



Controls
Electronics &
Mechatronics



FCC ROBOTICS - UPDATE

Content

1. **Robotics Work Package for FCC-ee Technology R&D | 2022 - 2025**
2. **Robotics WP RAMP | 2025 onwards**
3. **RMIS Prototype Update**
4. **Conclusion & Future Work**

Robotics Work Package for FCC-ee Technology R&D | 2022 - 2025



Deliverables	Task	Year
D1: Report on Procedures and Code of Practice	TASK 1	End of Y1
D2: Report on Integration	TASK 2	Mid of Y2
D3: Fully Operational Prototype (installed in B927 LHC Mockup)	TASK 3	End of Y3
D4: Report & Documentation: Summary of Achievements and Relation with Initial Goals	TASK 4	End of Y3

Excerpt from work package on deliverables. Full work package description [here](#)

Previous FCC week presentations on robotics:
[2024](#), [2023](#), [2022](#), [2021](#), [2017](#)

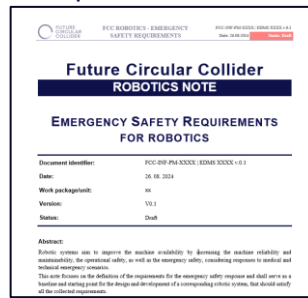
Robotics WP Deliverables

- **D1: Initial Study**
 - Requirements
 - Functional Analysis
- **D2: Integration**
- **D3: Prototype**
 - Design
 - Software
 - Hardware
- **D4: Report**

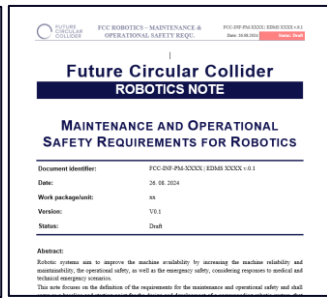
Situation

- In 2020 no robotic system integrated in FCC
- Extrapolating LHC data showed that automation is crucial!

Requirements:



EDMS 3220303



EDMS 3220312

Result

- Reserved space for robotic system in baseline design!
- Robotics as integral part of the safety concept

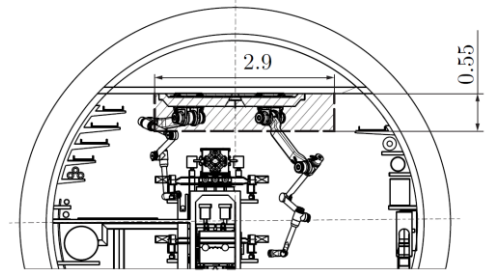
=> Robotics for Machine Availability and Safety

Functional Analysis:

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

Presentation of proposal to FCC Study board! ✓

Integration in FCC:



New Study Showed: FCC availability >= 80% means 15-fold increase of mean time between failure of infrastructure -> Robotics can relax this by factor 3!

Collaboration with HSE and CFRS on emergency response!

Robotics WP Deliverables

- **D1: Initial Study**
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=> Robotics for Machine Availability and Safety

1. Operational Safety
- Protect workers from dangerous interventions (radiation exposure, ...)

2. Availability
- Corrective & preventive maintenance increasing maintainability
 - Predictive maintenance increasing reliability



- ⇒ High versatility
- ⇒ Complex interactions with environment

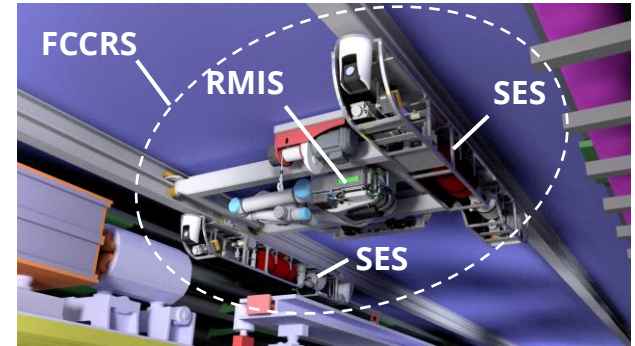
⇒ **Remote Maintenance & Inspection System (RMIS)**

3. Emergency Safety
- Technical/Medical Emergencies
 - Situation Awareness
 - Detect and engage hazards



- ⇒ standby-ready
- ⇒ Quick

⇒ **Surveillance & Emergency Shuttle (SES)**

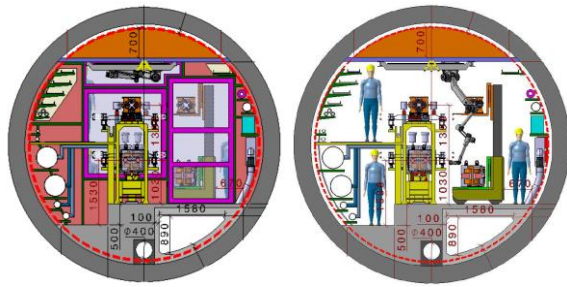


Robotics WP Deliverables

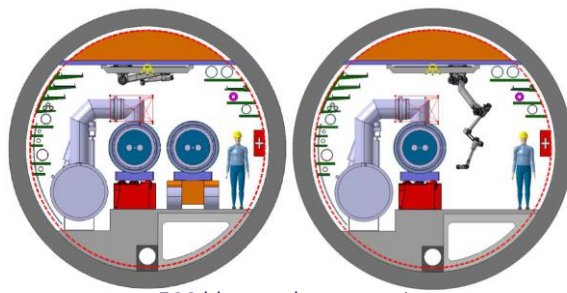
- D1: Initial Study
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- RMIS and SES integration in FCC tunnel
- Radiation safe parking spots in Service Caverns:
 - Protect hardware
 - Allow for maintenance work on robots

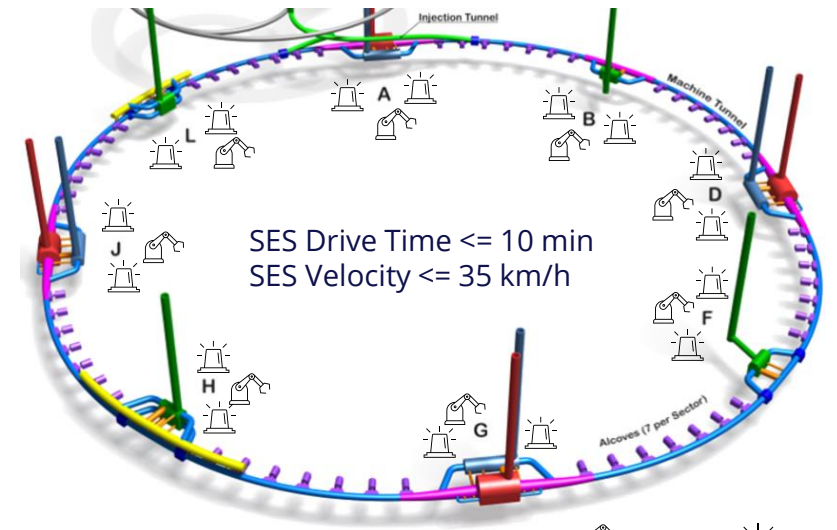
- System per Service Cavern:
 - ≥ 1 RMIS in different configurations for different interventions
 - ≥ 2 SES
- Total amount of Systems for FCC:
 - ≥ 8 RMIS
 - ≥ 16 SES (drive time ≤ 10 min, $v \leq 35$ km/h)



FCC-ee tunnel cross-section



FCC-hh tunnel cross-section



SES Drive Time ≤ 10 min
 SES Velocity ≤ 35 km/h

RMIS SES

Robotics WP Deliverables

- D1: Initial Study
 - Requirements
 - Functional Analysis
- D2: Integration
- D3: **Prototype Design**
 - Software
 - Hardware
- D4: Report

Situation

- Requirements dictate some parameters of the robot
- No requirements on topology or geometry!
- How to find an optimal design?

=> Development a novel design optimization technique "Kinematic Model Pruning":

$$\min_{\mathbf{x}, \mathbf{p}_l} J(\mathbf{x}, \mathbf{p}_l) = \mathbf{k}^T \mathbf{g}(\mathbf{p}) + \mathbf{\Gamma}^T(\mathbf{x}, \mathbf{p}) \mathbf{K} \mathbf{\Gamma}(\mathbf{x}, \mathbf{p})$$

$$\text{s.t. } \mathbf{f}(\mathbf{x}, \mathbf{p}_l) - \mathbf{z}_{des} = \mathbf{0}$$

$$-\mathbf{c}(\mathbf{x}, \mathbf{p}_l) \leq \mathbf{0}$$

$$\mathbf{ub}(\mathbf{x}, \mathbf{p}_l) \leq \mathbf{0}$$

$$\mathbf{lb}(\mathbf{x}, \mathbf{p}_l) \leq \mathbf{0}$$

More information [here](#)

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

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

and

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



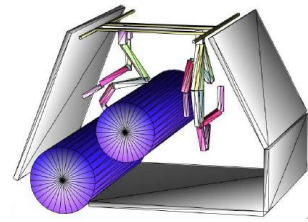

Article

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

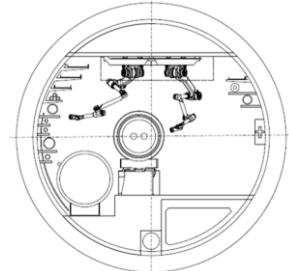
Hannes Gamper ^{1,2,*}, Adrien Luthi ¹, Hubert Gattringer ², Andreas Mueller ² and Mario Di Castro ¹

Result:

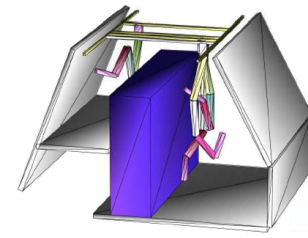
Optimal Geometry + Topology (11 Degree of Freedom)



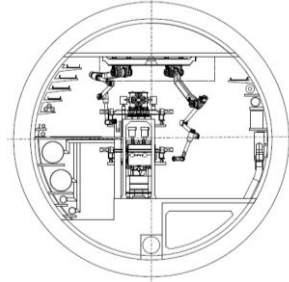
FCC-hh collision objects



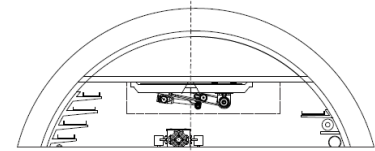
FCC-hh cross section



FCC-ee collision objects



FCC-ee cross section

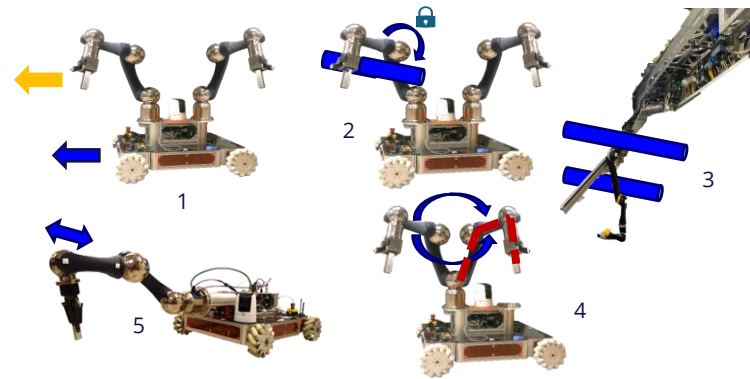


Robot folded in reserved space

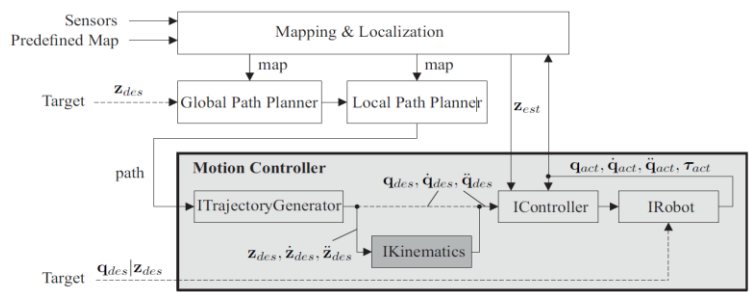
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=> Development a novel inverse kinematics algorithm incorporating five features: [More information here](#)

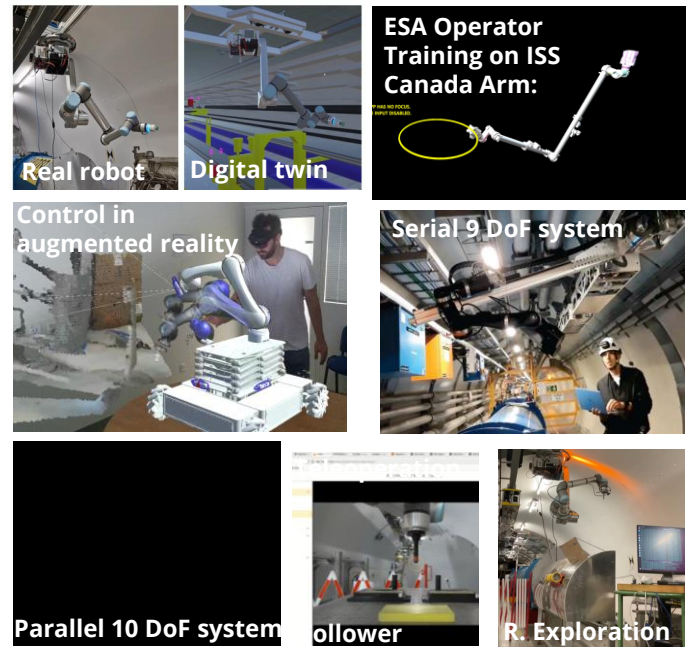


=> Development of a Generic Motion Controller



Result

- Control of highly redundant robots with CRF*
- ESA interest and collaboration
- Open-source publication



and many more thanks to the combined work of the BE-CEM-MRO Robotics team! More interesting work can be found [here](#).

*CERN Robotic Framework [More information here](#)

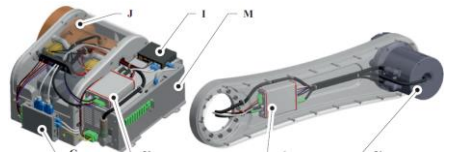
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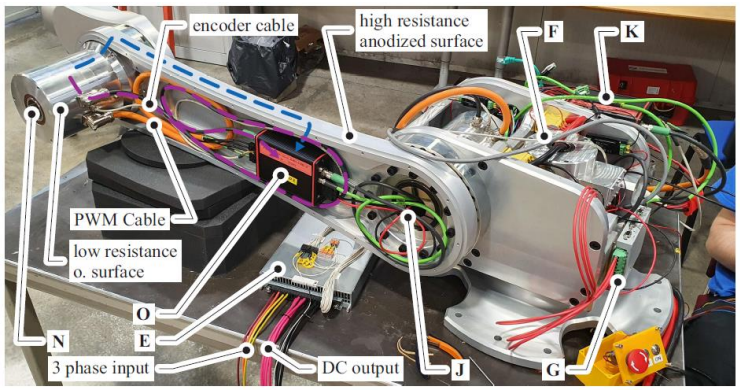
Design & Assembly of the Prototype

- Situation
- Simulate, calculate and select electro-mechanical robotic components
 - Design the robot links

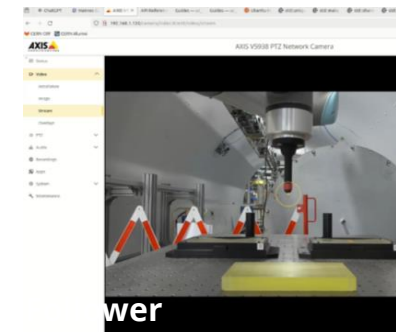
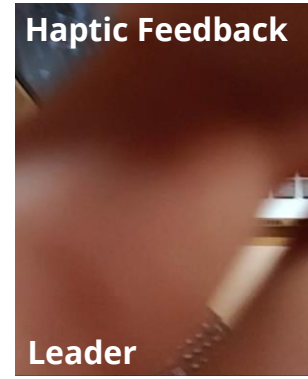
=> Need to understand the static and dynamic forces acting on the system



$$\mathcal{L} = -\frac{1}{4} F_m F^m + i F D \dot{\phi} + h.c + \frac{1}{2} \dot{\phi}_i \dot{\phi}_j \phi + h.c + \frac{1}{2} |D_a \phi|^2 - V(\phi)$$



Result:



Robotic WP RAMP | 2025 onwards

Robotic Automation for Maintenance and safety Platform

Previous FCC week presentations
on robotics:
[2024](#), [2023](#), [2022](#), [2021](#), [2017](#)

Why did we propose a new work package?

- Detailed study only done for the **main tunnel** and the **operational phase** of FCC
- New requirements frequently reaching us also for the main tunnel
- We receive new requests for the **entire FCC complex** and the **entire life cycle** of FCC at a high rate
- Up to now, no centralized body/service in place with the necessary mandate to process and coordinate these requests

Robotic WP RAMP | 2025 onwards

Robotic Automation for Maintenance and safety Platform

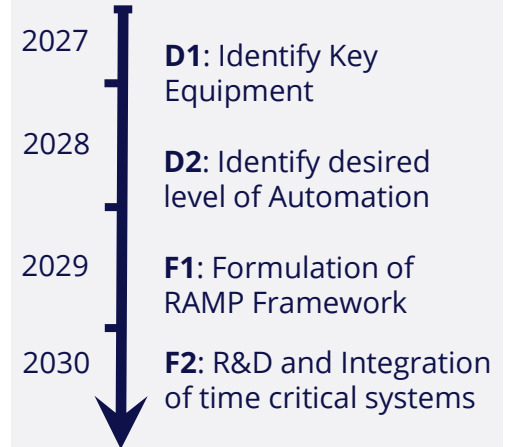
Previous FCC week presentations on robotics:

[2024](#), [2023](#), [2022](#), [2021](#), [2017](#)

Robotic WP RAMP Main Objectives

1. Complete the list of stakeholder participants of the robotic service
2. Raise awareness for robotics applications in installation and maintenance
3. Identify automation needs in FCC systems to enhance maintainability and safety
4. Analysis of the economically desirable level of automation
5. Establish a support service for FCC automation-compliant system design
6. Initiate the definition of standards, norms, and conventions for time-critical systems
7. Conduct R&D on automation and propose potential infrastructure enhancements to the current baseline

Rob. WP RAMP Outlook



=> The activity is currently de-scoped in line with the gap between allocated and required resources!

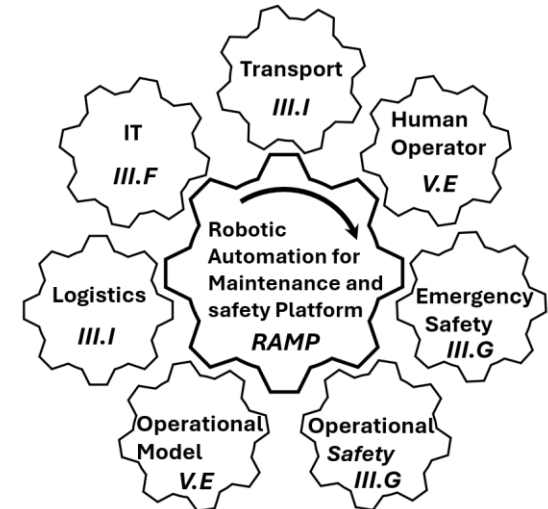
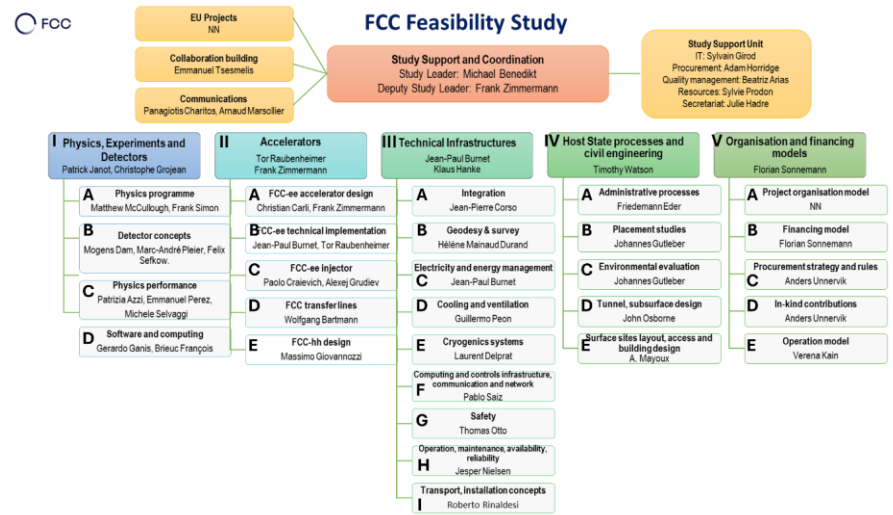
Robotic WP RAMP Deliverables

- D1: Identify Key Equipment
- D2: Identify Desired Level of Automation
- F1: Formulation of the RAMP
- F2: R&D and Integration of time critical systems

Identification of Key Equipment and Services Requiring Robotic Solutions

Situation

- Clear requirements on automation in **main tunnel** (EDMS Nr. [3220303](#), [3220312](#))
- New requests coming in regularly also for main tunnel
- No study conducted for other FCC areas or life stages
- List of stakeholders not complete



Result

- Clear definition of interfaces and dependencies between key elements.
- Complete list of stakeholders owning the requirements.

Example and preliminary analysis (limited maturity) of the relevant key elements that have to be addressed in the scope of the RAMP WP.

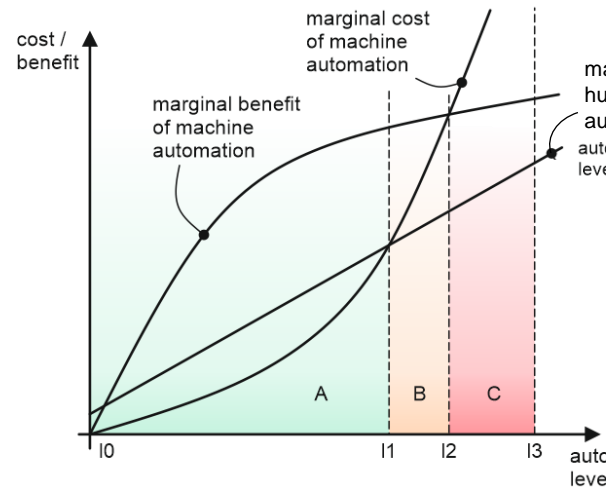
Robotic WP RAMP Deliverables

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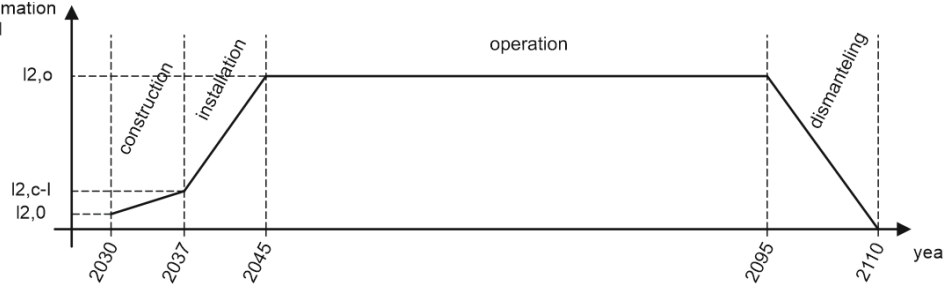
Analysis of the Economically Optimal Level of Automation/Robotics

Situation

- The desired (economically optimal) level of automation is unknown



Qualitative graph of the cost/benefit analysis as function of the automation level in the FCC.



Qualitative graph of the level of robotics/automation in the FCC complex over its lifetime.

Result

- Identified the economically optimal level of automation for each stage of the lifetime of the FCC

Robotic WP RAMP Deliverables

D1: Identify Key Equipment

D2: Identify Desired Level of Automation

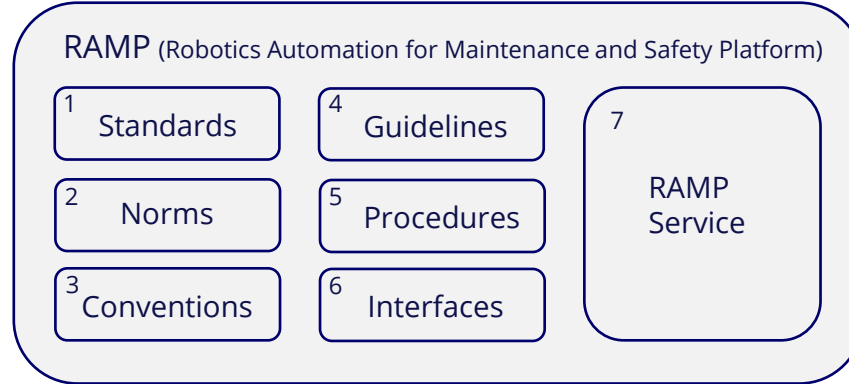
F1: Formulation of the RAMP

F2: R&D and Integration of time critical systems

Formulation of the RAMP

Situation

- No central point of contact for automation requests
- No mandate to take decisions on Standards, Norms, Interfaces, etc.
- No support for automation friendly infrastructure design



preliminary layout (limited maturity) of the RAMP framework

Result

- RAMP Service consults on automation friendly infrastructure design, collects requirements, identifies synergies and dependencies in automation tasks
- RAMP Service receives mandate to define Standards, Norms, Interfaces, etc.

Robotic WP RAMP Deliverables

- D1: Identify Key Equipment
- D2: Identify Desired Level of Automation
- F1: Formulation of the RAMP
- **F2: R&D and Integration of time critical systems**

R&D and Infrastructure Integration for Time Critical Systems

Situation

- Some infrastructure design is already well advanced and requires timely proposals for automation compliant design.



Maintenance



Search and Rescue



Machine Automation and Control

Result

- Automation compliant design can be considered at an early design phase with minimal econ. impact

From Unstructured to Structured Environment

Universal Systems



Tesla Optimus



Flyability Elios



Telerob Telemax

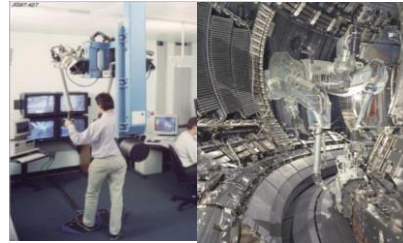


Unitree Go1

Task Specific Systems



SNS - Oakland National Laboratory



JET - Primary (RACE)

JET - Secondary (RACE)



CERN - TIM



ISS - Canada Arm

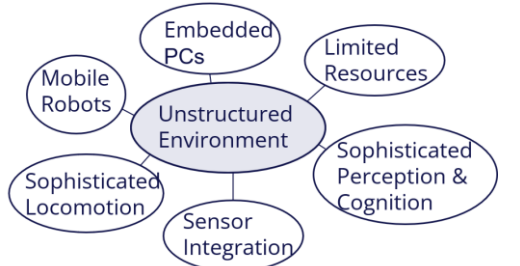


Prototype of the Vehicle Manipulator
ITER - RACE

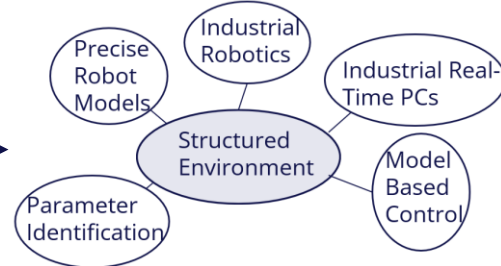
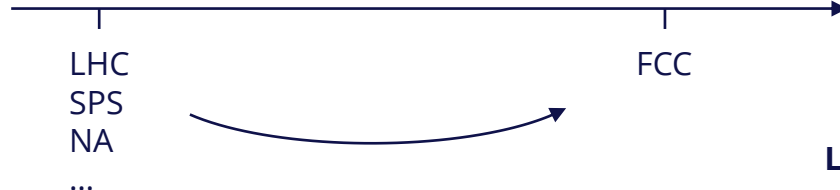
Industrial Automation S.



KUKA W8 center



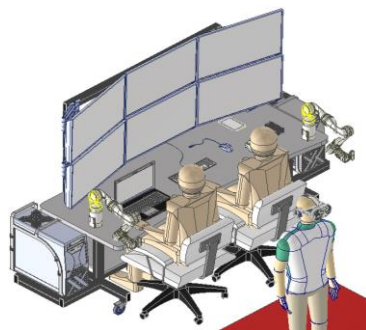
High Versatility / Low Efficiency



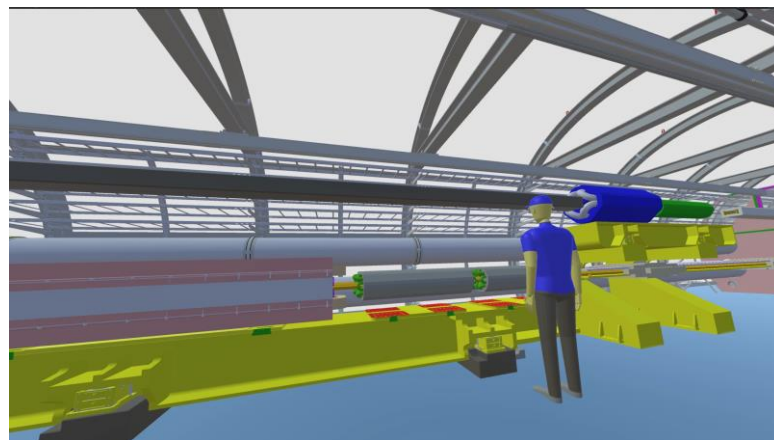
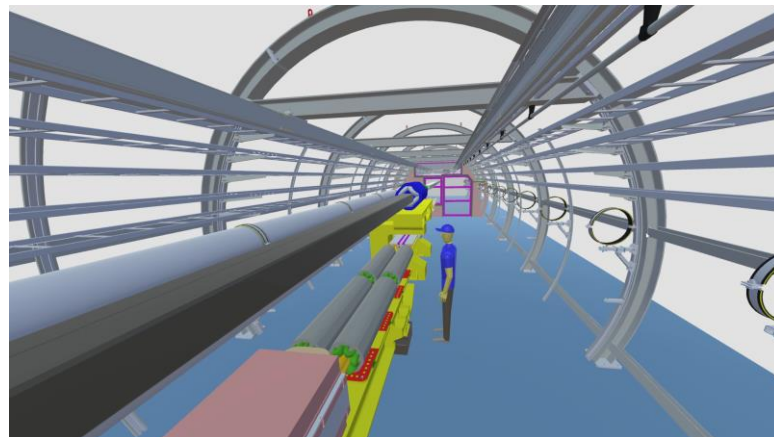
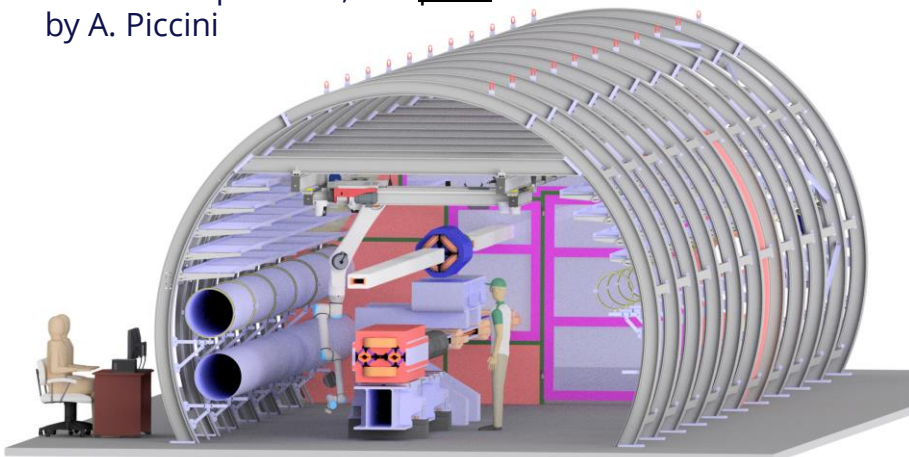
Low Versatility / High Efficiency

RMIS Prototype Update

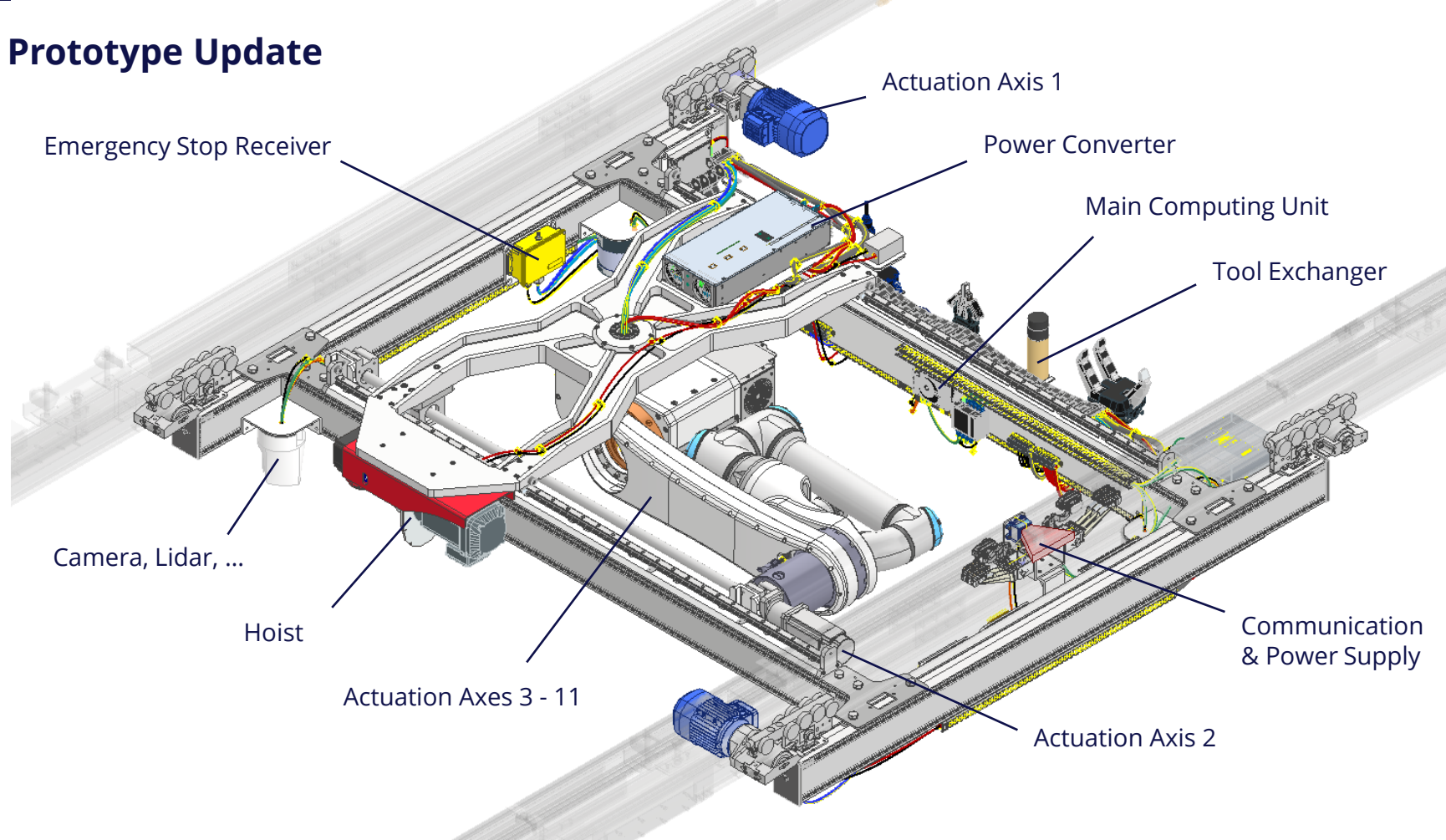
- Installation in Bldg. 355-358
- Aim of Robot integration:
 - Robotic R&D
 - Proof of Concept Studies
 - Raise awareness for automation
- For Mock-Up details, see [pres.](#) by A. Piccini



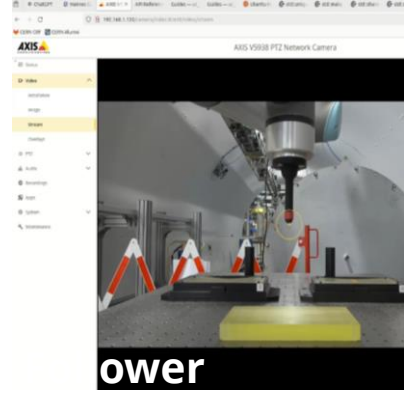
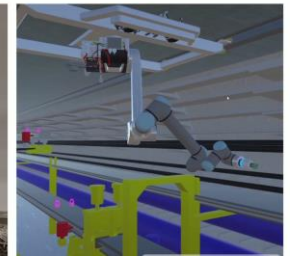
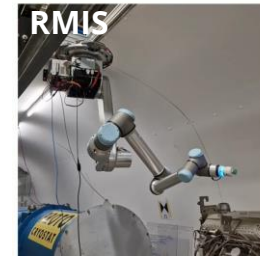
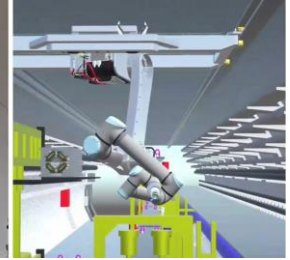
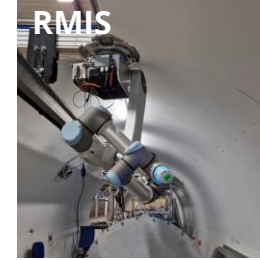
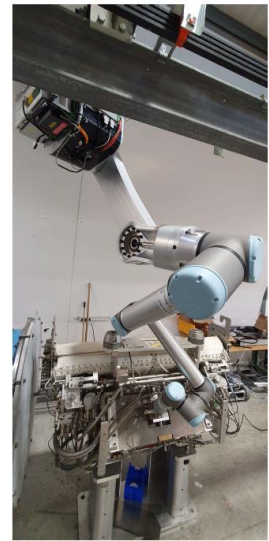
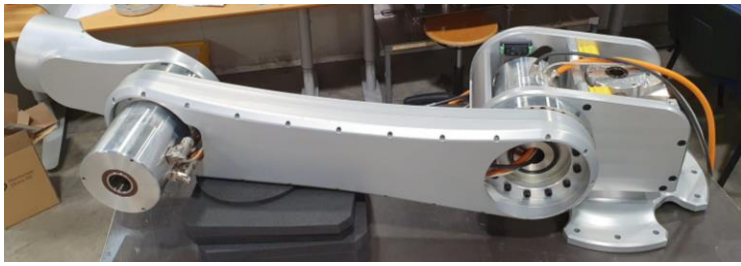
HRI Control Station including AR Interfaces and Haptic Feedback



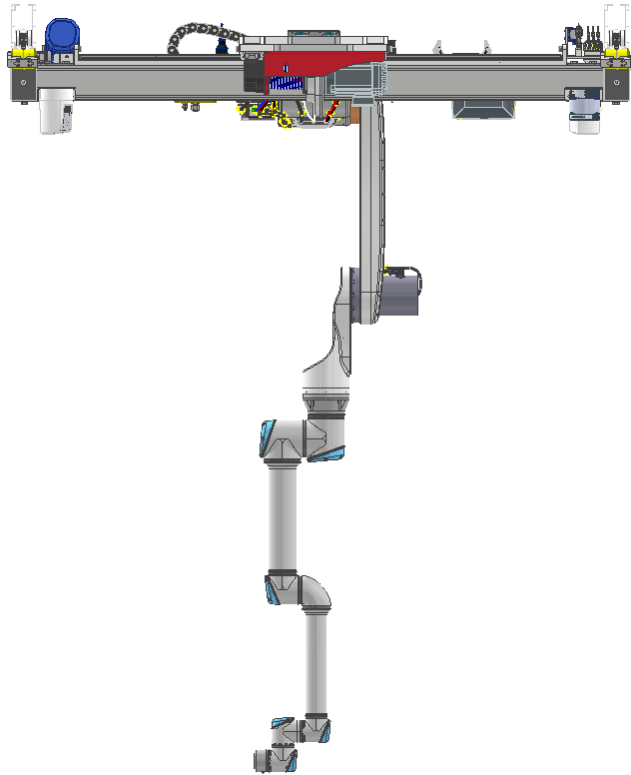
RMIS Prototype Update



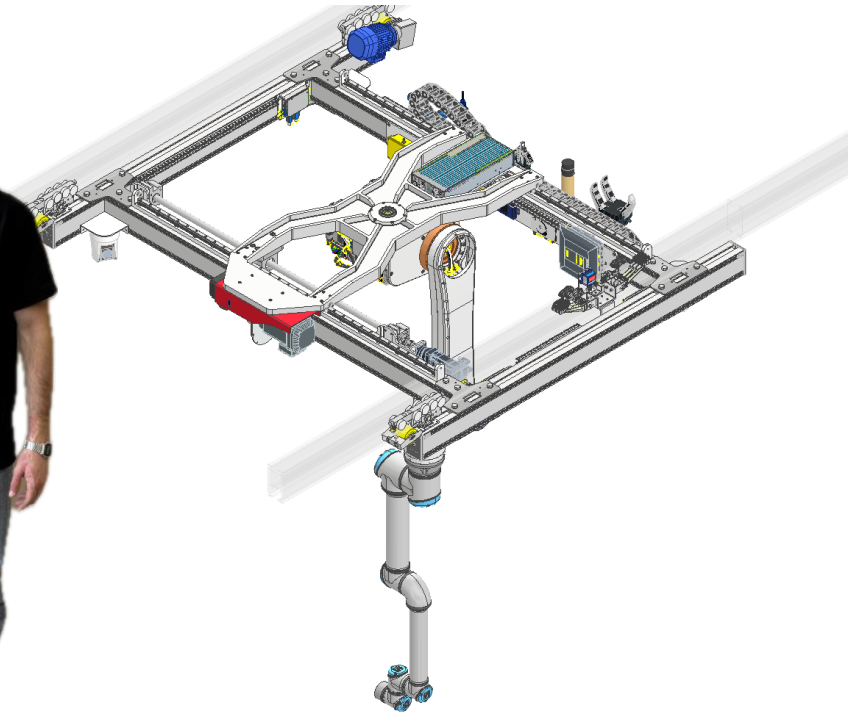
RMIS Prototype Update



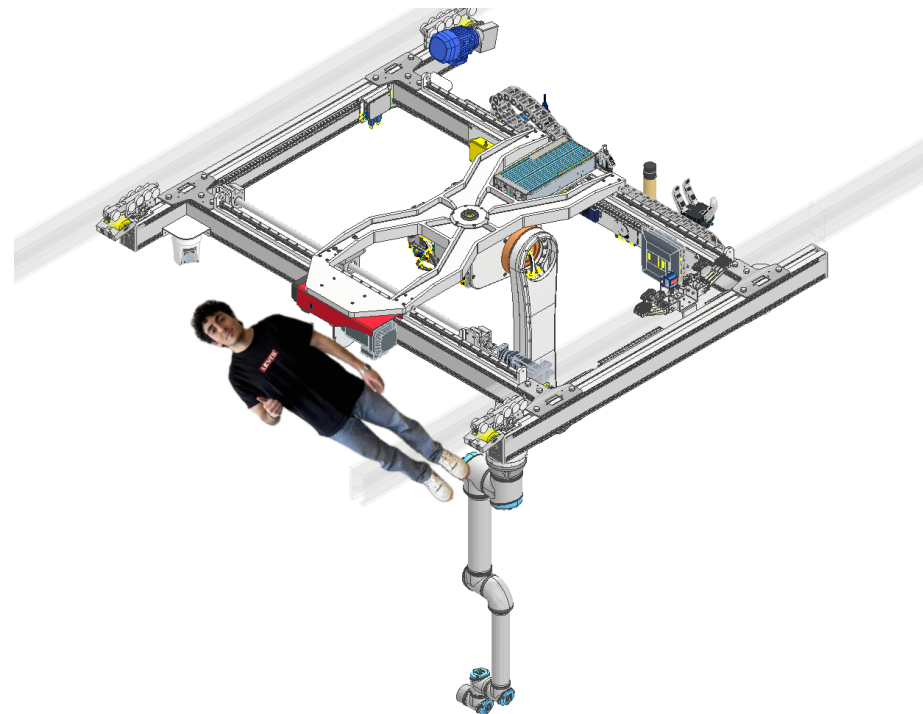
RMIS Prototype Update - To scale



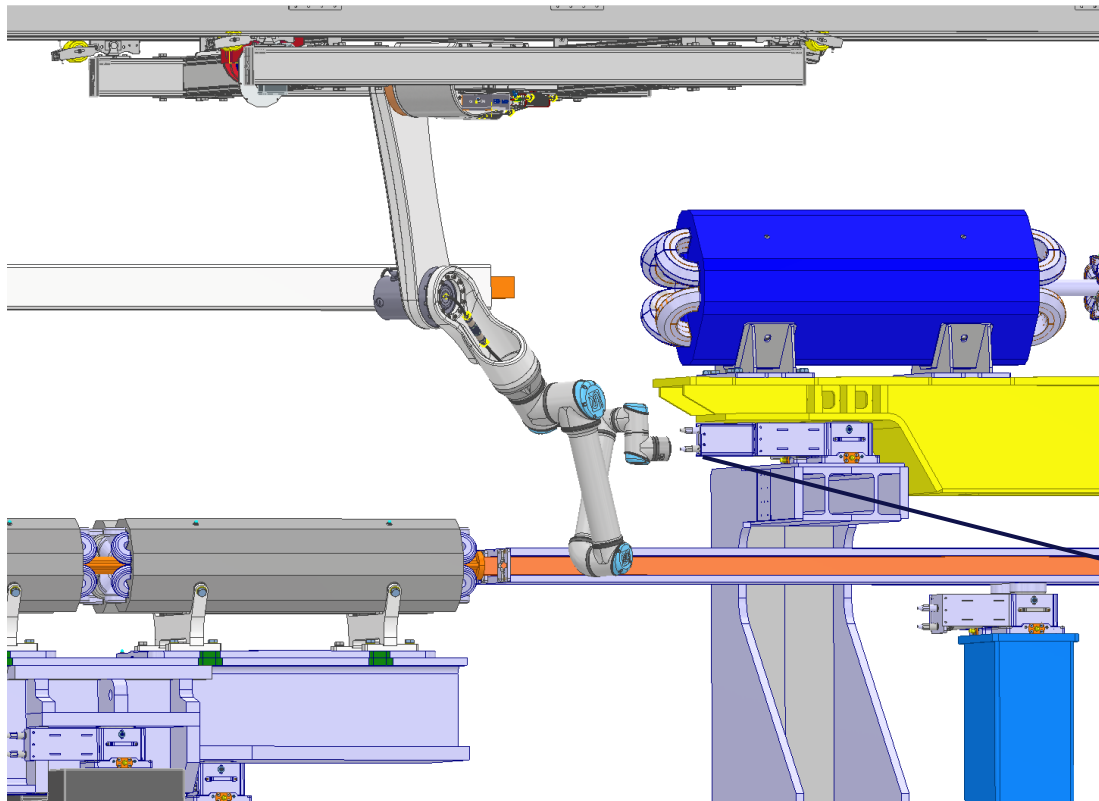
Paolo Langella, MSc
Mechanical Engineer



RMIS Prototype Update - To scale



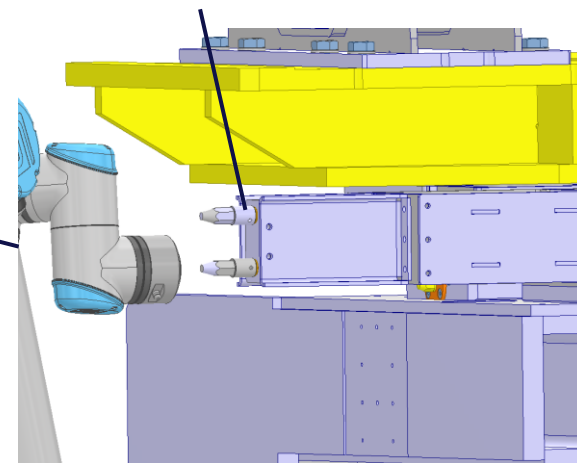
RMIS Prototype Update – Task Girder Alignment



Proof of Concept: **Fully Autonomous Alignment**

1. Request to BE-CEM-MRO
2. Requirement Collection
3. Adaptation of Environment
4. Dev. Of Fiducial Marker System
5. V&V

Robot Compatible Design
of Screwheads



Conclusions

Robotics Impact on FCC

- **Increased Availability** by ...
 - Corrective/Preventive Maintenance impacting Maintainability
 - Predictive Maintenance impacting Reliability
- **Increased Operational and Emergency Safety**

Key Takeaways

- **Consider robotic maintenance at an early design phase**
- Think **automation first, then robotics**
- Design early for robotic intervention: This approach leads to **tailored, cost-effective, and sustainable** solutions
- **Standardized infrastructure** design, interfaces and intervention procedures **is key**
- Designing interfaces for **entire lifecycle**: Installation to Decommissioning
- Robotic capabilities are advancing at a high rate => **be ready to exploit the full potential in 2035**

Current Status of Robotics for FCC

- Integration of Robotic Infr. for Availability and Safety in FCC **main tunnel** => RMIS* + SES**
- Prototype for Proof of Concept Studies and **Integration in FCC Mock-Up in full progress**
- New requests raised at a high rate for the **entire FCC complex** and **entire life cycle** of FCC.

RAMP Work Package

Milestones

1. Identification of Key Equipment and Services Requiring Robotic Solutions
2. Analysis of the Economically Optimal Level of Automation/Robotics
3. Formulation of the RAMP***
4. R&D and Infrastructure Integration for Time Critical Systems

* Remote Maintenance and Inspection System

** Surveillance and Emergency Shuttle

***Robotic Automation for Maintenance and safety Platform

Collaborations

- Many Collaborations with Universities and external Companies
- Aim to be at top of technological standards by continuous exchange with partners
- Commitment from Universities for future R&D concerning the FCC Robotics developments
- **Thank you for the various fruitful collaborations within CERN!**



BE-CEM-MRO Robotics Team

Established within the FCC Robotics efforts



High-tech guardians: Robotics at the heart of the Future Circular Collider



Thank you
for your attention!