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Controls Electronics & Mechatronics

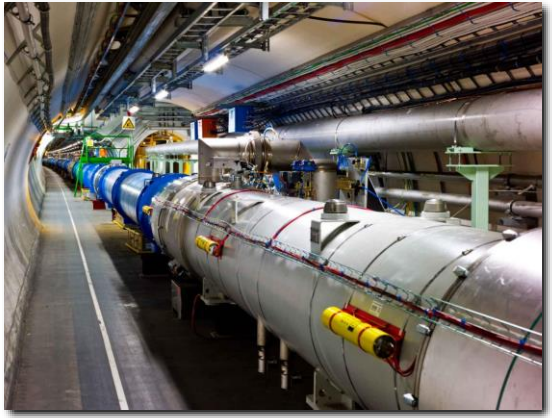
ROBOTIC SOLUTIONS FOR THE INSPECTION AND REMOTE MAINTENANCE OF PARTICLE ACCELERATORS

Content

Robotic Service at CERN – Needs and Challenges

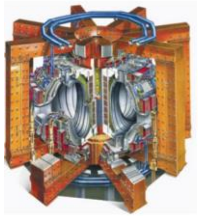
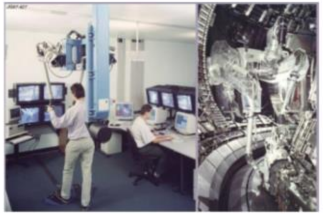
- **Needs:**
  - ✓ Inspection, operation and maintenance of radioactive particle accelerators devices for reliability, maintainability and availability increase
- **Challenges:**
  - ✓ Harsh and semi-structured environments
  - ✓ Experimental areas and objects not built to be remote handled/inspected
  - ✓ 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.






Examples of Maintenance in Big Science Facilities

➢ Joint European Torus (JET)

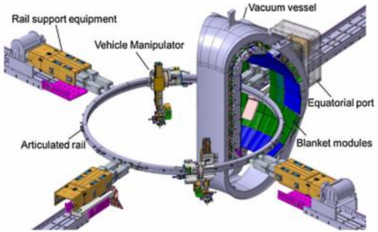



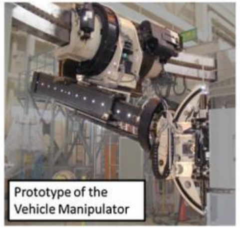
JET Torus (left) and remote handling approach using the MASCOT system

➢ Spallation Neutron Source (SNS)


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

➢ International Thermonuclear Experimental Reactor (ITER)





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

- ➢ Mainly master-slave tele-manipulators
  - ✓ Bulky installation in structured environment
  - ✓ Tasks well defined
  - ✓ Extremely well trained operators
    - ❖ <u>High maintenance costs</u>
    - ❖ <u>Not scalable/feasible for FCC</u>

Developments for Remote Maintenance in Universities and Research Centers

- Many recent developments towards maintenance and robotic exploration in space applications
  - ✓ Developments towards human behavior reproduction
  - ✓ Need for well-defined interfaces and tools, as well as hyper-trained operators

- Specific developments on teleoperation for medical applications with constraints not always present in big science facility scenarios (limited supervisory control, no autonomy, large scaling of motion etc.)

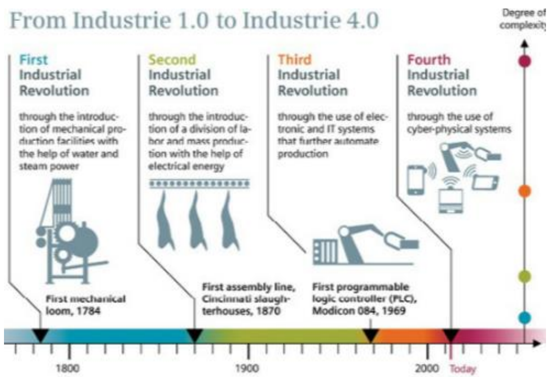
Intuitive Surgical: https://www.youtube.com/watch?v=TGjnb86HndU

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

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

Automation in Industries

- ➢“No room” for teleoperation applications, need of quick repetitive tasks
- ➢Long history of industrial robots applied to industrial scenarios mainly for manufacturing
- ➢Recently human-robot collaborations have been started for highly repetitive scenarios



- ➢ Mainly robots performing repetitive tasks in well structured environment
- ➢ Changing environment/type-of-place where the robots are deployed often implies a refactoring of mechatronic components
  - ✓ Bulky installation in structured environment
  - ✓ Tasks well defined

Teleoperation: a step of 80 years

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

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

Courtesy of Argonne National Labs

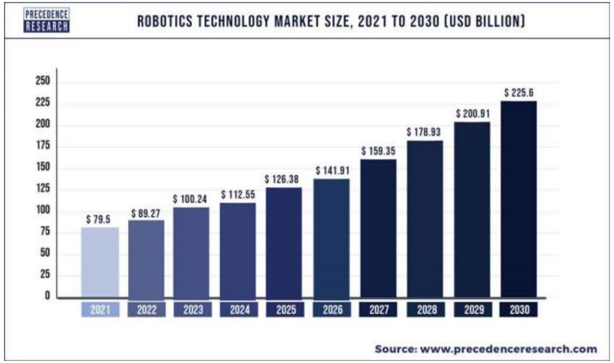
Courtesy of DLR

Automation: step of 25 years

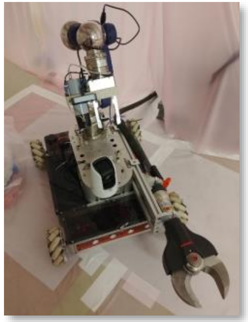
1997 packaging at AMAZON

2020 fully automatic groceries packaging machines at OCADO

2020 automatic handling at AMAZON



Robotic Service at CERN – Robots Pool



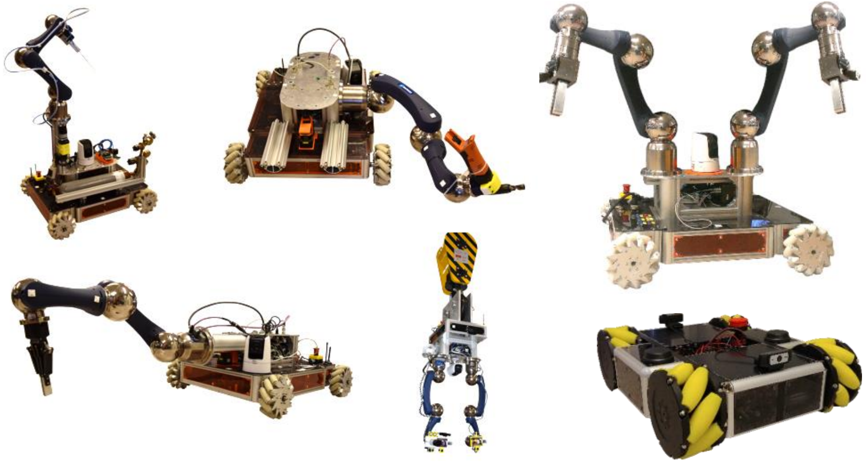
Telemax robot

Train Inspection Monorail [1] (CERN made)

Teodor robot

EXTRM robot (CERN controls)

Drone for tele-operation support



CERNBot [2] in different configurations (CERN made)

Robotic Service at CERN – Custom Developments [3-4]

Main Motivations for Custom Robotic Development:

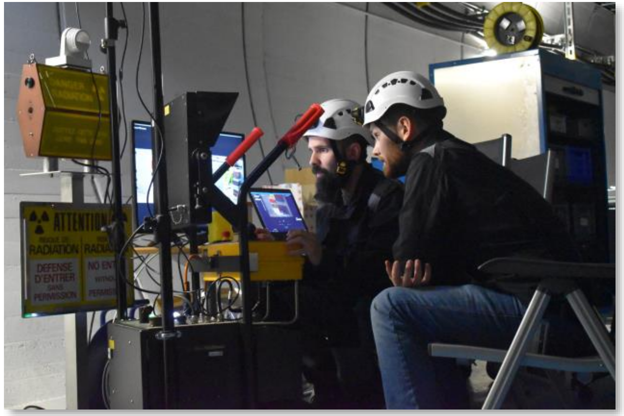
- Industrial robot have **very complicated human-robot interfaces demanding intense operators training,** controls are not open to be integrated in our control system, communication channel is often via radio signal, not built to reduce contamination risks etc.

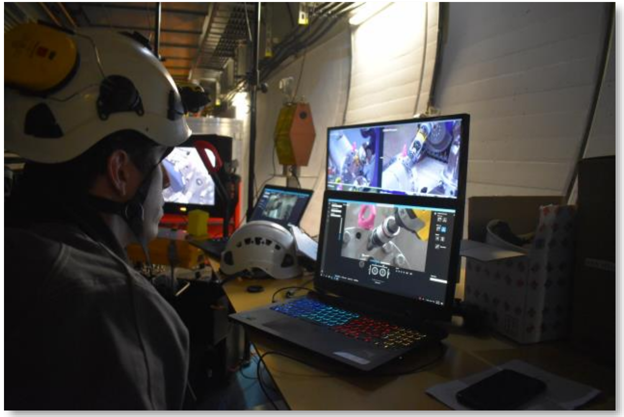
- Necessity of having the human, the machine and the interface working together adopting **user friendly interfaces** [5-8]
  - ✓ Increase of **proprioception** reducing operators stress

- Customized Robots, tailored to the specific needs of a task have shown a **significant increase in efficiency**.

Robotics technologies are currently mainly used at CERN for:

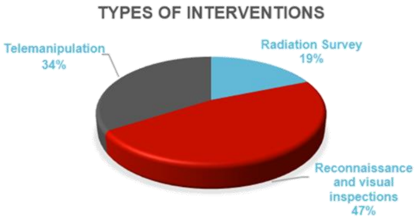
- Environmental measurements, equipment maintenance, tele-operation and inspection in dangerous areas
  - ✓ Data taking in harsh environment, used also for reliability studies
- Human intervention preparation
- Quality assurance
- Post-mortem analysis/inspection of radioactive devices
  - ✓ Boosting machine reliability helping design improvements from the quick understanding of cause of failure
- Safety, reconnaissance, search and rescue
- And others…

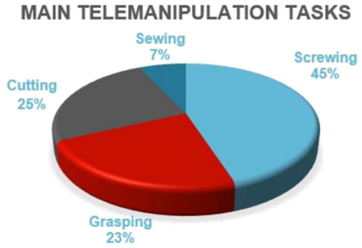


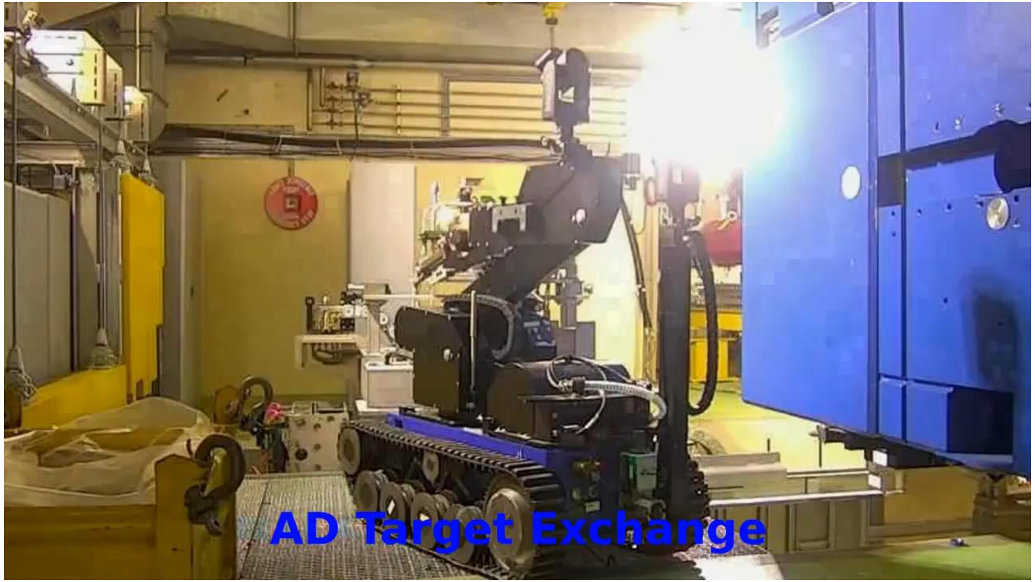


Robotic Interventions done at CERN within Beams Dept. [10]

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

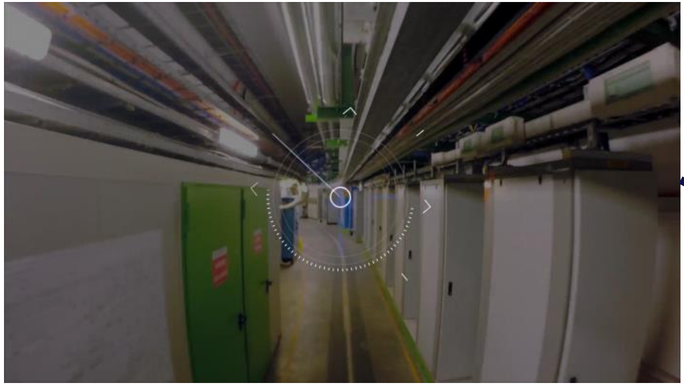






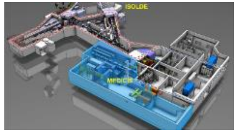
Video of main robotic interventions done in 2022

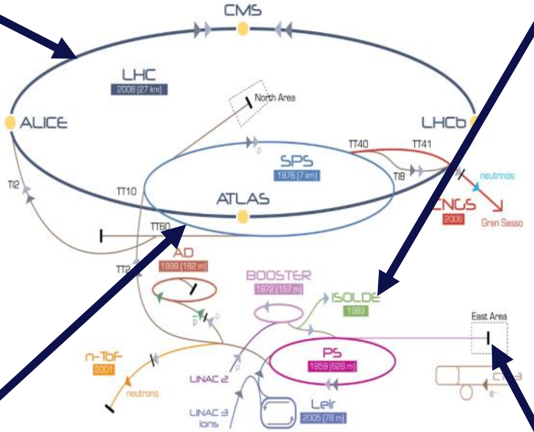
Robotic Service at CERN – Robots Integrated within Facilities

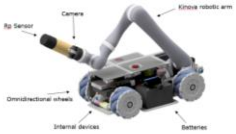


4x TIM operated by OP

2X SPS robot under commissioning







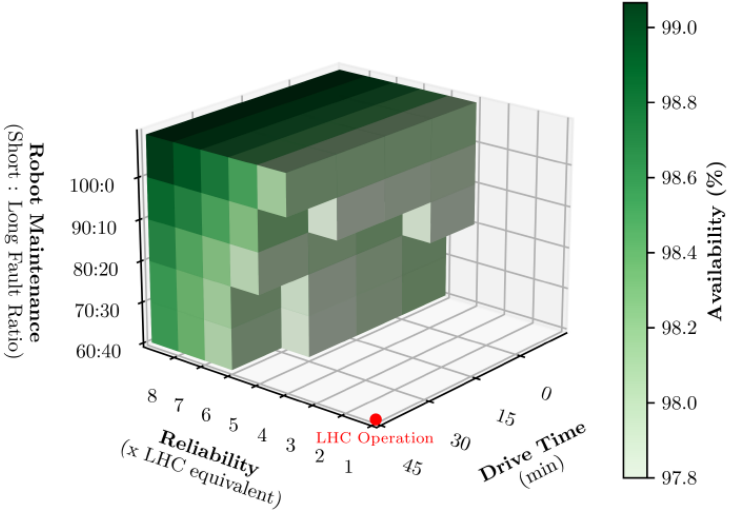
3X Kuka Robots

CHARMbot

Benchmarks & Maintainability - Machine Availability, Reliability and Safety

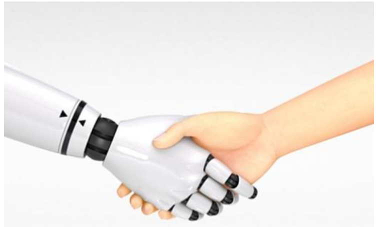
- Availability has 2 components, Reliability and Maintainability

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



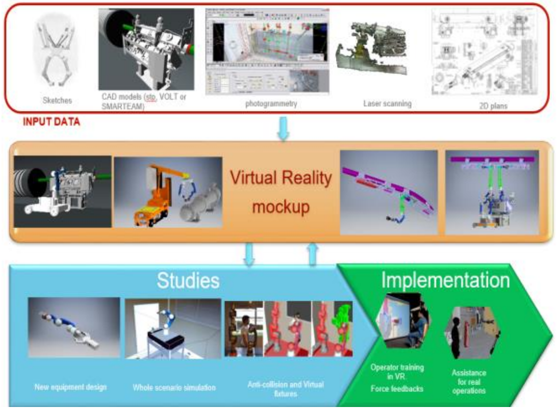
See talk from J. Heron: https://indi.to/3TndY

- @ constant machine reliability, maintainability drives availability
- Improve maintainability increasing efficiency of human interventions
  - ✓ using robots in collaborations with humans
- Accelerator Reliability Workshop (ARW) [10]

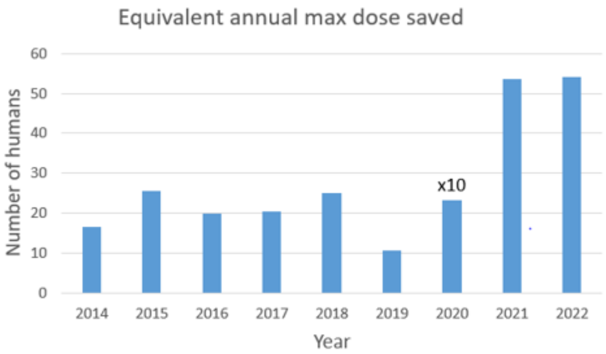


Reliable robots must be developed, and recovery scenarios must be foreseen

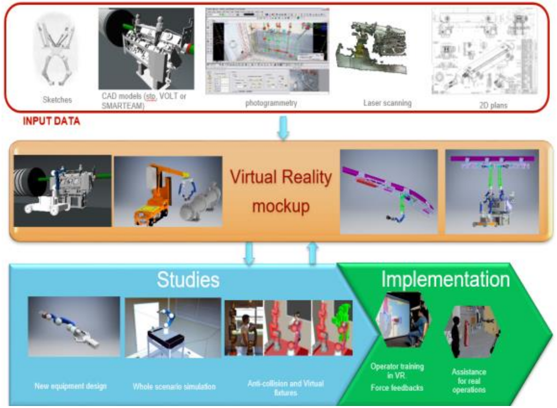
Personnel Safety Increase



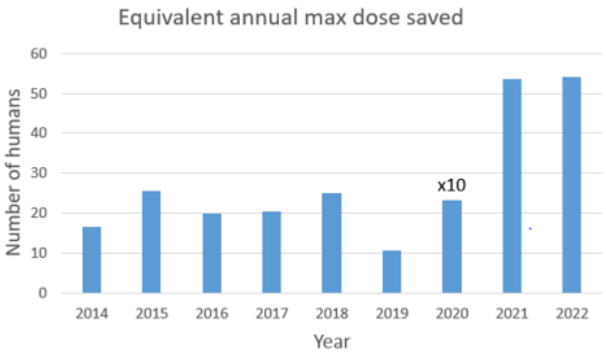
Intervention preparation workflow



Personnel Safety Increase



Intervention preparation workflow

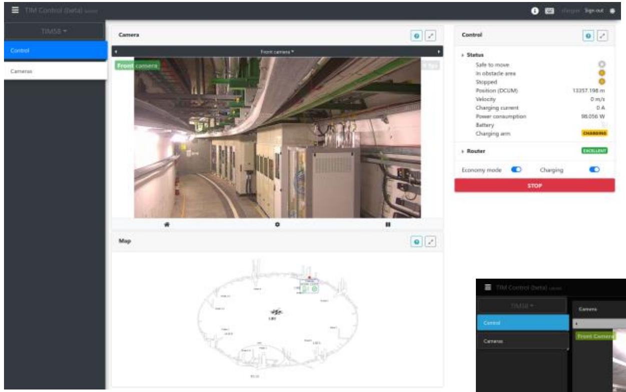


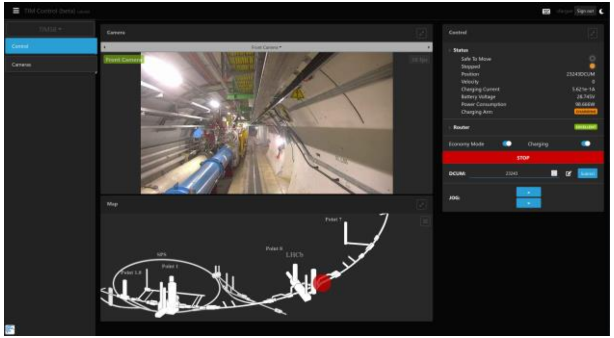
BDF target handling and nToF target pit cleaning

N_ToF target dismounting endorsed by robotic intervention

Example of Maintainability increase: TIM RP surveys

- 4X TIM integrated currently within the LHC Technical Infrastructure island doing remote visual inspection and environmental measurements (Radiation, Temperature, oxygen %, communication coverage)





Screenshot of TIM dashboard/monitoring-interface

- ✓ **RP survey within the LHC takes 1.5 days**
- ✓ **With the help of TIMs this is reduced to one morning**

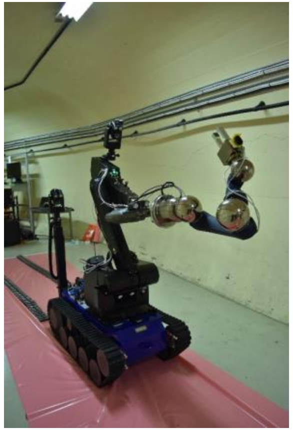
Comparatif des horaires de fin des surveys RP avec ou sans l'utilisation des 4 TIMs

Point d'accès	Horaires des retraits des vetos RP (fin des surveys)		PAD (Secteurs)	Commentaires
	Surveys manuels	Surveys manuels + utilisation simultanée des 4 TIMs		
Point 1	09h15	10h00	UJ16 / (1-2) (1R)	Survey entre UJ16 et la porte R19
	11h15	09h50	UJ14 / (1-8) (1L)	Survey entre UJ14 et la porte R11
Point 2	11h45	12h00	UJ27 / (2-3) (2R)	Survey entre UJ27 et la porte R34
	13h45	09h00	UJ23 / (2-1) (2L)	Survey entre UJ23 et la porte R19
	16h00	10h45	TI2 (côté LHC)	Survey entre les portes TI2 et PPG 2145
BA7 / TI2	16h00	12h00	TI2 (côté SPS)	Survey entre TCC6 et la PPG2145
Point 3	10h30 le lendemain	11h00	PZ33 (LSS3)	Survey entre les portes R34 et R37
Point 4	11h45	10h30	UJ43 / (4-3) (4L)	Survey entre UJ43 et la porte R37
	09h45	09h50	UX451 / (LSS4)	Survey entre les portes RA43 et RA47
	08h45	09h20	UJ47 / (4-5) (4R)	Survey entre UJ47 et la porte R51
Point 5	09h15	09h45	UJ56 / (5-6) (5R)	Survey entre UJ56 et la porte R59
	11h15	09h00	UJ561/UL55 / (5-4) (5L)	Survey entre UJ561 et la porte R51
Point 6	09h15	10h15	UJ67 / (6-7) (6R)	Survey entre UJ67 et la porte R74
	Pas de survey / Accès avec accompagnement RP		UD 68	Survey « zone DUMP » UD68
	10h15	09h20	UP 63 / (LSS6)	Survey entre les portes RA63 et RA67
	12h15	09h00	UJ63 / (6-5) (6L)	Survey entre UJ63 et la porte R59
	Pas de survey / Accès avec accompagnement RP		UD62	Survey « zone DUMP » UD62
Point 7	10h30 le lendemain	10h45	PM76 (LSS7)	Survey entre les portes R771 et R74
Point 8	09h15	12h00	UJ83 / (8-7) (8L)	Survey entre UJ83 et la porte R771
	11h15	09h45	UJ87 / (8-1) (8R)	Survey entre UJ87 et la porte R11
	13h00	10h45	TI8 (côté LHC)	Survey entre les portes TI8 et PPG8270
TAG42/TI8	15h30	12h00	TAG42 / TI8 (côté SPS)	Survey entre TJ8 et la porte PPG8270

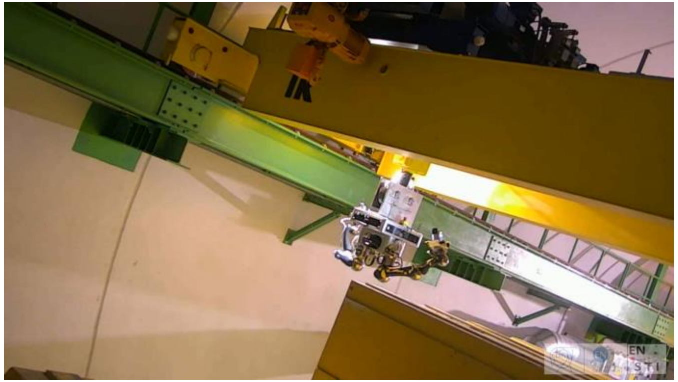
Courtesy of C. Tromel, CERN

Adapting Robotic Solutions to Complex Environments

- Remote interventions have not been considered during the design phase of many current facilities at CERN
  - ✓ 80% of our effort goes into the adjustment of our robots, procedures and tools to facilities not designed to be maintained by remote/automatic systems
  - ✓ We have to build complex robots, tools and procedures tailored to complex environments
- Machines components should be designed to be handled as much as possible by automatic systems
  - ✓ Specially for repetitive, maintenance and dismantling tasks



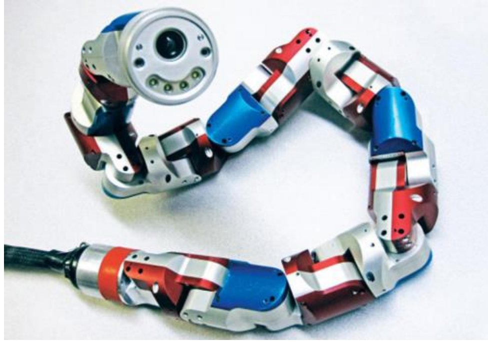
RP samples retrieval from BDF bunker



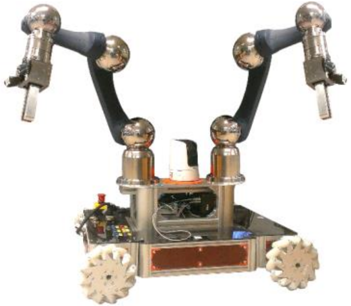
Measurements and inspection of LHC Dump downstream flange using CRANEbot

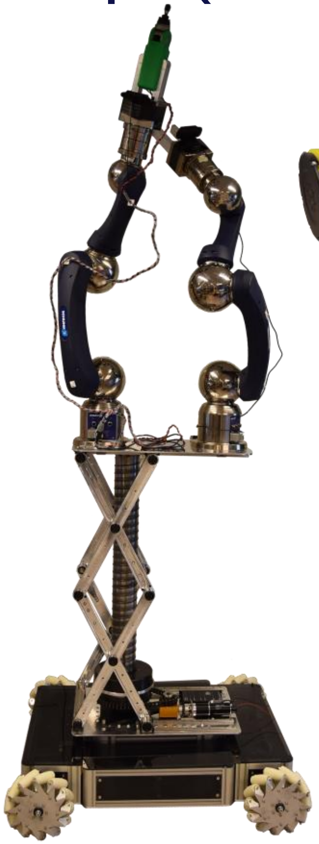
Suitable Robots for Current Maintenance Needs

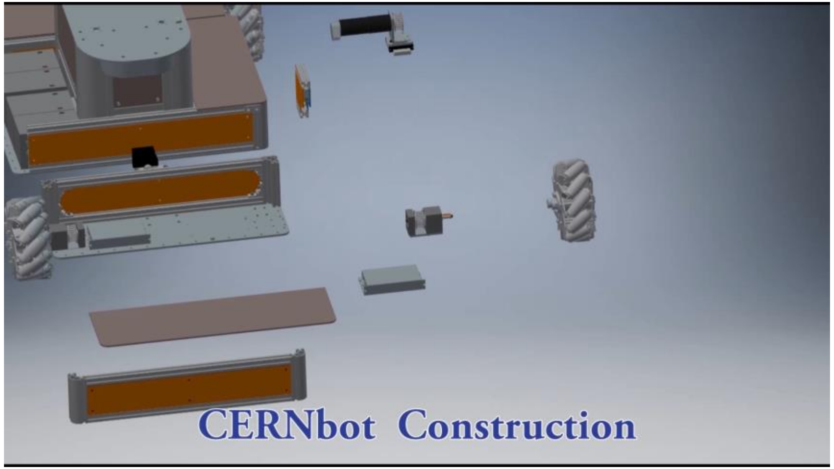
- No single existing robotic solutions can fulfill the needs
- Mobility and manipulation capabilities are required
  - ✓ A “fusion” of several type of robot would be needed
  - ✓ **<u>Modular robot</u> could fulfill several needs**

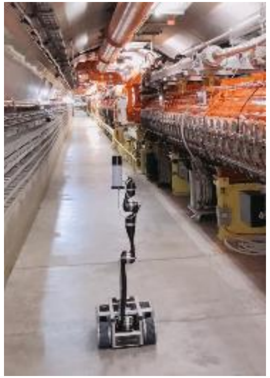


Modular Robot/Concept (CERNbot)









CERNbot, CERNbot2, CHARMbot, MIRA, CRANEbot

Design of Machines that could be Maintained by Remote and Automatic Systems

- **Due to the FCC size, standardized solutions would reduce the necessary robot complexity by…**

  - ✓ Following guidelines for machine design that results in simple, robot friendly environments
  - ✓ Following procedures for maintenance interventions
  - ✓ Considering Robot friendly machine design at an early design phase
  - ✓ Automation can transform apparently complex tasks in easy ones thanks to "smart and ergonomic infrastructures"
  - ✓ Automation improves equipment reliability by enhancing maintenance operations, data management, and quality control
  - ✓ Automation helps on migrating from high-cost preventive and on-condition maintenance to predictive maintenance reducing the corrective interventions
  - ✓ Automation relies heavily on digital twins and big data

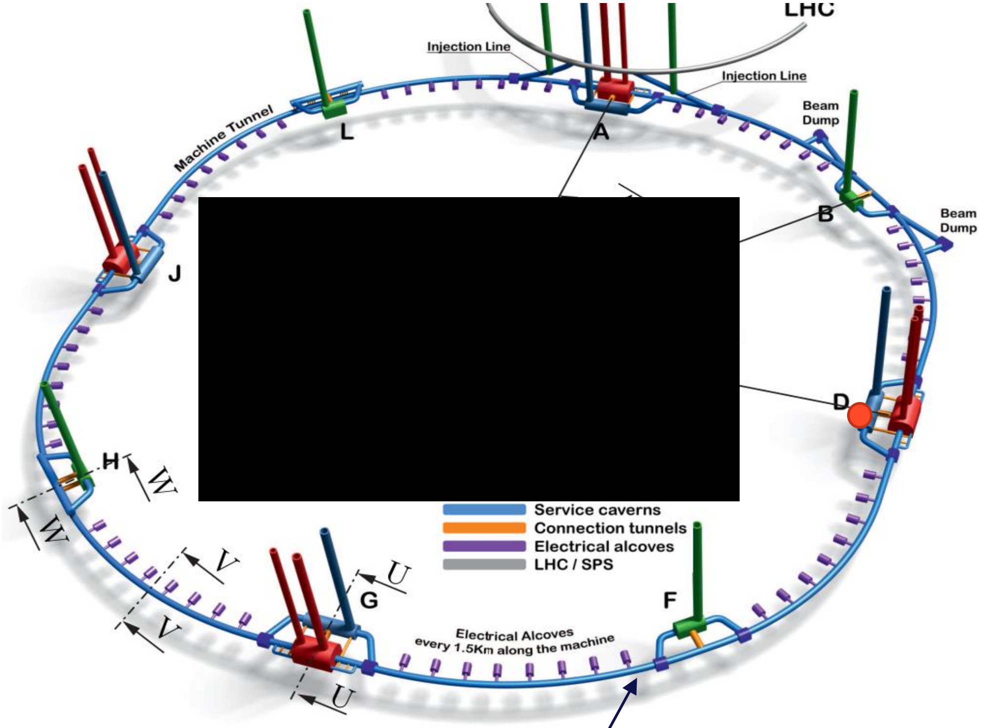
Best Practice for “automation/robotic” friendly equipment design

- **Remote maintenance code of practice – Discussions with MME and soon with other groups at CERN**
  - ✓ EDMS Document number 2263542
  - ✓ Being integrated by MME within the Engineering Design Manual
  - ✓ Used already by different groups for new equipment design
  - ✓ Guidance for remote maintenance friendly connectors, accessibility, patch panels etc.
  - ✓ Standardization of interfaces → standardized tools and procedures, reduce costs and intervention time
  - ✓ Procedures and tools on how to use robots within accelerator facilities

Robotics for FCC [11-14]

The Vision:

- Conduct all planned repetitive interventions fully autonomous
- Move fully autonomous to a Point of Interest
- Automatic systems must be foreseen, however operator can take over to inspect/repair at any time
- Carry Different Tools
- In every point of the tunnel within 10min (1 Robot ~300km/h or 15 Robots ~20km/h)
- Emergency System to Guide/Rescue People
- Detect Hazards like Fire, Fluid Leaks, etc.
- …



⇒ Decrease maintenance costs
⇒ Decrease downtime of the FCC
⇒ Workers away from dangers

Robotics for FCC

Development

Initial Study
- Requirements
- Restrictions
- Integration

Design Optimization

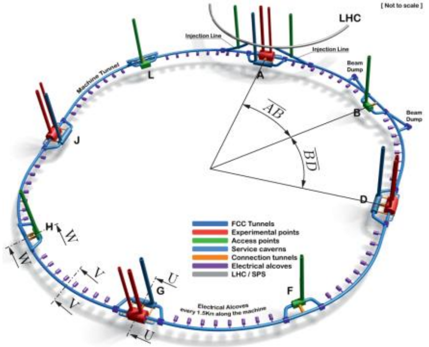
Control Concepts

Prototype PoC

Summary & Status

The Goal:
⇒ Decrease maintenance costs
⇒ Decrease downtime of the FCC
⇒ Protect workers from dangerous interventions

The Vision:
A fully autonomous, integrated robotic system.

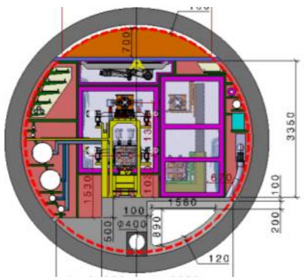


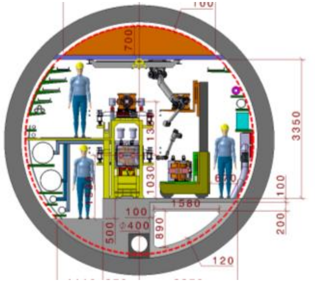
Requirements & Restrictions:

	Sec.	Task Group	Derived Requirements
Maintenance	6.1	Measuring Radiation; Monitor Tunnel; Integrity	M1: Cover full work space; M2: Stable movement along tunnel axis; M3: Pass Fire Doors; M4: Robust Collision Avoidance;
	6.2	Test BLM Sensors	M5: High Dexterity Manipulator; M6: Autonomous operation; M7: Operate in cluttered work space;
	6.3	Measure Oxygen; Measure Alignment; Audio Inspection; Vacuum Leak Detection; General Interventions	M8: Specific Tools; M9: Tool Changer; M10: Fast Interventions; M11: Modularity; M12: Precise Teleoperation with Haptic Feedback;
	6.4	Docking Station;	M13: Payload ~ 15kg
	6.5	Transport Tools/Material;	M14: Payload ~> 50 kg
Emergency	6.6	Guide People; Follow Monitor People; Search for Life;	E1: Not Blocking Emergency Ways; E2: Specific Tools (Infrared Camera, Radar); E3: Move in Harsh Cluttered Environment
	6.7	Locate Approach Fire; Extinguish;	E4: Robot Speed ~ 34.2 km/h ; E5: Specific Tool;

	Geometry Req.			Power S.		Comm.		Emergency			Maintenance				Costs				
Index	M1	M3	M4	G5	G1	G7	G(	E1	E3	E4	M11	M14	M10	G4	G10				
Requirement	Workspace ~3200x3600	Go through fire doors	Robust Coll. avoidance	Reliability/ Redundancy	Autonomy	Intuitive HR Interface	Robust	Not Blocking Exit	Move in harsh env.	Intervention Time in CoE	Modularity	Payload	Fast Intervention	Few Maint. For robot	Construction Material Env.	Sensors	Actuators	Construction Material	Summed up Rating in %
Weight	1	0.8	1	1	0.6	1	1	1	0.8	1	0.6	0.8	0.8	0.8	1	0.8	0.8	1	
Hol. Mobile Robot	2	3	2	2	4	2	3	1	1	1	4	2	2	2	3	4	4	3	53
Non-Hol. Mobile Robot	2	3	2	2	4	2	3	1	1	2	4	2	2	2	3	4	4	3	54
Rail Guided Robot	3	3	3	3	2	3	3	4	3	4	3	3	4	3	1	4	3	3	67
Aereal Robot	4	3	1	2	3	2	2	3	4	3	1	1	3	2	4	2	4	4	51
Legged Robot	3	2	2	2	2	2	2	1	3	2	4	2	2	1	4	1	1	1	45
Legged Robot + Wheels	3	2	2	2	2	2	2	1	3	3	4	2	3	1	4	1	1	1	48
Robot in Hyperloop	2	3	2	2	2	2	3	1	1	4	2	2	4	2	1	3	3	3	53

Integration:





Robotics for FCC

Development

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Summary & Status

The Challenge:

⇒ Many requirements on some parameters of the manipulator

⇒ No requirements on the topology or geometry

The Method:

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

Definition 1 (Pruning Function). *A vector function* $\mathbf{g} = [g_1(l_1) \quad g_2(l_2) \quad \dots \quad g_N(l_N)] : \mathbb{R}^N \to \mathbb{R}^N$ *with argument* $\mathbf{p} = [l_1 \quad l_2 \quad \dots \quad l_N]^T \in \mathbb{R}^N$ *that satisfies*

$$\frac{\partial \mathbf{g}}{\partial \mathbf{p}} > 0 \ \forall \ l_i > 0, \ i \in \{1, 2, \dots, N\} \tag{12}$$

and

$$\frac{\partial^2 \mathbf{g}}{\partial \mathbf{p}^2} < 0 \ \forall \ l_i > 0, \ i \in \{1, 2, \dots, N\}. \tag{13}$$

robotics MDPI

Article

Kinematic Model Pruning: A Design Optimization Technique for Simultaneous Optimization of Topology and Geometry

Hannes Gamper [1,2,*], Adrien Luthi [1], Hubert Gattringer [2], Andreas Mueller [2] and Mario Di Castro [1]

The Solution:

- Set of optimal Geometric Parameters (link lengths)
- Optimal Topology (11 DoF, Joint Configuration)

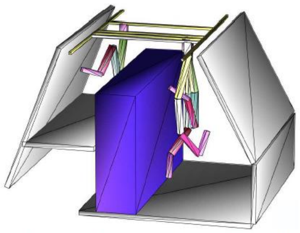


Figure 10: Optimization results FCC-ee (collision objects)

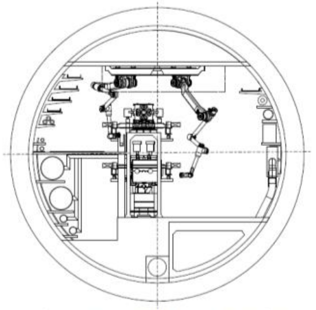


Figure 14: Prototype in FCC-ee cross-section

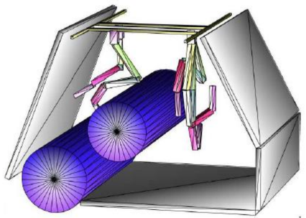


Figure 11: Optimization results FCC-hh (collision object

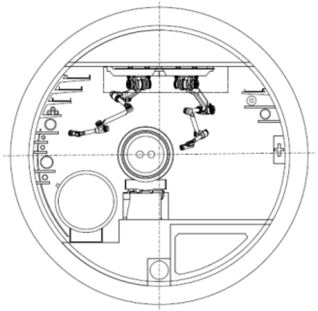


Figure 15: Prototype in FCC-hh cross-section

Robotics for FCC

Development

Initial Study

Requirements

Restrictions

Integration

Design Optimization

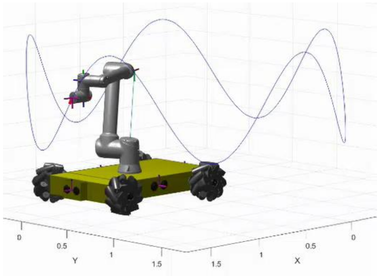
Control Concepts

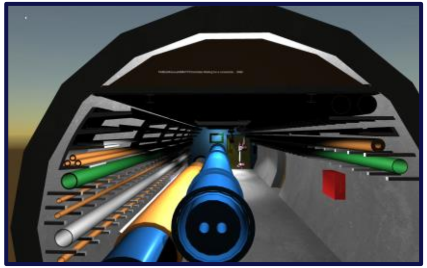
Prototype PoC

Summary & Status

Development of a Kinematics Library

- Highly Redundant Inverse Kinematics Resolution
- Generic Architecture for all Robots
- Written in C++ for the CERN Robotic Framework





Development of a Generic Motion Controller

- Parsing URDF Format
- Generic Architecture for all Robots in MRO
- Written in C++ for the CERN Robotic Framework

Generic Controller

Architecture that allows an easy and fast implementation of different controllers

Holonomic

Non-holonomic

Impedance control

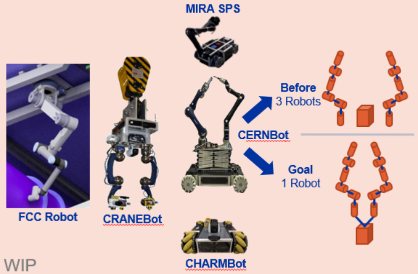
Torque control

Teleoperation optimized

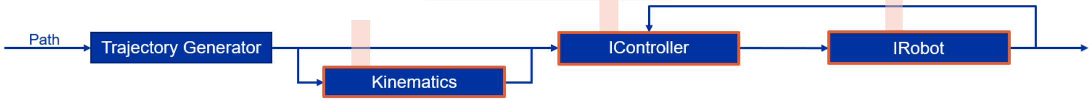
WIP

Flexible Robot Definition

Designed for the control of multiple end-effector robots.



WIP



Robotics for FCC

Development

Initial Study

- Requirements
- Restrictions
- Integration

Design Optimization

Control Concepts

Prototype PoC

Summary & Status

Design Process of the Prototype:

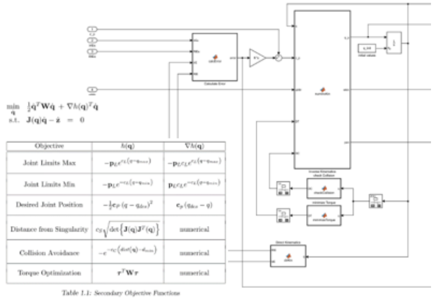
Update of Parameters and Topology

Analytic Description:

$$\sum_{n=1}^{N_{sub}} \left(\frac{\partial \mathbf{y}_n}{\partial \dot{\mathbf{q}}}\right)^T \left\{\sum_{i=1}^{N_n} \left[\left(\frac{\partial\, {}_R\mathbf{v}_{IS}}{\partial \dot{\mathbf{q}}}\right)^T \left(\frac{\partial\, {}_R\boldsymbol{\omega}_{IS}}{\partial \dot{\mathbf{q}}}\right)^T\right]_i \begin{bmatrix} {}_R\dot{\mathbf{p}} + {}_R\tilde{\boldsymbol{\omega}}_{IR}\, {}_R\mathbf{p} - {}_R\mathbf{f}^e \\ {}_R\dot{\mathbf{L}} + {}_R\tilde{\boldsymbol{\omega}}_{IR}\, {}_R\mathbf{L} - {}_R\mathbf{M}^e \end{bmatrix}_i \right\} = 0$$

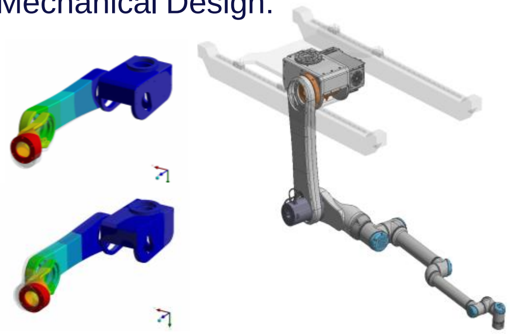
Update of Equation of Motion

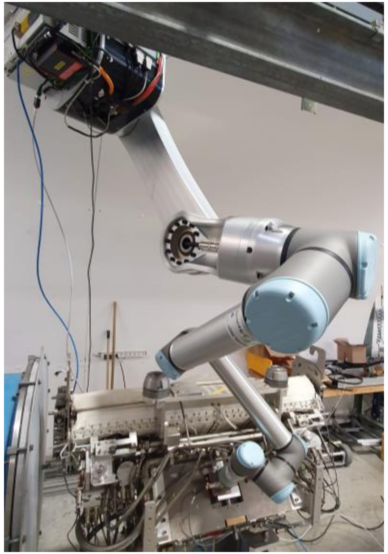
Numerical Simulation:

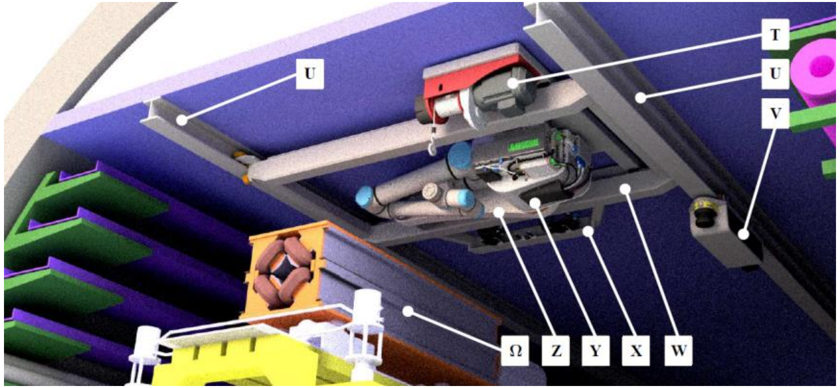


Update

Mechanical Design:







Robotics for FCC

Development

Initial Study

- Requirements
- Restrictions
- Integration

Design Optimization

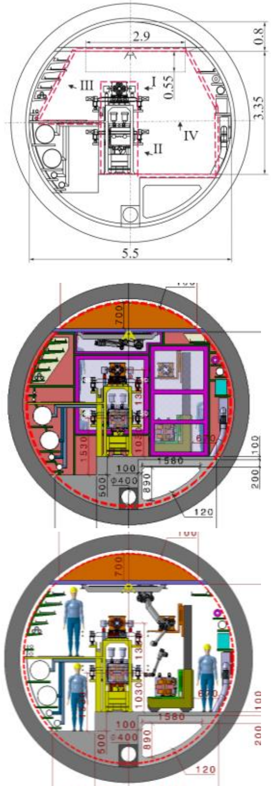
Control Concepts

Prototype PoC

Summary & Status

Requirements, Restrictions & Integration → Design Optimization → Model, Simulation, Control → Mechanical Design → HR Interface → Proof of Concept

Ongoing...



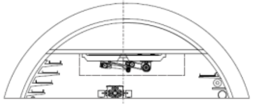


Figure 13: Prototype in FCC-ee - folded configuration

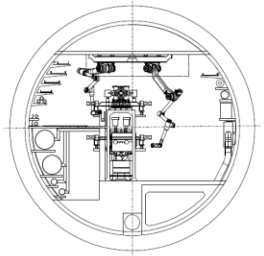


Figure 14: Prototype in FCC-ee cross-section

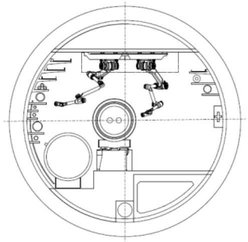
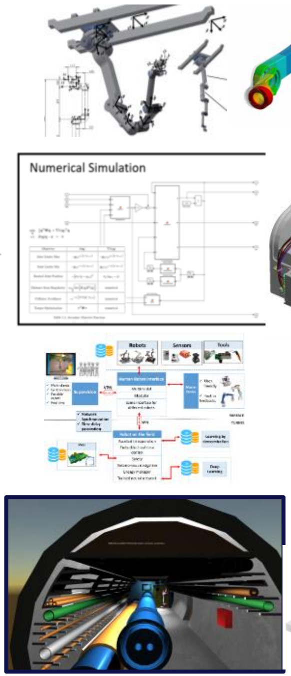
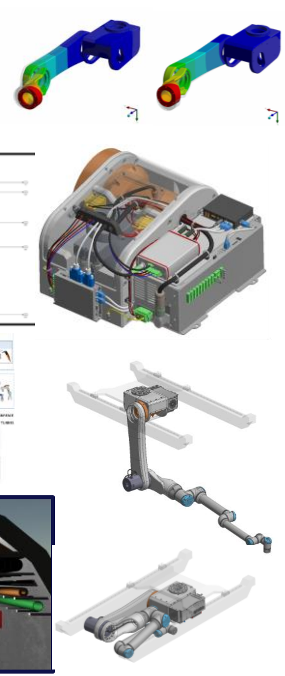
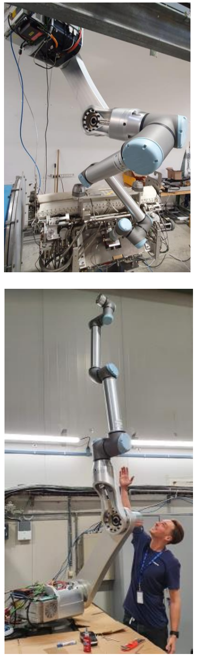


Figure 15: Prototype in FCC-hh cross-section







Test ongoing in the LHC tunnel mock-up and foreseen to be continued in the FCC Arc Half-Cell mock-up (see Federico Carra presentation)

Robotics for FCC

Synergies with other working groups

- **Transport** - Installation, Material …

  R. Rinaldesi: https://indi.to/thdjv

- **Survey** - RP, Alignment, …

  L. Watrelot: https://indi.to/bPtGS

- **Civil Engineering** - Remote structural health monitoring, large-scale tunnel defect data collection, preventive maintenance planning, …

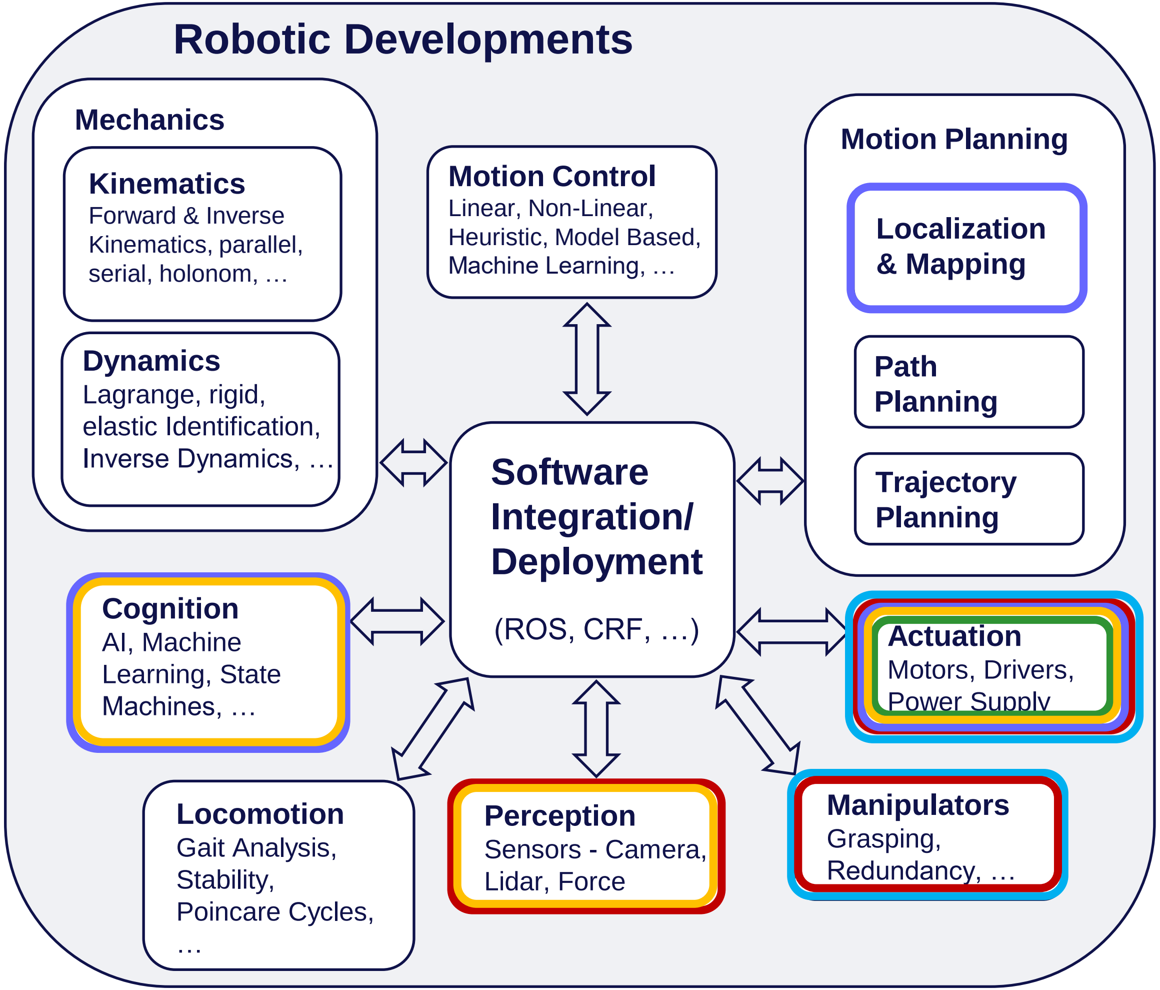
  J. Osborne, T. Watson: https://indi.to/VZLDh

- **Infrastructure** - Maintenance of Installation

  J. Nielsen, K. Hanke: https://indi.to/b9LSf

- **Safety** - Patrols, Early monitoring of fire events, Support CFRS initial tactical plan, Early fire suppression with extinguishing substances, Evacuation guidance/support, …

  O. Rios: https://indico.cern.ch/event/1064327/contributions/4888563/attachments/2452162/4208491/Robots_To_The_Rescue_1.0_r.pdf



Future Vision

- Current solutions used in Big Science Facilities and based on teleoperation are not suitable for maintenance tasks in FCC
- **Robotic community, and not only, is investing a lot in AI technologies**, boosting perception and autonomous behavior of cybernetic systems in structured environment.
  - ✓ In next two decades problems like automatic robotic positions within accelerators will be solved [15-18]
- **More investment should be done in "controlling" the physical interaction between cybernetic systems and environment**
  - ✓ Adaptive controls
  - ✓ Smart/soft materials
  - ✓ Actuation technologies used in robots are really old and there is no strong investments on their future developments from the mechatronic/robotic community
  - ✓ Most of the recent effort is put on Information Technology/AI
- **Assistance in emergency situations**
  - ✓ Early monitoring of the fire event. Support CFRS initial tactical plan
  - ✓ Early fire suppression with extinguishing substances
  - ✓ Evacuation guidance/support
  - ✓ Emergency interventions using robots are possible but not yet implemented basically because technology is not yet mature enough causing lack of trust → Investments should be done in reliable robots and not only in next generation of prototypes
- Robotic technology has huge potential to be beneficial for people and FCC availability.
  - ✓ Open for collaboration with all the interested working groups

Collaborations with institutes on robotics

- Many Collaborations with Universities and external Companies
- Aim to be at top of technological standards by continuous exchange with partners all over the world

Collaborations with institutes on robotics

- Many Collaborations with Universities and external Companies
- Aim to be at top of technological standards by continuous exchange with partners all over the world

Already collaborating or willing to collaborate on robotics for FCC

Conclusions & Outlook

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

- Automation and robotics can mitigate the safety hazards to personnel in the FCC arcs
  - ✓ Keep **persons out of the arcs** for routine tasks (monitoring, patrols, standard repair)
  - ✓ **Standardize** all **equipment** so that maintenance and/or exchange can be remotely executed
  - ✓ Robots are key part on emergency concept in FCC

- Advancements in robotics are already present in current accelerators technology, journey is still long for FCC operation

- External collaboration with other research organizations, robotics Research Centres and Universities is crucial to take advantage of the cutting-edge technology

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Mario Di Castro, Hannes Gamper, Luca Buonocore,
Eloise Matheson, Alessandro Masi

Thank you
for your attention!