FUTURE
CIRCULAR
COLLIDER

A ROBOTIC SYSTEM FOR REMOTE INTERVENTIONS IN THE FCC COMPLEX

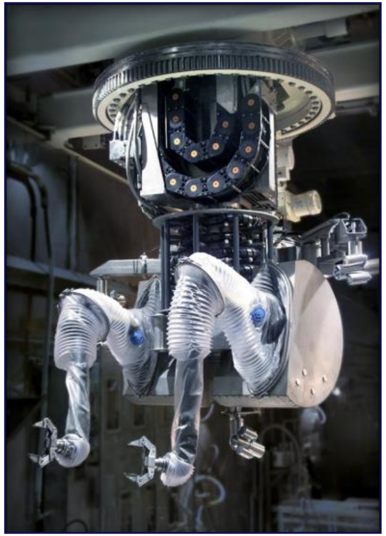
H. Gamper, A. Mueller, H. Gattringer, M. Di Castro

Content

1. **Robotics in Big Science Facilities**
   - State of the Art
   - Robotics at CERN
2. **The Vision**
3. **Development Process**
   - Requirements & Restrictions for a Robotic System
   - Integration and Logistics
   - Current Research
4. **Remote Maintenance - Code of Practice**
5. **Collaborations**

Content

Robotics in Big Science Facilities - State of the Art



Spallation Neutron Source Target – Oakland National Laboratory

Universal Systems

Figure 2 RESQ-A

Figure 4 RESQ-C

Figure 19 TALON equipped with rad-mapping system ©TEPCO

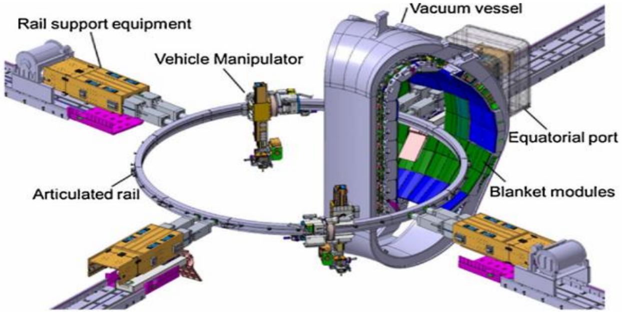
Figure 24 Warrior ©TEPCO

Figure 22 BROKK 90 ©TEPCO

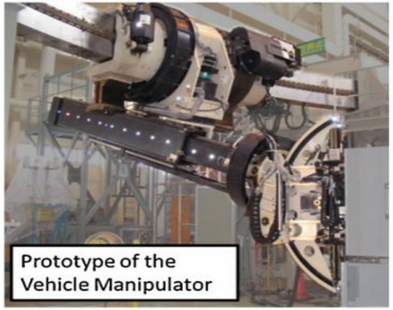
Task Specific Systems

JET – Primary (RACE)

JET – Secondary (RACE)



ITER – RACE



Robotics in Big Science Facilities – Robotics at CERN

Telemax robot

EXTRM robot with single arm (CERN made)

The TIM (CERN made)

CRANEbot (CERN made)

EXTRM robot (CERN made)

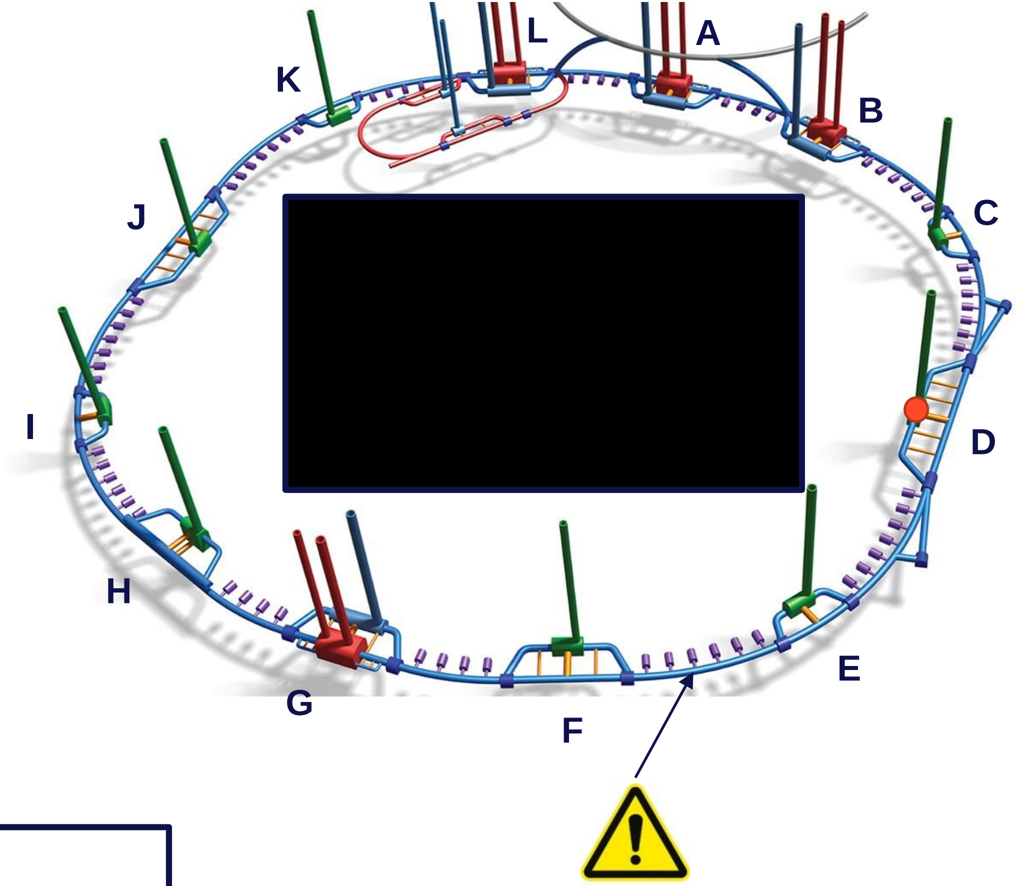
CERNbot (CERN made)

BE-CEM-MRO

Content

The Vision

- Conduct all planned repetitive interventions fully autonomous
- Move fully autonomous to a Point of Interest
- 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
⇒ Protect workers from dangerous interventions

BE-CEM-MRO

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Development Process

- Initial Study
  - Requirements
  - Restrictions
- Integration & Logistics
- Design Optimization
- Control Concepts
- Prototype PoC

	Task								Derived Requirements	
	Nr	Name	Description: When – Repetitive	Periodic	T	How	Why		Description	Detailed
Maintenance	1	Measuring Radiation	yes	yes	wks - mts	Industrial Radiation Sensor measures radiation at beam level. Sensor is carried by extendable arm of TIM.	To know the risk of sending people to the tunnel or use this information as indication for other problems.		Reach Beam level in front and behind pipe; Position accuracy for repeatable measurements;	WSP: 3.2x3.6m
	2	Take Pictures	yes	yes	wks - mts	Cameras and 3D Cameras mounted on mobile platforms are taking pictures and mapping the tunnel. 3D Cameras check the geometry of the tunnel and RNN detect optical changes at the tunnel walls (e.g. new cracks, ...)	To monitor health of the tunnel; Many new cracks could indicate other problems		Stable movement; carry a camera array	
	3	Test BLM Sensors	yes	yes	wks - mts	Rough map of sensors exists, go to rough sensor position and find exact position with RNN, scan environment with depth camera to find allowed operating space, plan path with these restrictions (random points constrained by ellipse, RRT or PRM), plan smooth trajectory, bring radioactive probe to sensor, precise distance from BLM measured with additional sensor, thus approaching sensor slowly and precision of robot is not a problem	Test if Sensors are working normal, sensors are measuring radiation, higher radiation indicates beam loss which implies bigger problems and force a shutdown, should be done by robot because of radioactive sample		Reach BLM Sensors in front and behind pipe; texture of robot must allow nullspace movement to provide collision avoidance while maintaining probe position	WSP: 3.2x3.6m (1,5x1,5m -> every orientation)
	4	Measure Oxygen	yes	yes	wks - mts	Industrial Oxygen measurement sensor; measured throughout the whole tunnel;	Make sure its save for people to work down there		Reach different hights to maesure oxygen	WSP: 3.2x3.6m
	5	Measure Alignment	yes	yes	wks - mts	Strings are placed by STI on fixed mounted sockets in tunnel, TIM goes to strings as reference and measures some indicators on the Collimators & Dipoles, same distance => align! This only happens on the straight sections of LHC? New method will automatically place the strings: outter robots hold the string and inner robots does the alignment measurement, same procedure for horizontal distance, for vertical distance new ultrasonic sensor is used	With non-align tubes, beam would get lost.		Version1 : (manually placed string) reach string with existing technology; stable movement; Version2: (automotively placed string) need of two outter robots and one inner robot with existing technology	
	6	Audio Inspection	yes	yes	wks - mts	Microphone is carried through whole tunnel, detect unusual noise (e.g. frequency domain -> 100Hz peak	To detect unusual noise which can indicate other problems (e.g.			

Development Process

Importance: 100% / 80% / 60%

Rating: 4 very positive for solution; 3 positiv for solution; 2 negativ for solution; 1 very negativ for solution

Restrictions: Tunnel & Environment; Tasks; General

- Initial Study
  - Requirements
  - Restrictions
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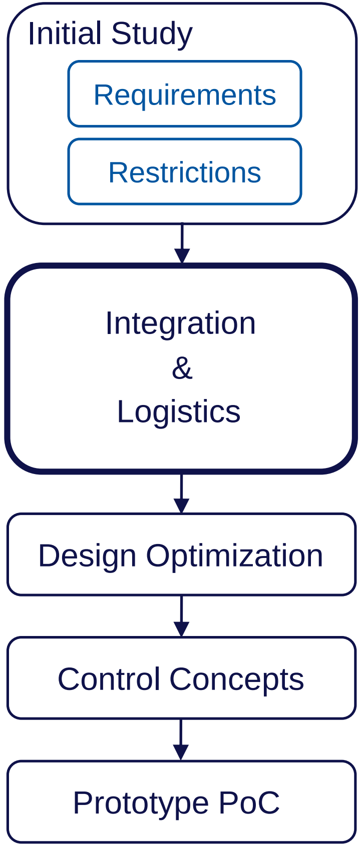
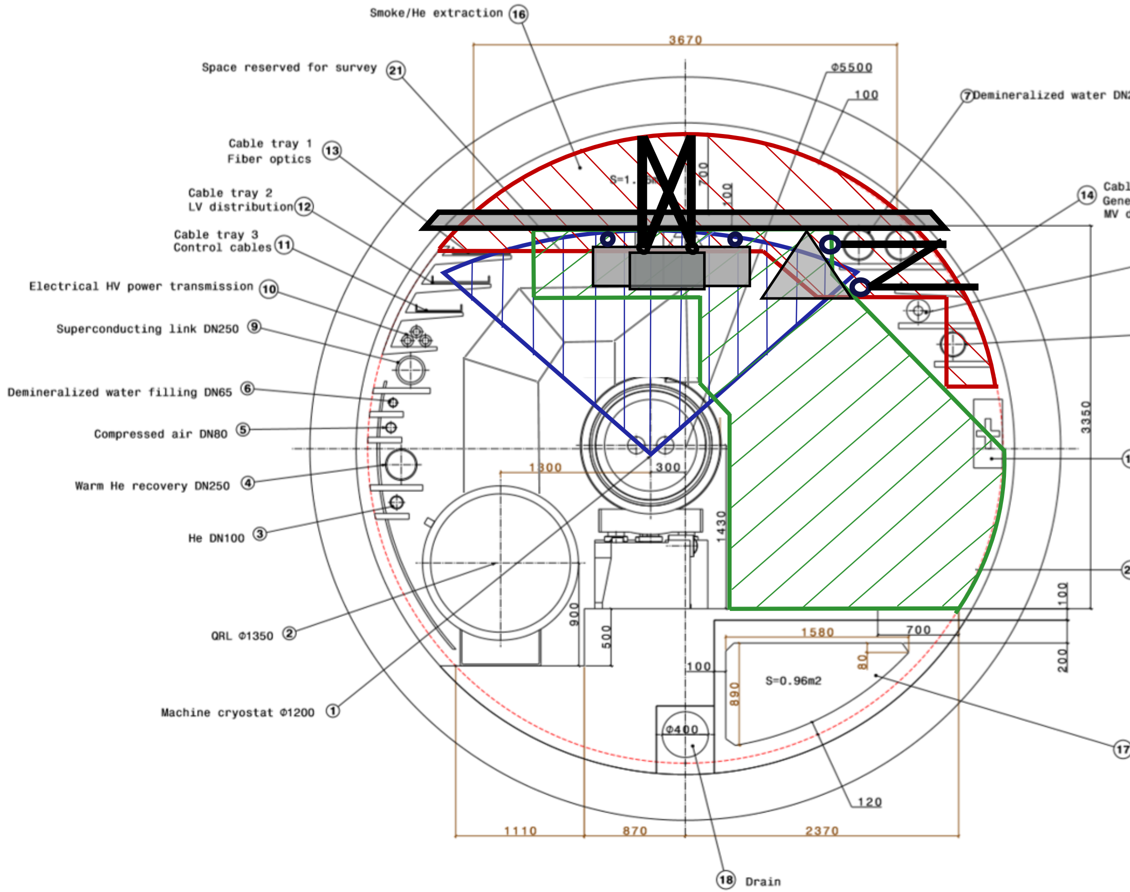
Task								Derived Requirements	
Nr	Name	Description							
		When			How	Why			
		Repetitive	Periodic	T				Description	Detailed

SOL \ REQ	Geometry Req.				Power Supply				Communication				Maneuverability				Radiation				Control				Emergency				Summed up Rating in %
	Workspace ~3200x3600	Go through fire doors	Collission avoidance		Maintenance	Reliability	Costs	Consumption	Easy Teleoperation	Robust			Stable Movement	Turn within 1500mm	Go under or behind pipe		No further cont. by rob	Radiation Tolerant			Simple	Robust	proofen Stability	Autonomous	Not Blocking Exit	Move in harsh env.	Modular	Intervention	
	1	0.8	1		0.8	1	1	0.6	1	1			0.8	1	0.8		1	0.8			0.8	1	1	0.8	1	0.8	0.6		
Mobile Robot (holonomic)	2	3	2		2	2	3	4	2	3			1	4	4		3	1			4	4	4	1	1	1	2		65.7
Mobile Robot (non-holonomic)	2	3	2		2	2	3	4	2	3			3	2	2		3	1			4	4	4	1	1	1	2		64.8
Rail Guided Robot (ceiling)	3	3	3		3	3	1	2	3	3			4	4	1		4	1			3	4	4	2	4	3	2		74.3
Drone	4	3	1		2	2	3	3	2	2			1	4	3		1	1			2	2	3	1	3	4	1		58.1
Legged Robot (ANYbotics, ...)	3	2	2		2	2	1	2	2	2			1	4	3		3	1			1	2	2	2	1	3	2		52.0
Legged Robot + Wheels (Boston Dynamics, ...)	3	2	2		2	2	1	2	2	2			2	4	2		3	1			1	2	2	2	1	3	2		53.7
Holonomic Robot travel in Hyperloop	2	3	2		2	2	2	2	2	3			4	4	4		3	1			2	4	4	2	1	1	1		62.0
Rail Guided Robot w. robotic arm & hol. Robot	3	3	3		2	3	1	2	3	3			4	4	4		3	1			3	4	4	2	4	3	2		75.4
Holonomic Robot w. Robotic Arm	3	3	2		2	2	3	4	2	3			1	4	4		3	1			3	4	4	1	1	1	3		63.9
RailGuided Robot w. Snake Robotic Arm	3	3	3		3	3	1	2	3	3			4	4	2		4	1			3	4	4	2	4	3	2		71.3

Development Process



- Good Access for Inspections
- Allowed Area for moving Robot
- Allowed Area for permanently installed material



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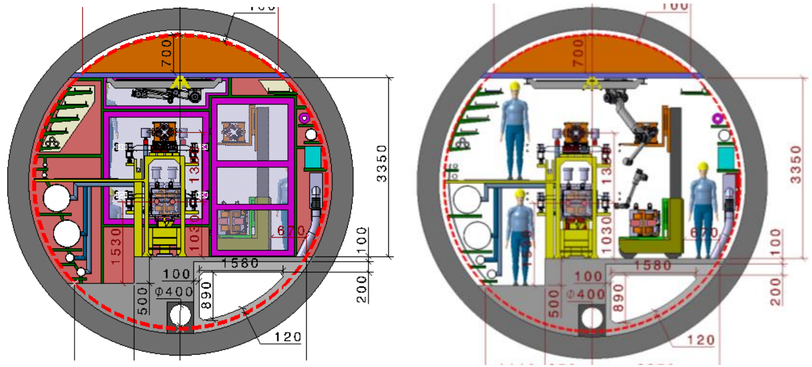
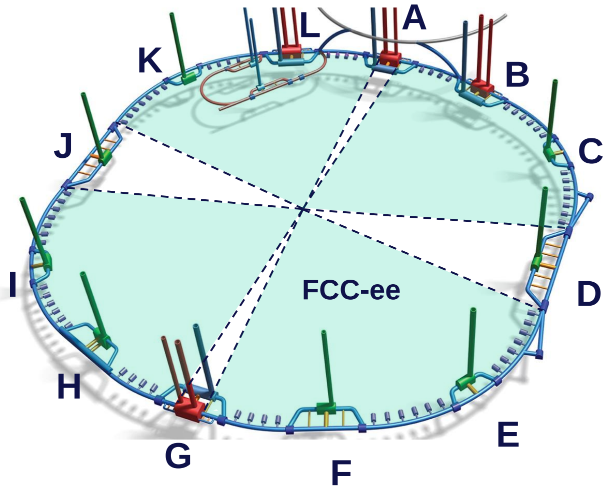
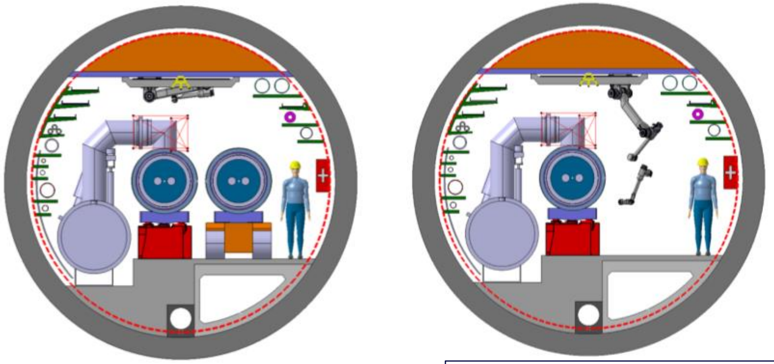
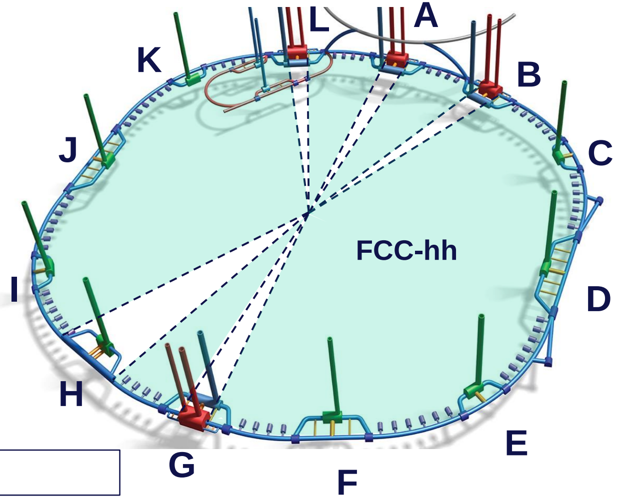
Regular Tunnel FCC-ee: covers ~93% of the complex





Regular Tunnel FCC-hh: covers ~95% of the complex





Fani Valchkova-Georgieva

Development Process

Initial Study
- Requirements
- Restrictions

↓

Integration & Logistics

↓

Design Optimization

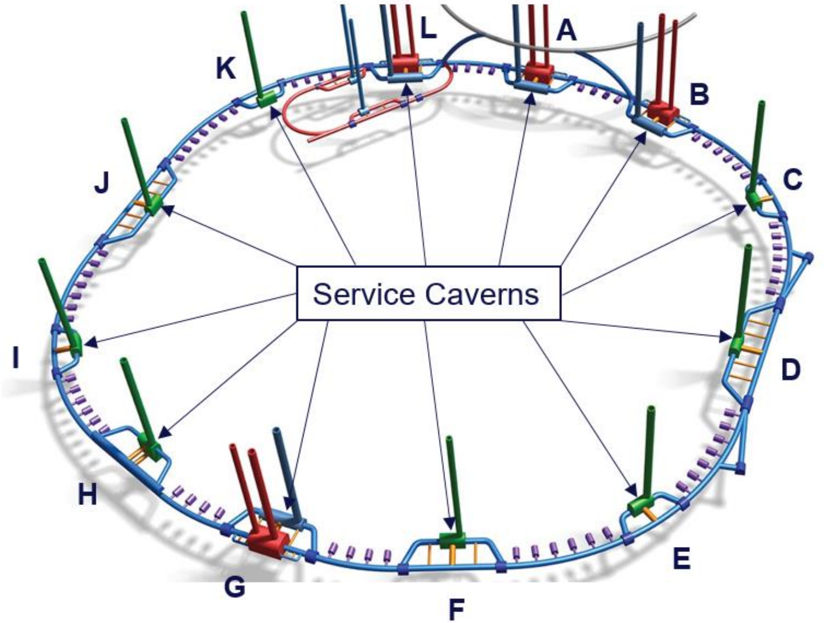
↓

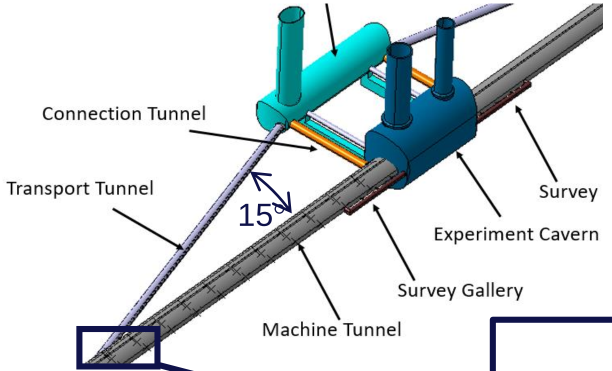
Control Concepts

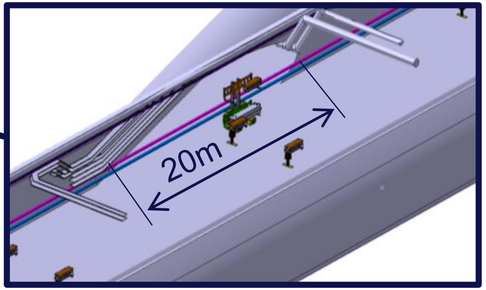
↓

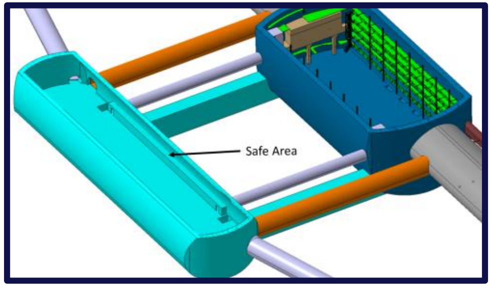
Prototype PoC

Parking in Service Caverns:
- Radiation Safe
- Accessible for Maintenance work
- Multiple Points Distributed along the ring









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Development Process

Initial Study
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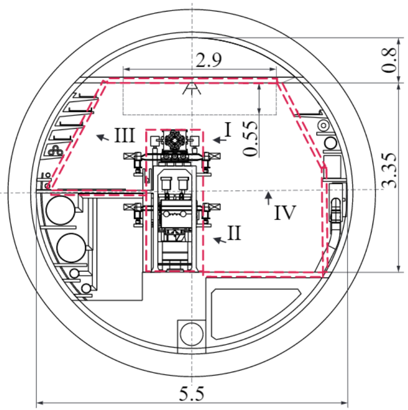
- Restrictions

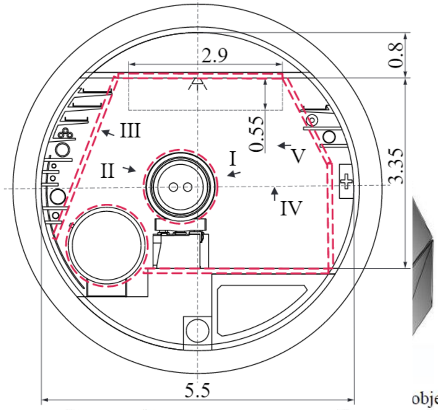
Integration & Logistics

Design Optimization

Control Concepts

Prototype PoC





Requirements:
- Reach points I-IV (workspace of 3.35x5.50x10^5m)
- Pack up in limited space (2.9x0.55m) while moving along tunnel axis
- Avoid Obstacles

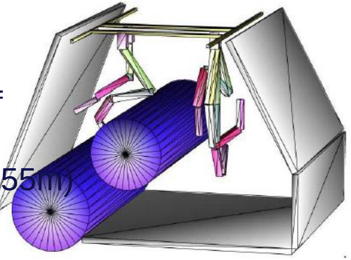


Figure 11: Optimization results FCC-hh (collision objects)

Gamper, H.; Gattringer, H.; Müller, A. and Di Castro, M. (2021). Design Optimization of a Manipulator for CERN's Future Circular Collider (FCC). In Proceedings of the 18th International Conference on Informatics in Control, Automation and Robotics, ISBN 978-989-758-522-7

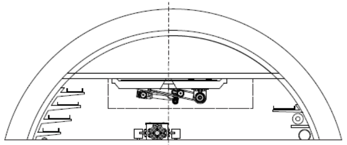


Figure 13: Prototype in FCC-ee - folded configuration

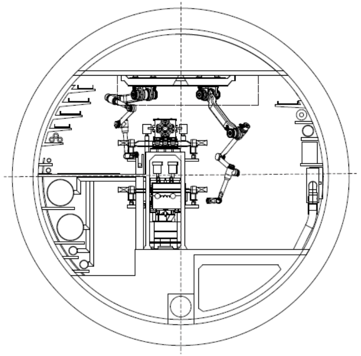


Figure 14: Prototype in FCC-ee cross-section

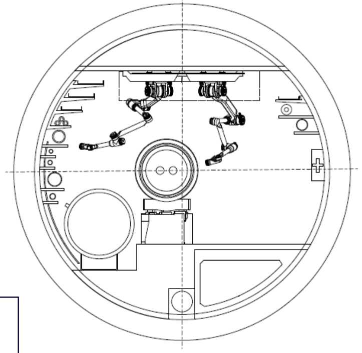


Figure 15: Prototype in FCC-hh cross-section

Development Process

Initial Study
- Requirements
- Restrictions

↓

Integration & Logistics

↓

Design Optimization

↓

Control Concepts

↓

Prototype PoC

Mechanical Design

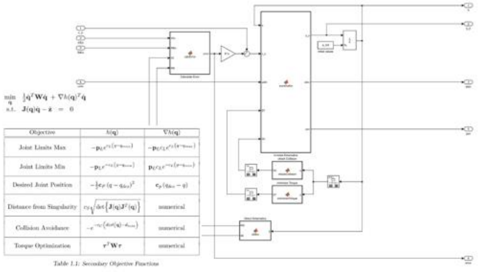
Update Topology & Parameters →

Analytic Description

Update Torque

Update EoM

Numerical Simulation



Deployment to CRF (C++ Framework) on Real-Time Linux Machines

Development Process

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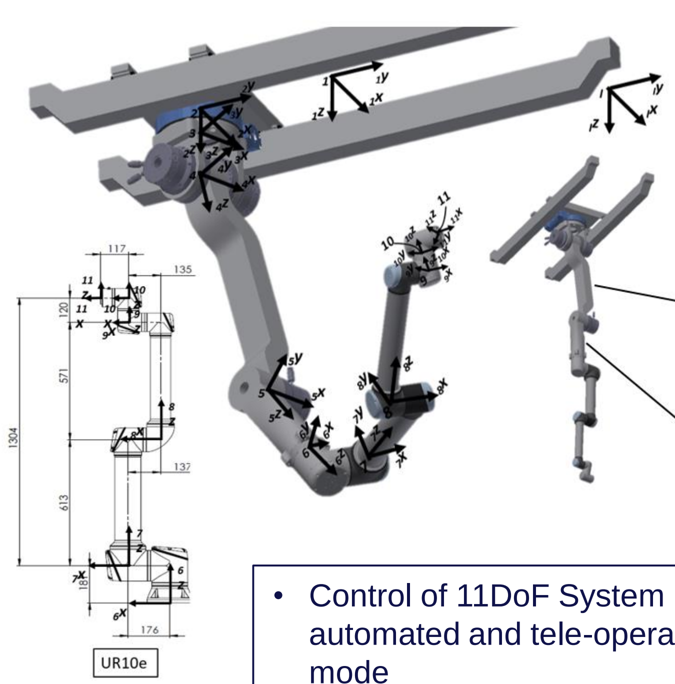
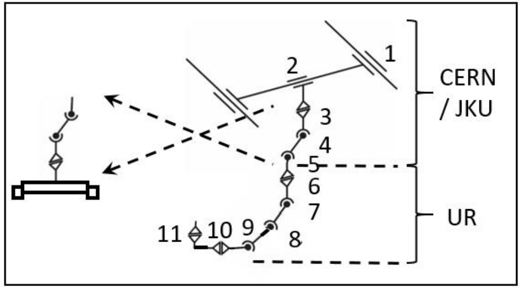
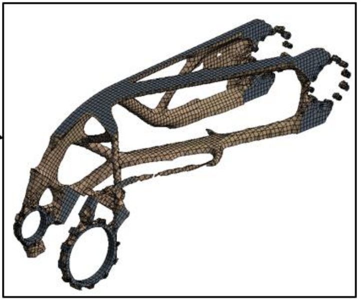
- **Prototype PoC**







- Control of 11DoF System in automated and tele-operated mode
- Proof of Concept for most critical tasks, based on experience from past and ongoing interventions

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Remote Maintenance – Code of Practice

- Experience from over 200 interventions and over 1000 tasks
- Following the Code of Practice increases efficiency of remote maintenance and dismantling tasks

- The Code of Practice includes mainly:

1. **Guidelines** for the Design Process of…
    - Equipment
    - Remote intervention procedures
    - Tool definitions

1. **Proposal** for common…
    - Interfaces
    - Connectors
    - Placement

=> Decrease downtime of FCC machine and maintenance costs

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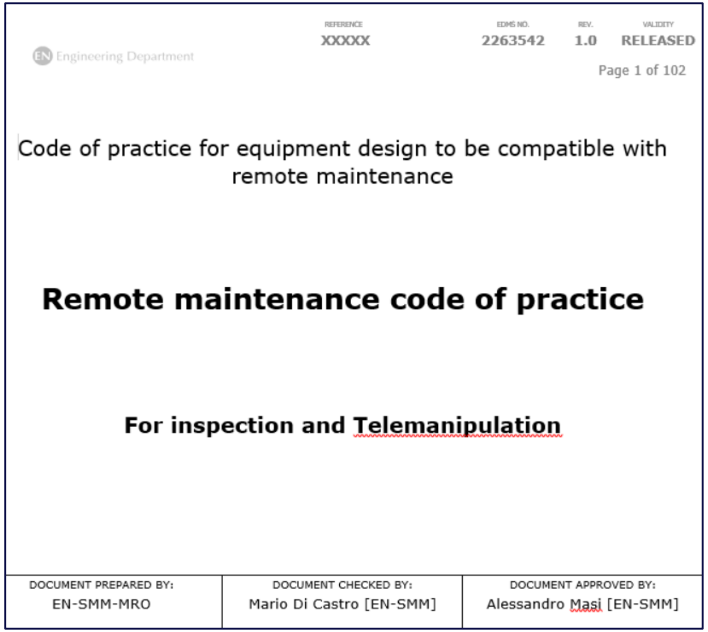
EN Engineering Department

REFERENCE	EDMS NO.	REV.	VALIDITY
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Code of practice for equipment design to be compatible with remote maintenance

Remote maintenance code of practice

For inspection and Telemanipulation

DOCUMENT PREPARED BY:	DOCUMENT CHECKED BY:	DOCUMENT APPROVED BY:
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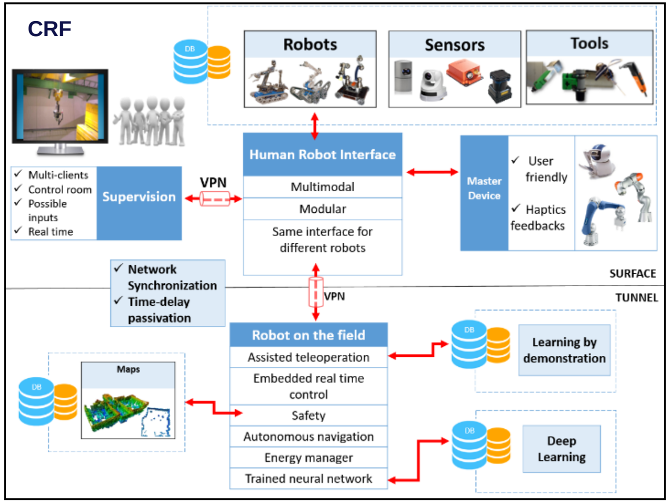
Mario Di Castro, Luca Rosario Buonocore, Sergio Di Giovannantonio,

Content

Collaborations

- Many Collaborations with Universities and external Companies
- Well defined interfaces in CRF for seamless integration
- Aim to be at top of technological standards by continuous exchange with partners all over the world



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Thank you
for your attention!