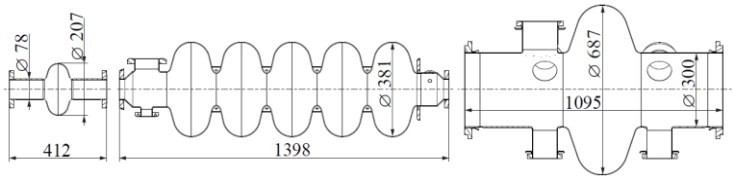
Teleoperated control of TIM in the LHC using the keyboard or gaming controllers in the CERN Control Center.



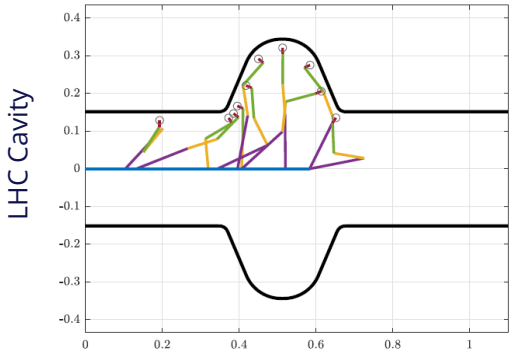
Enhanced situational awareness.

Deployed Systems

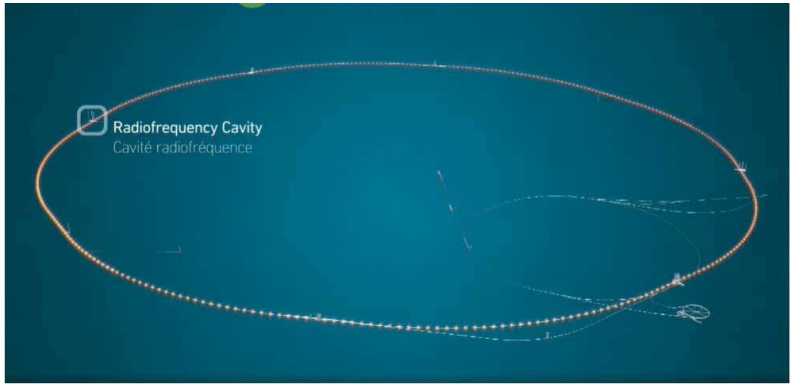
- RF Cavity Inspection System ARIS
- Visual inspection of inner surface after assembly
- Confined allowed robot space
- Inspections increase reliability



FCC LINAC LHC



The tentative topology and geometry defining the design space



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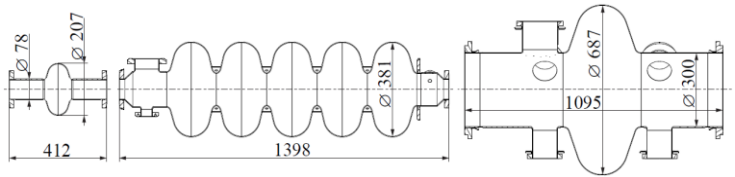

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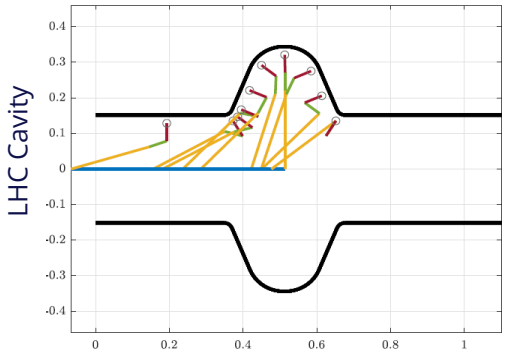
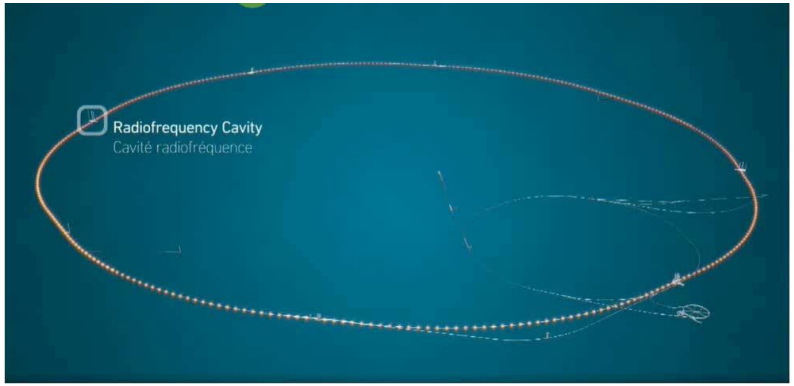
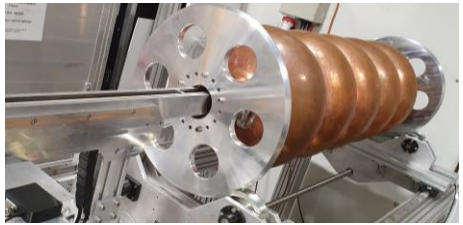
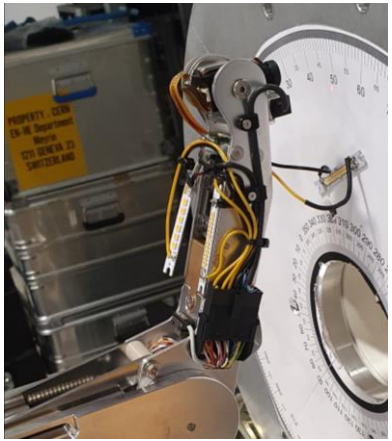


The optimal topology and geometry of the cavity inspection arm after applying the model pruning technique





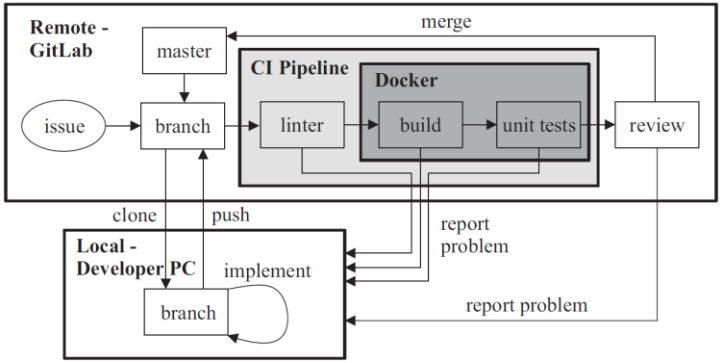


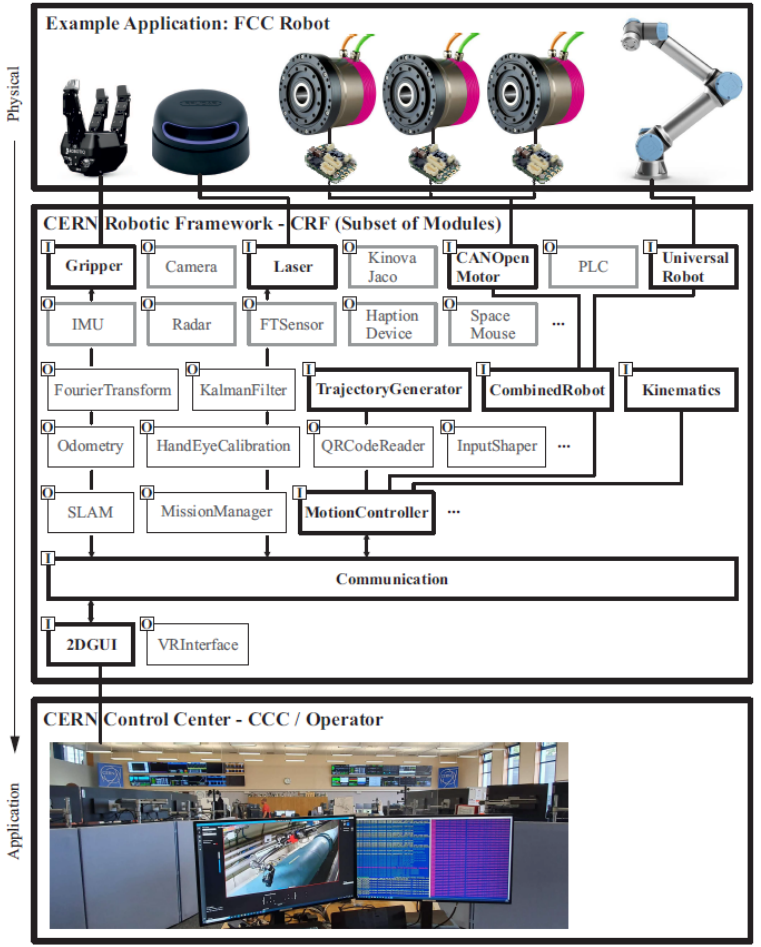
Gamper, H.; Luthi, A.; Gattringer, H.; Müller, A. and Di Castro, M.; Design Optimization of Quality Inspection Robots for Particle Accelerator Components, In Proceedings of the ECCOMAS Multibody Dynamics Conference, 2021

Tools

The CERN Robotic Framework - CRF

- modular architecture
- C++ 17 framework
- cmake
- CI pipeline on gitlab
- open-source based
- Mujoco for physics
- CANopen via EtherCAT





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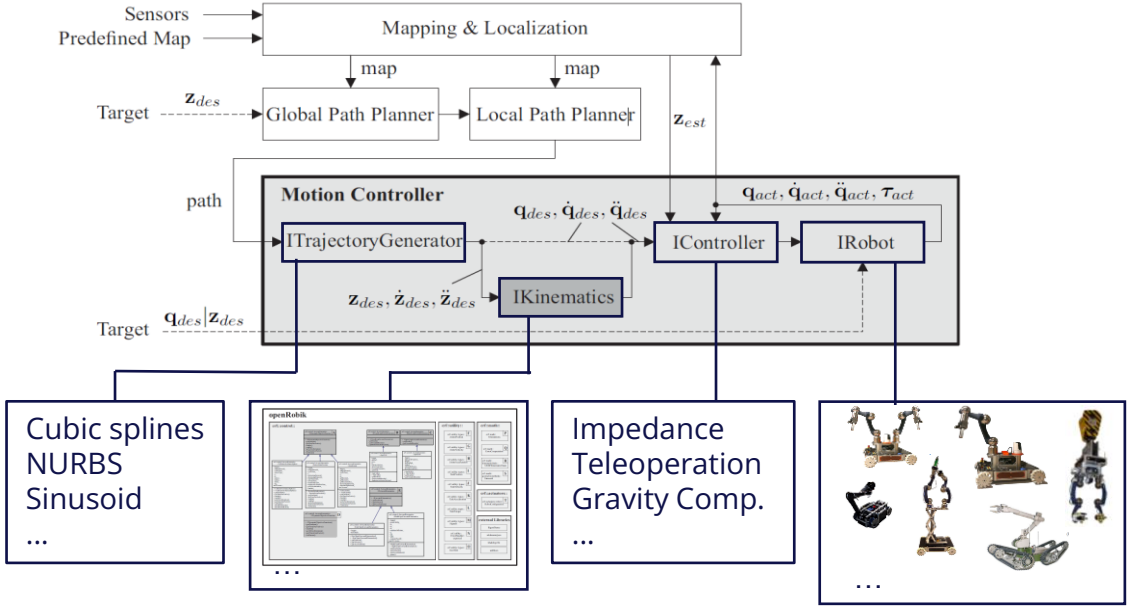

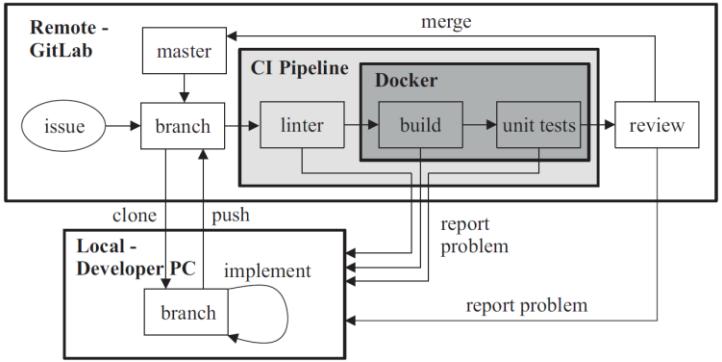

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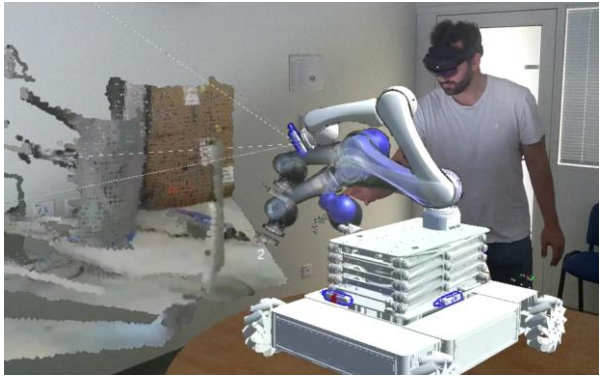
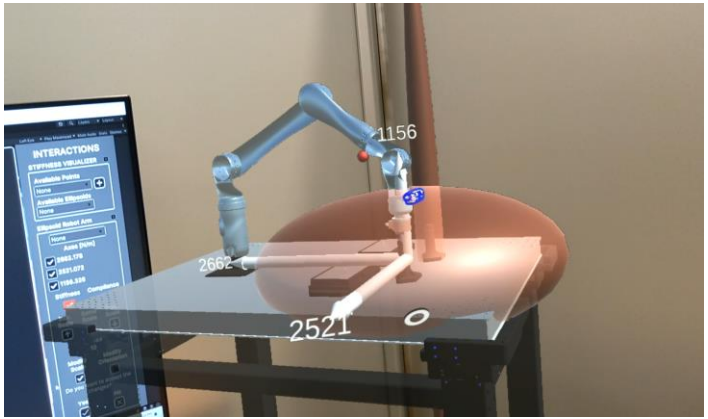
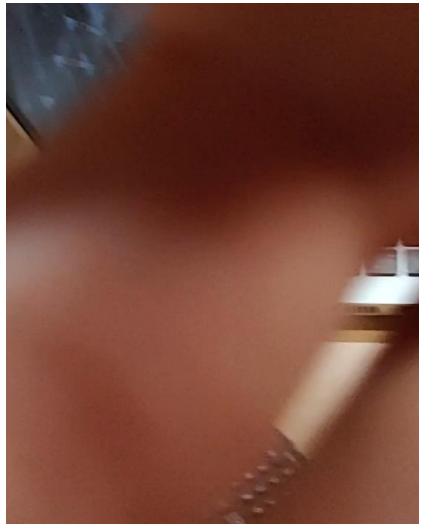
Operator Interface

- Cameras
- Keyboard, Gaming Controllers
- Unity
- Hololens
- Haption Motion







A. Diaz Rosales, J. Rodriguez-Nogueira, E. Matheson, D. A. Abbink, and L. Peternel, “Interactive multi-stiffness mixed reality interface: controlling and visualizing robot and environment stiffness,” IROS 2024, IEEE, October 2024.

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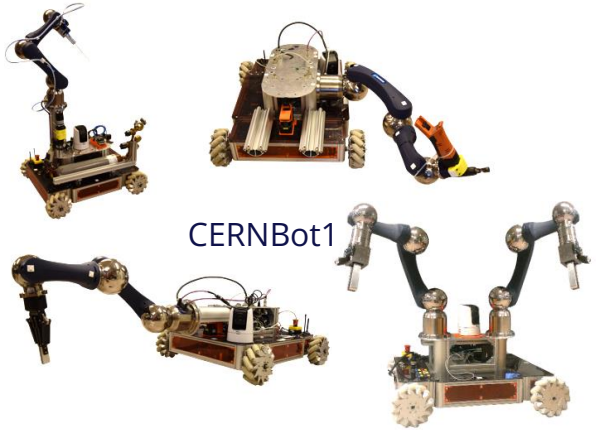
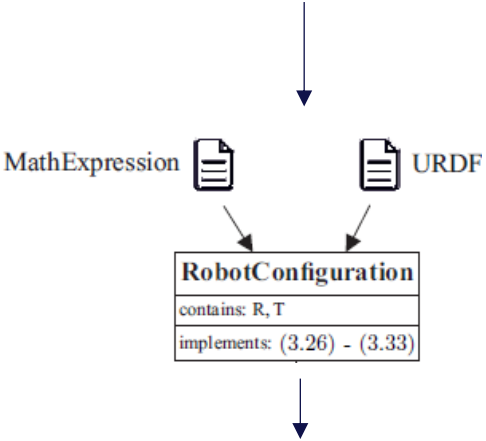
Hardware

- Modular Hardware Architecture
- Design in Inventor
- Structural Analysis in Ansys
- Topology & Geometry passed on in URDF format or “MathExpressions”



AUTODESK INVENTOR



CRF

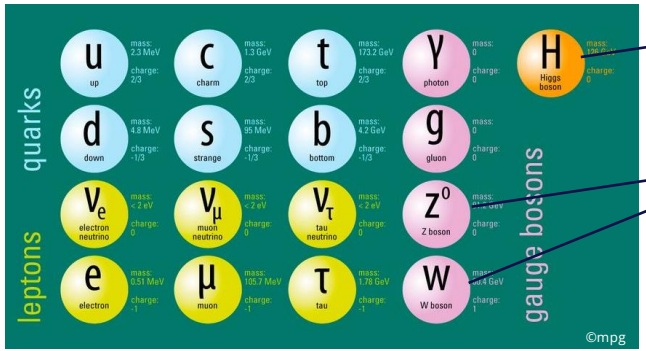
Unit tests
V&V

Future Research Directions

- Trying to model the universe
- Colliding Particles at 99.9999% the speed of light
- Building Particle Accelerators: PS -> SPS -> LHC
- Best model so far: The Standard Model of Particle Physics

The Standard Model of Particle Physics

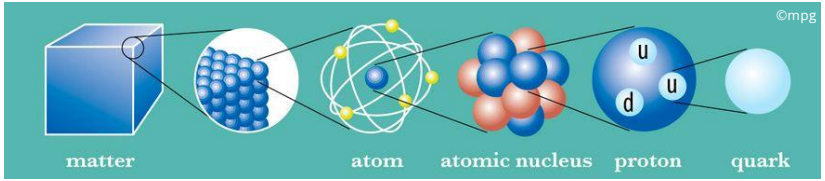
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c + \psi_i y_{ij} \psi_j \phi + h.c + |D_\mu \phi|^2 - V(\phi)$$



Discovered in 2012 by CERN (LHC). Noble Prize to Higgs & Englert in 2013.

Discovered in 1983 by CERN (SPS). Nobel Prize to Rubbia & Van der Meer in 1984.

Discovery of neutral currents in 1972 by CERN (PS).
Nobel Prize in 1979 to Glashow, Salam & Weinberg



Fundamental Forces

Strong	>	Electro-magnetic	>	Weak	>	Gravity
1		$\frac{1}{137}$		10^{-6}		10^{-39}

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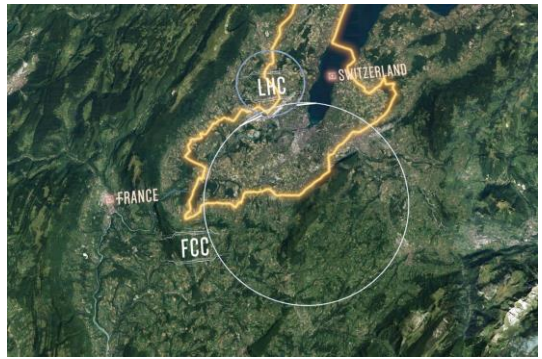
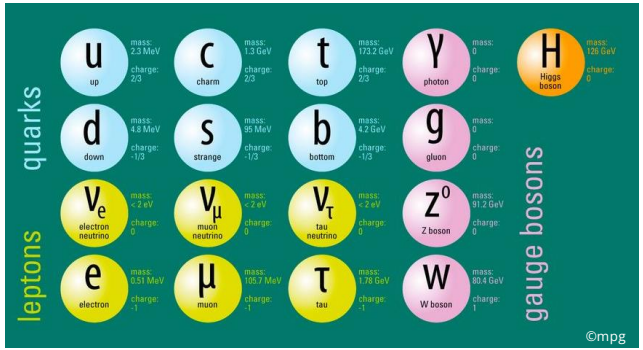
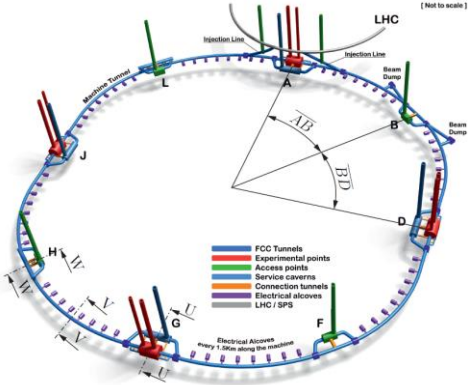
- Building Particle Accelerators: PS -> SPS -> LHC
- Best model so far: The Standard Model of Particle Physics

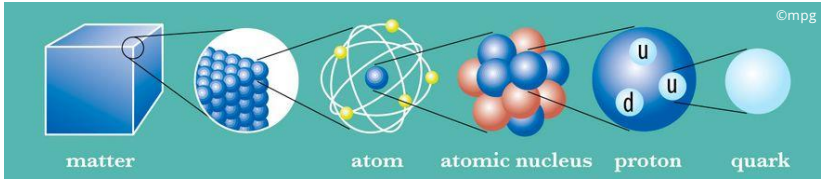


The Standard Model of Particle Physics

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c + \psi_i y_{ij} \psi_j \phi + h.c + |D_\mu \phi|^2 - V(\phi)$$







Fundamental Forces

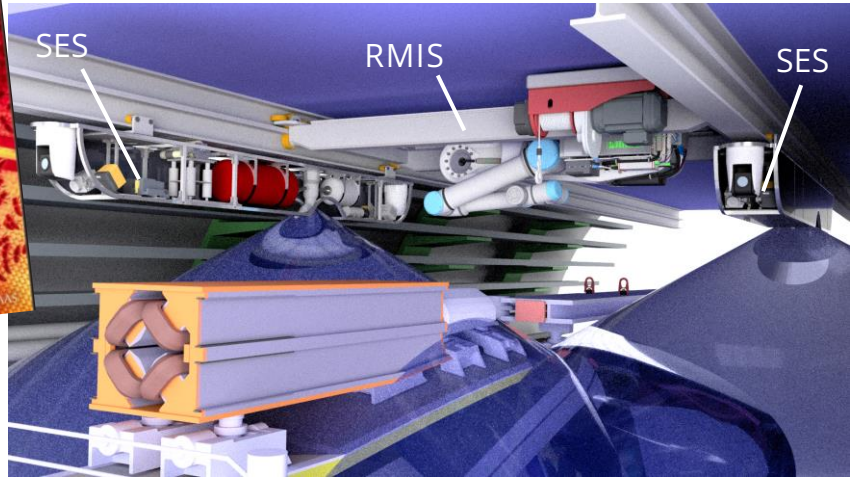
Strong	>	Electro-magnetic	>	Weak	>	~~Gravity~~
1		$\frac{1}{137}$		10^{-6}		10^{-39}

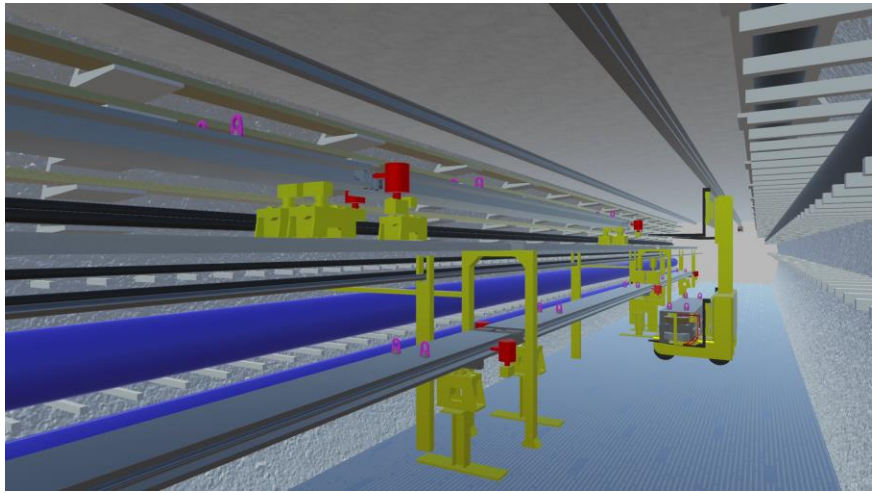
Future Research Dir.

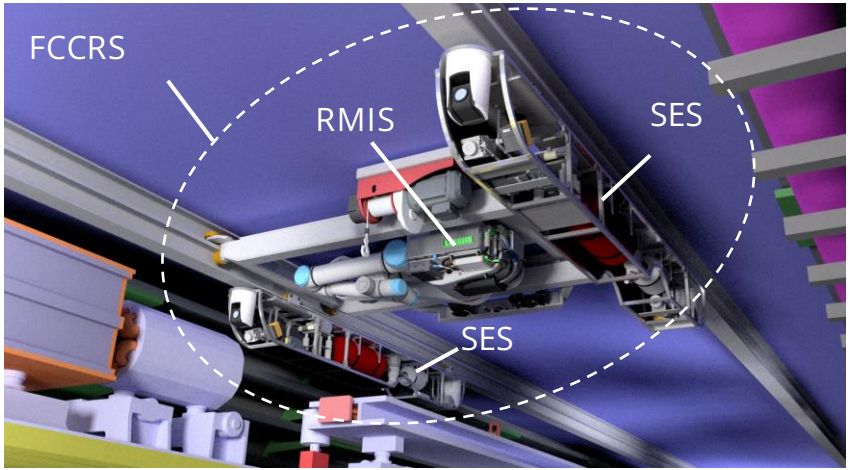
FCCRS Key Features

- Holistic Robotic concept for availability and safety
- Emergency (SES) & Operational System (RMIS)
- Highly redundant RMIS manipulator

Gamper, H.; Müller, A.; Di Castro, M.; High-Tech guardians: Robotics at the heart of the Future Circular Collider, Science Robotics



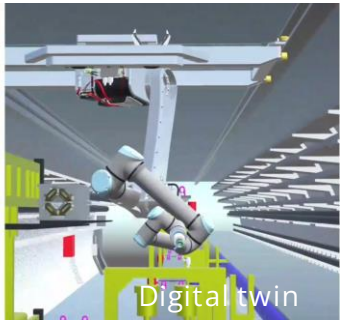


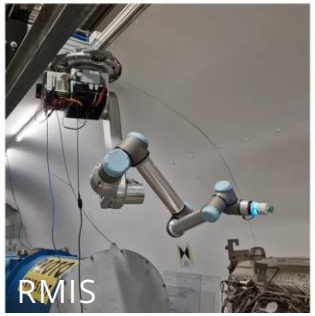


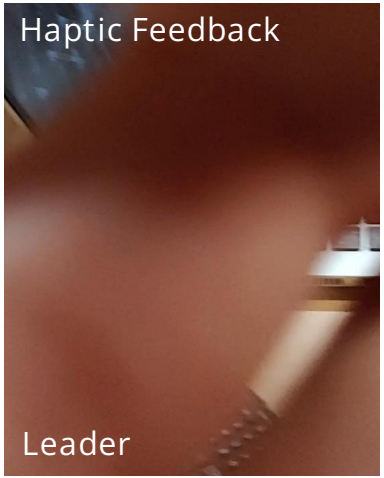
RMIS… Remote Maintenance & Inspection System SES… Survayance & Emergency Shuttle

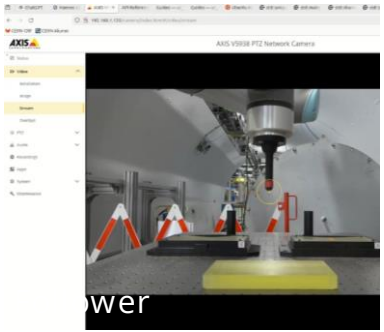
Future Research Directions

FCCRS
- Proof of concept studies & testing of new control strategies ongoing
- Biggest Challenge: Software & Control









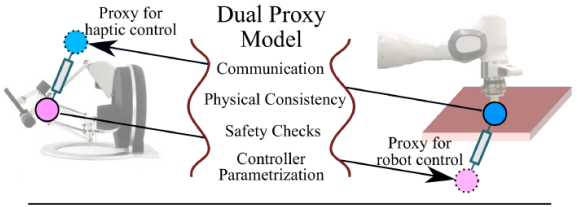
Future Research Directions

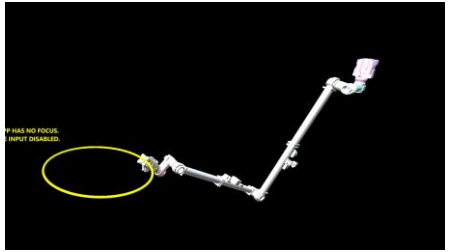
- Open Source Publication of CRF Modules
- Improvement of Bilateral Haptic Feedback
- Whole body control integration for legged robots
- Preparation of proof of concept studies for FCC
- Many robotic interventions scheduled
- Working towards shared control and full autonomy
- New robotic systems in the pipeline
- Neuromorphic computing

IEEE ROBOTICS AND AUTOMATION LETTERS, VOL. 9, NO. 5, MAY 2024 4527

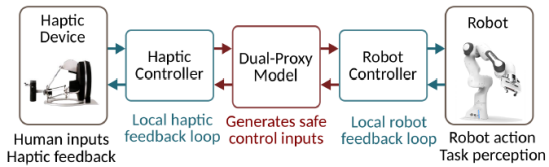
An Inverse Kinematics Algorithm With Smooth Task Switching for Redundant Robots

Hannes Gamper, Laura Rodrigo Pérez, Andreas Mueller, Alejandro Díaz Rosales, and Mario Di Castro

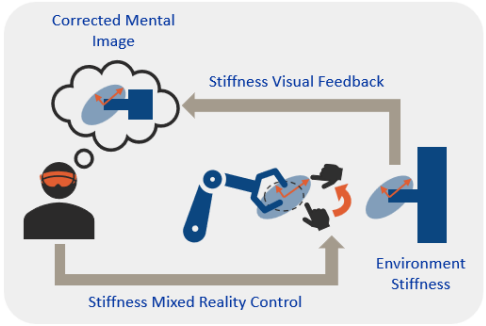




ESA Canada Arm



Stanford Robotics Lab

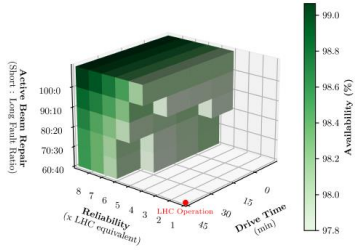


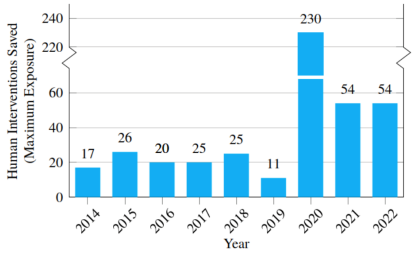
Unitree Go1

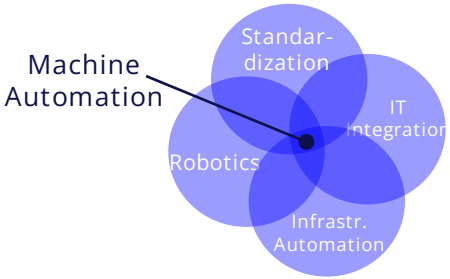
Angatec X Kawada

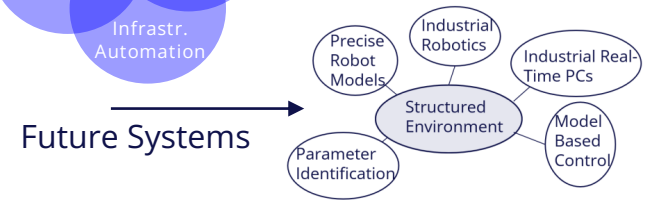
Take away messages

- Robotics can effectively increase machine availability by …
  - increasing maintainability through corrective and preventive maintenance
  - increasing reliability by predictive maintenance
- Robotics can increase operational and emergency safety
- Consider robotics as one component in machine automation
- Push new infrastructure design towards a structured environment to facilitate high robotic efficiency
- We created a sustainable system/team based on students-technicians-engineers that boosted the robotics developments over the last years at CERN, also thanks to the many collaboration built with universities and industry

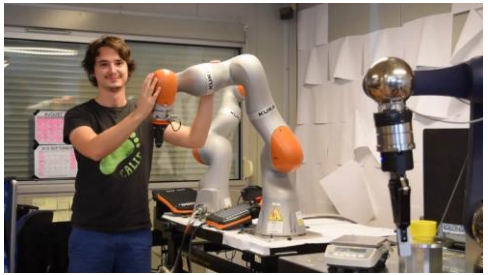






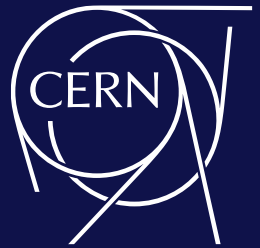


Thanks to …



BE-CEM-MRO Team

Controls
Electronics &
Mechatronics



Thank you for your attention!

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