Hannes Gamper
BE-CEM-MRO



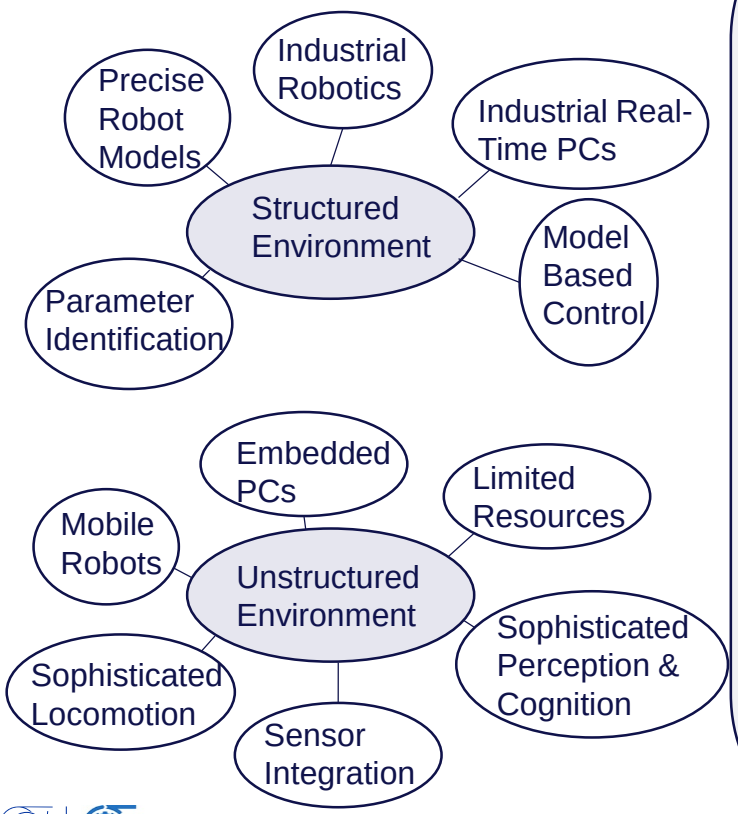
Controls Electronics & Mechatronics

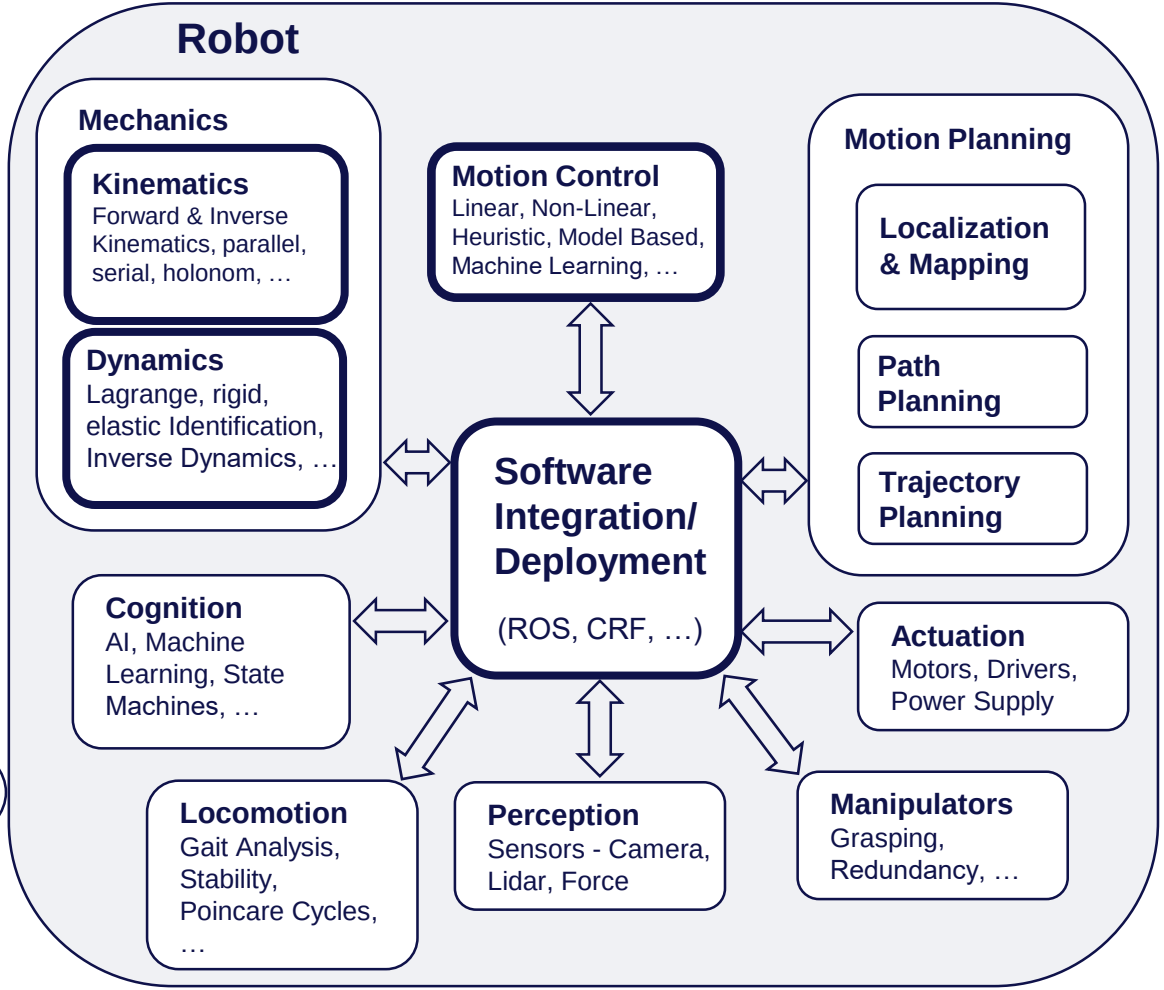
# BE SEMINAR

## ROBOTICS AT CERN – A SYSTEM FOR REMOTE INTERVENTIONS IN THE FCC COMPLEX

# Content

# What is Robotics?



# What is Robotics?

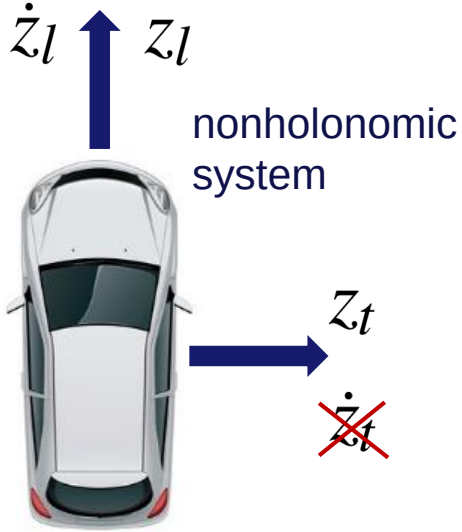
- Example 1: The equation of motion

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

$$L = T - V$$

$$\cancel{\frac{d}{dt}\frac{\partial L}{\partial \dot{\mathbf{q}}} - \frac{\partial L}{\partial \mathbf{q}} + \frac{\partial R}{\partial \dot{\mathbf{q}}} = \mathbf{Q}}$$

$$\cancel{\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{g}(\mathbf{q}, \dot{\mathbf{q}}) = \mathbf{Q}}$$




mechanical solution

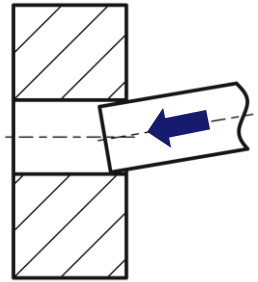
RP measurements on old LHC TDE w/ CERNbot

# What is Robotics? (Ex. 2)

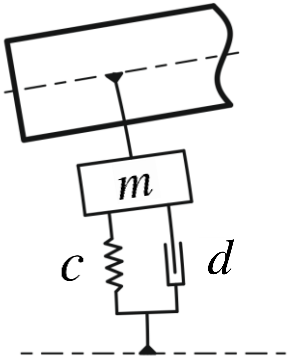
- Example 2: Compliant Control


TIM Handling Radioactive Source for BLM Tests

Problem:



Solution:



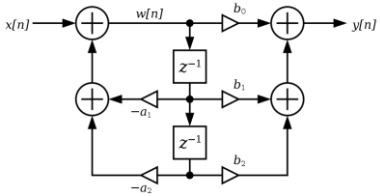

1. Mass spring damper system

$$\mathbf{M}\ddot{\mathbf{x}} = \mathbf{h} - \mathbf{C}\mathbf{x} - \mathbf{D}\dot{\mathbf{x}}$$

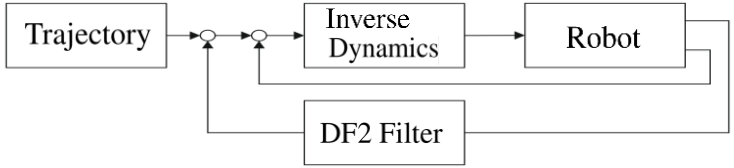
2. Discrete Frequency domain

$$\mathbf{G}(z) = \frac{\mathbf{b}_0}{\mathbf{1} + \mathbf{a}_1 z^{-1} + \mathbf{a}_2 z^{-2}}$$

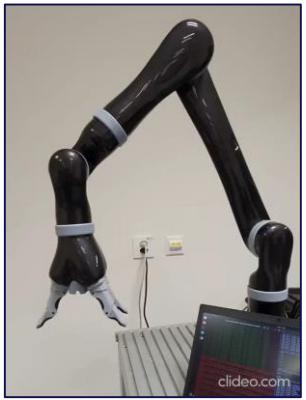
3. Implementation in C++ Framework in Direct Form II




4. Controller




Low Damping:




High Damping:

# What is Robotics?

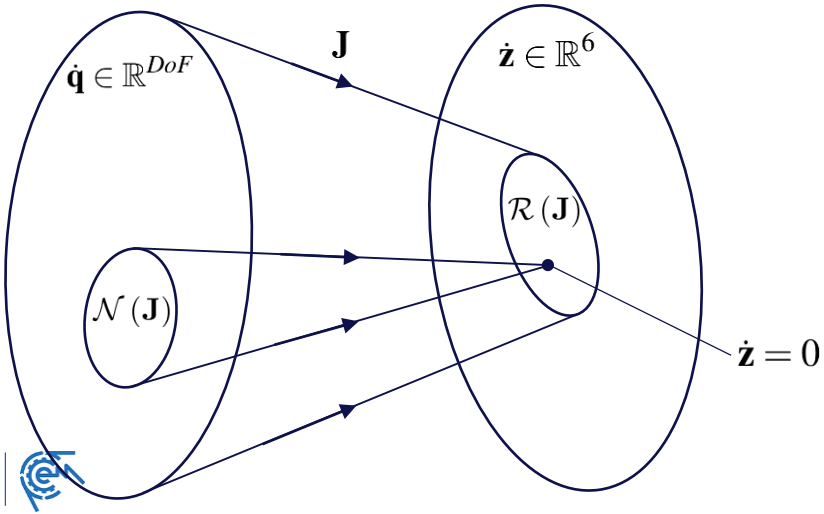
- Example 3: Inverse Kinematics

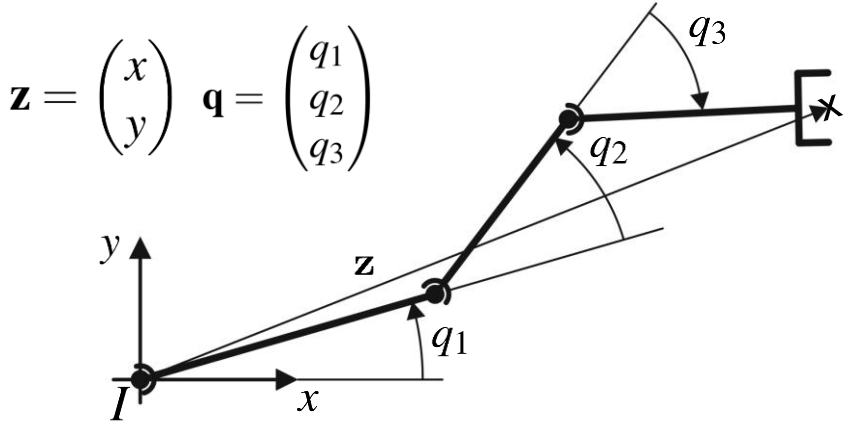
$$\mathbf{z} = \mathbf{f}(\mathbf{q})$$

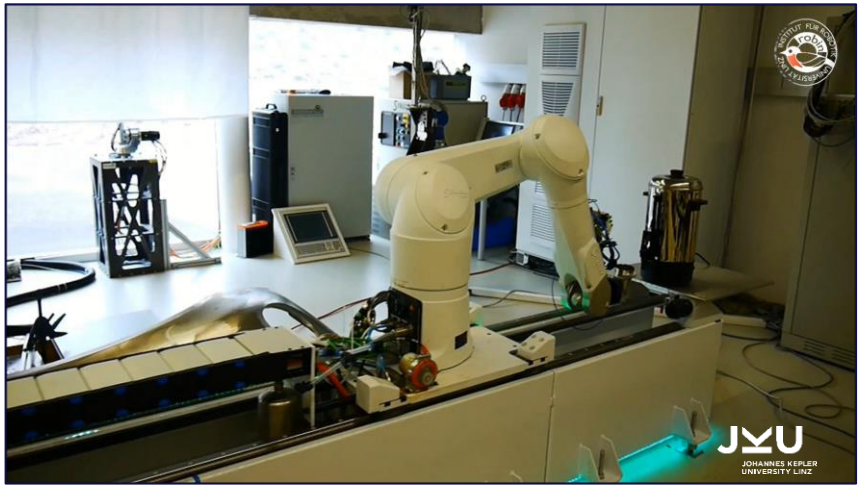
$$\dot{\mathbf{z}} = \frac{\partial \mathbf{f}(\mathbf{q})}{\partial \mathbf{q}} \frac{\partial \mathbf{q}}{\partial t} = \mathbf{J}(\mathbf{q})\dot{\mathbf{q}}$$

Jacobian

$$\dot{\mathbf{q}} = \mathbf{J}(\mathbf{q})^{-1}\dot{\mathbf{z}}$$



# What is Robotics?

M. Di Castro, M. Ferre and A. Masi, "CERNTAURO: A Modular Architecture for Robotic Inspection and Telemanipulation in Harsh and Semi-Structured Environments," in IEEE Access, vol. 6, pp. 37506-37522, 2018

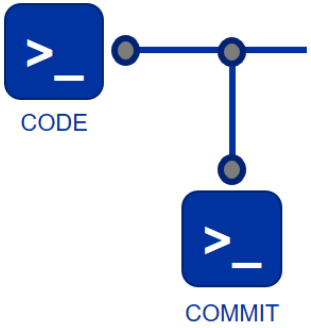
## Example 4: The CERN Robotic Framework - CRF

**C++**

C++17 support with GCC9
Compiler & Build Tools: GCC9 & CMake
Unit Testing: Google Test
Code Style: Google Style

**Python**

Python 3
Unit Test: Pytest
Code Style: Pylint




Alejandro Diaz Rosales, Mario Di Castro (CEM Tech. Meetings - https://indico.cern.ch/event/1087057/ )

# Content

# Robotics in Big Science Facilities - State of the Art

## Universal Systems

Figure 2 RESQ-A

Figure 4 RESQ-C

Figure 19 TALON equipped with rad-mapping system ©TEPCO

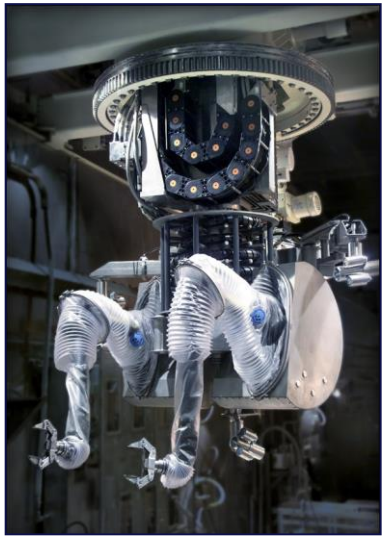
Figure 24 Warrior ©TEPCO

Figure 22 BROKK 90 ©TEPCO

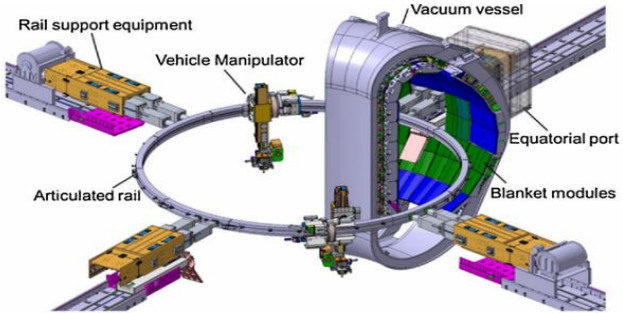
## Task Specific Systems

JET – Primary (RACE)

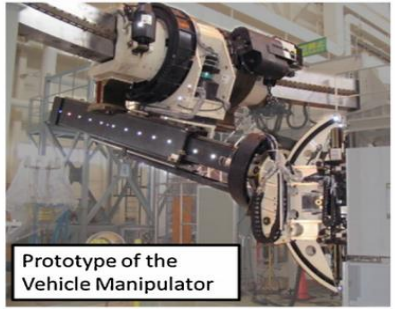
JET – Secondary (RACE)



Spallation Neutron Source Target – Oakland National Laboratory




ITER – RACE



# Robotics in Big Science Facilities – Robotics at CERN

Telemax robot

EXTRM robot with single arm (CERN made)

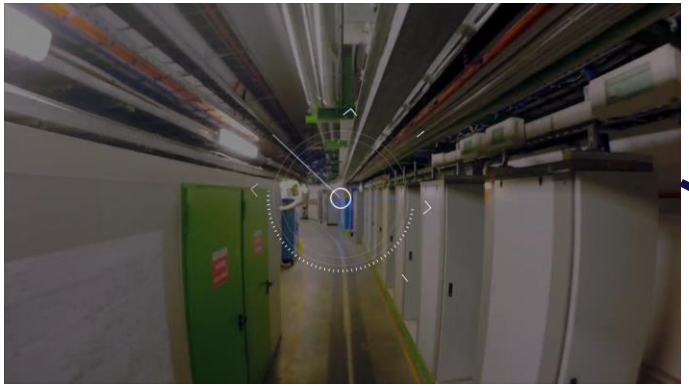
The TIM (CERN made)

CRANEbot (CERN made)

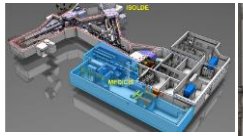

EXTRM robot (CERN made)

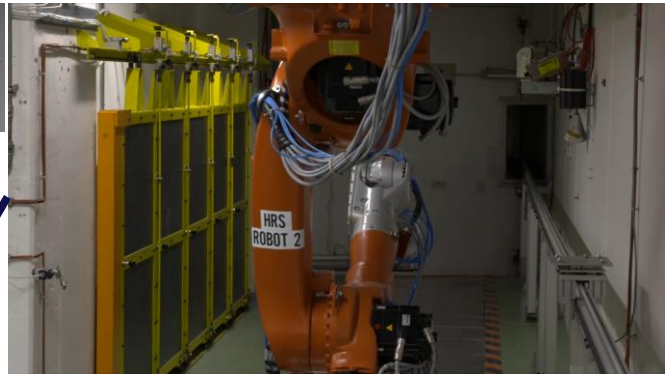
CERNbot (CERN made)

# Robotics in Big Science Facilities – Robotics at CERN



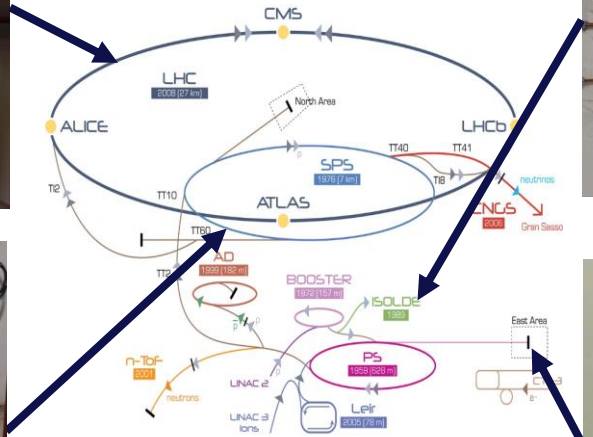
TIM (x5)






Kuka Robots (x3)

MIRA - CERNbot



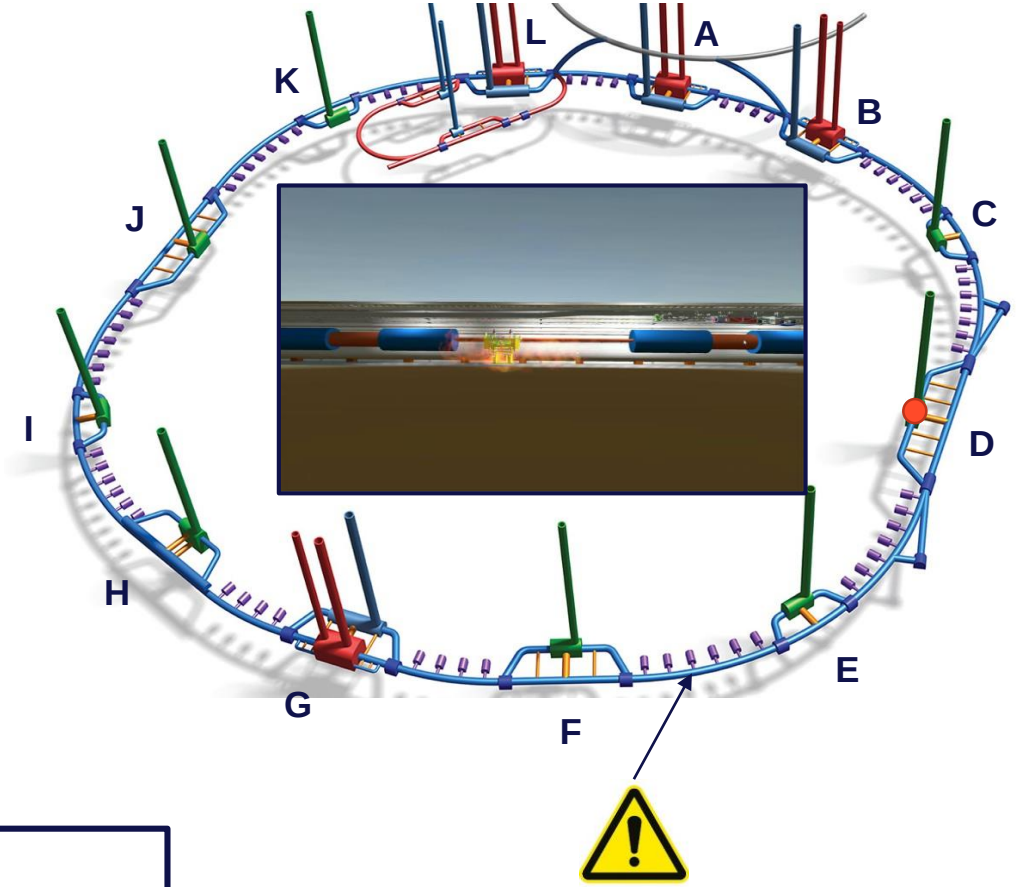

BE-CEM-MRO

CHARMbot

# Content

# The Vision

- Conduct all planned repetitive interventions fully autonomously
- Move fully autonomous to a Point of Interest
- Operator can take over to inspect/repair at any time
- Carry Different Tools
- At 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

# Content

# Development Process

Initial Study
- Requirements
- Restrictions

↓

Integration & Logistics

↓

Design Optimization

↓

Control Concepts

↓

Prototype PoC

| | Task | | | | | | | Derived Requirements | |
|---|---|---|---|---|---|---|---|---|---|
| | Nr | Name | Description | | | | | | |
| | | | When | | | How | Why | | |
| | | | Repetitive | Periodic | T | | | 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!<br>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;<br><br>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
- Integration & Logistics
- Design Optimization
- Control Concepts
- Prototype PoC

| 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

Initial Study
- Requirements
- Restrictions

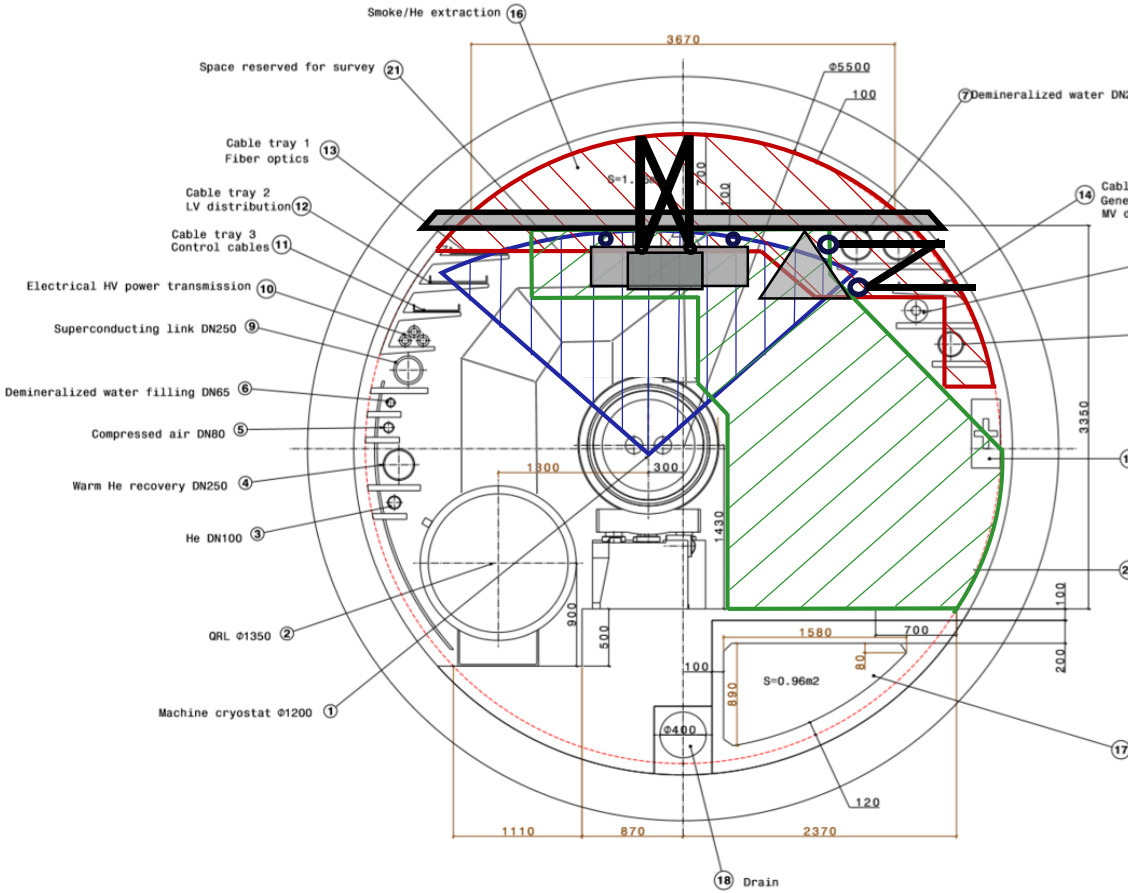
Integration & Logistics

Design Optimization

Control Concepts

Prototype PoC

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



# Development Process

Initial Study
- Requirements
- Restrictions

↓

Integration & Logistics

↓

Design Optimization

↓

Control Concepts

↓

Prototype PoC

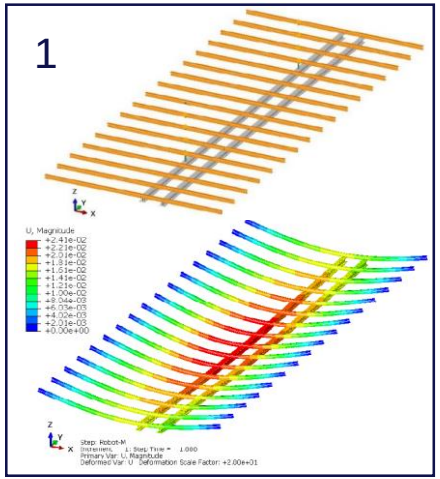
**Version 1**: Original ceiling support structure

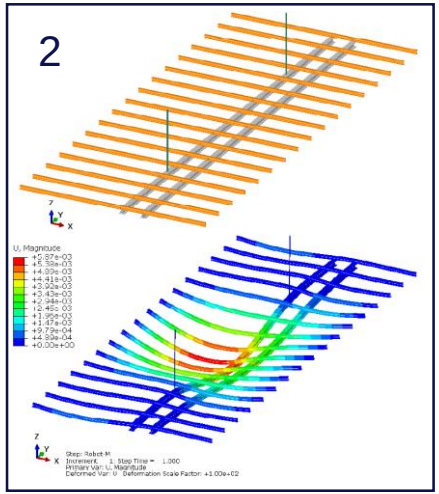
**Version 2**: Hangers to tunnel wall every 5m

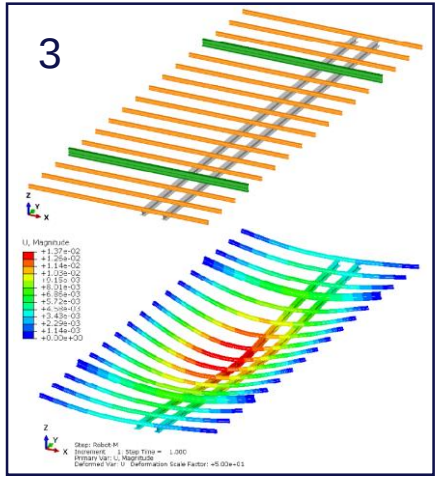
**Version 3**: Stronger main beam every 5m

Dynamic Simulations not done yet!

| Part | Mass [kg] |
|---|---|
| Links, motors 6-11 | 34 |
| 2 x link | 20 |
| 4 x motor 3-5 | 50 |
| Linear link | 80 |
| 2 x linear motor | 30 |
| Control, electronics, cable | 30 |
| Payload | 15 |
| Tools | 0 ... 30 |
| ESTIMATED TOTAL | 259 ... 289 |




Alexandra Tudora, ILF

# Development Process

Initial Study
- Requirements
- Restrictions

↓

Integration & Logistics

↓

Design Optimization

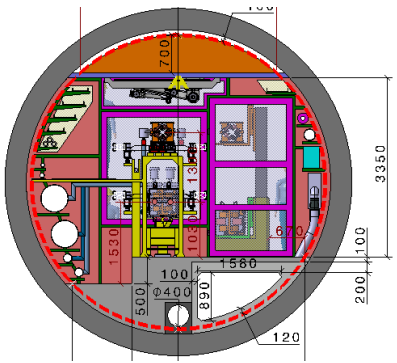
↓

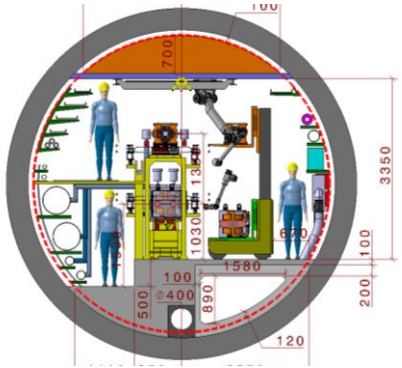
Control Concepts

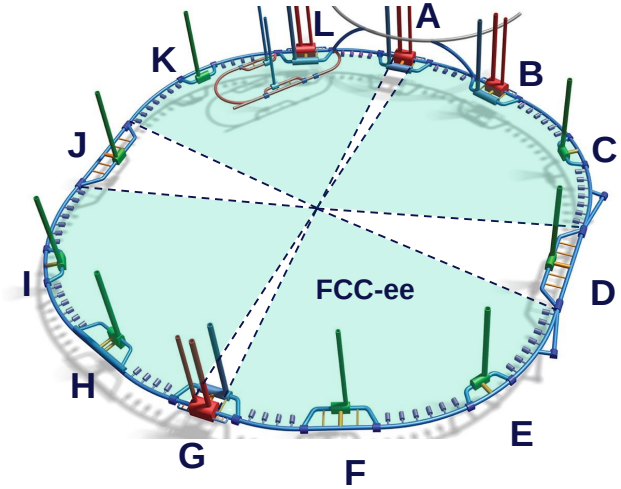
↓

Prototype PoC

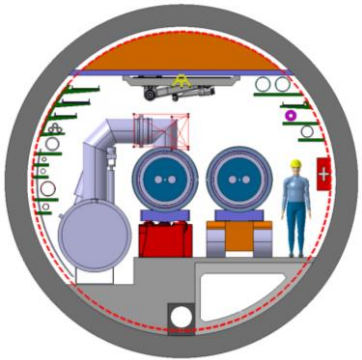
Regular Tunnel FCC-ee: covers ~93% of the complex

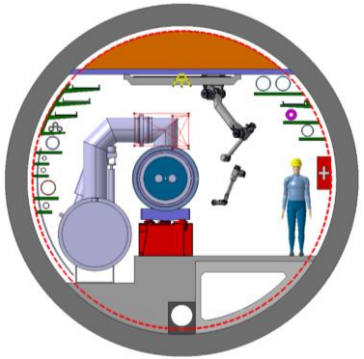


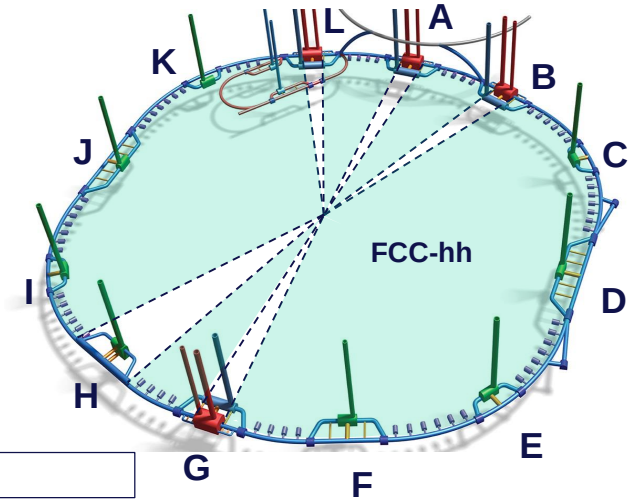




Regular Tunnel FCC-hh: covers ~95% of the complex








Fani Valchkova-Georgieva

# Development Process

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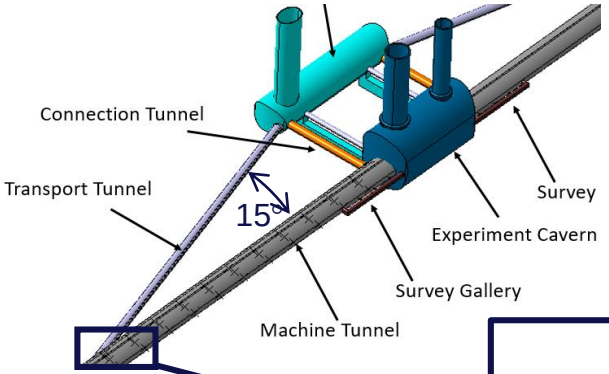
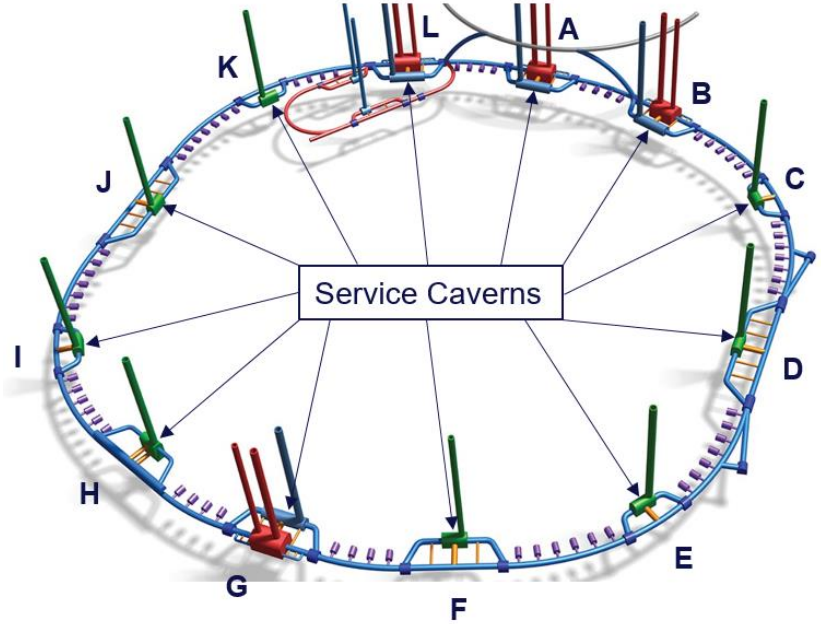
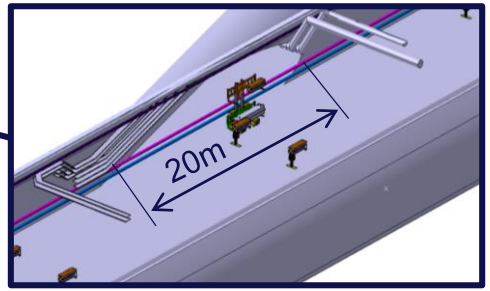
Control Concepts

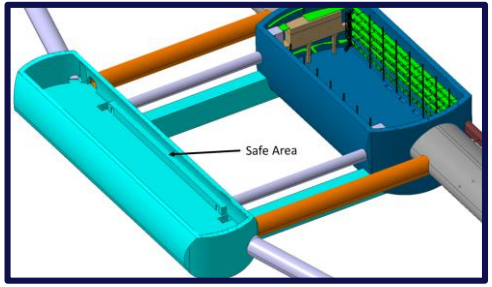
Prototype PoC

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




Fani Valchkova-Georgieva

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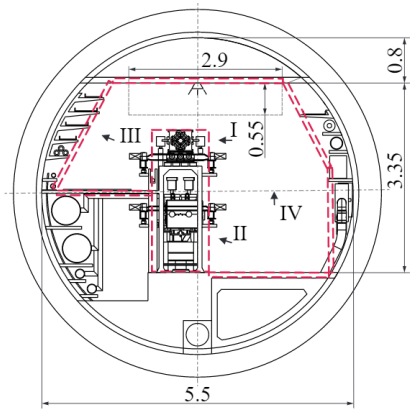
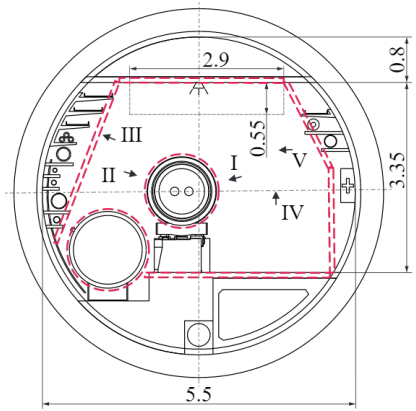
- Prototype PoC




Requirements:

- Space:
  - 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
- Mass:
  - Min. payload (~15kg)
  - Max. robot weight (~300kg)

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

# Development Process

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

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

$$
J(\mathbf{x},\,\mathbf{p}_l) = \underbrace{\mathbf{Q}^T(\mathbf{x},\,\mathbf{p}_l)\mathbf{K}_Q\mathbf{Q}(\mathbf{x},\,\mathbf{p}_l)}_{J_1} + \underbrace{\mathbf{k}_p^T \arctan(\mathbf{p}_l)}_{J_2} + \underbrace{\mathbf{k}_w^T \mathbf{w}(\mathbf{x},\,\mathbf{p}_l)}_{J_3}
$$

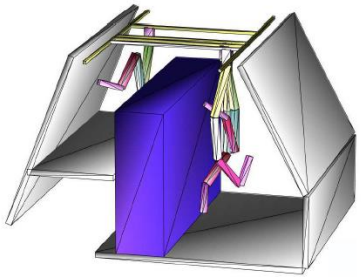


Figure 10: Optimization results FCC-ee (collision objects)

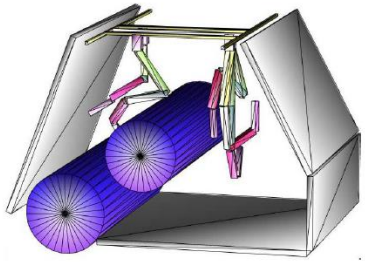


Figure 11: Optimization results FCC-hh (collision objects)

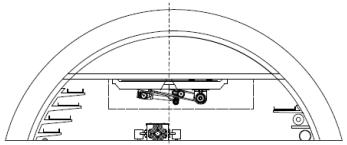


Figure 13: Prototype in FCC-ee - folded configuration

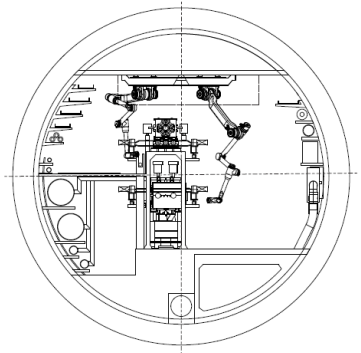


Figure 14: Prototype in FCC-ee cross-section

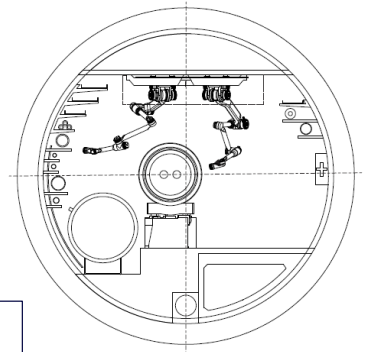


Figure 15: Prototype in FCC-hh cross-section

<u>Optimal Solution:</u>

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

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

# Development Process

Initial Study
- Requirements
- Restrictions

↓

Integration & Logistics

↓

**Design Optimization**

↓

Control Concepts

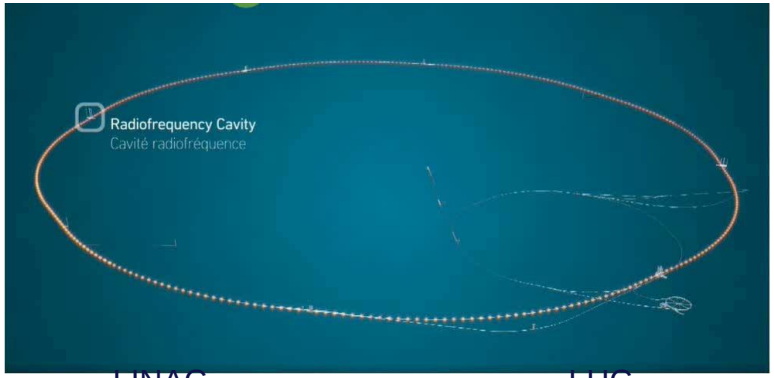
↓

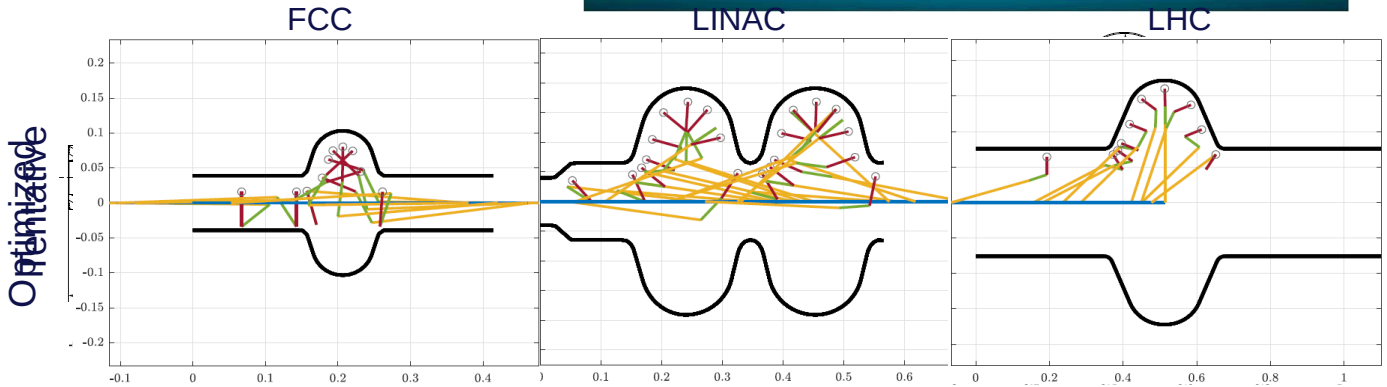
Prototype PoC

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

## Off topic: Cavity Design Optimization

- Visual inspection of inner surface after assembly
- Small allowed robot space
- Big workspace for inspection
- No restrictions on robot design (topology, geometry)



# Development Process

Initial Study
- Requirements
- Restrictions

↓

Integration & Logistics

↓

**Design Optimization**

↓

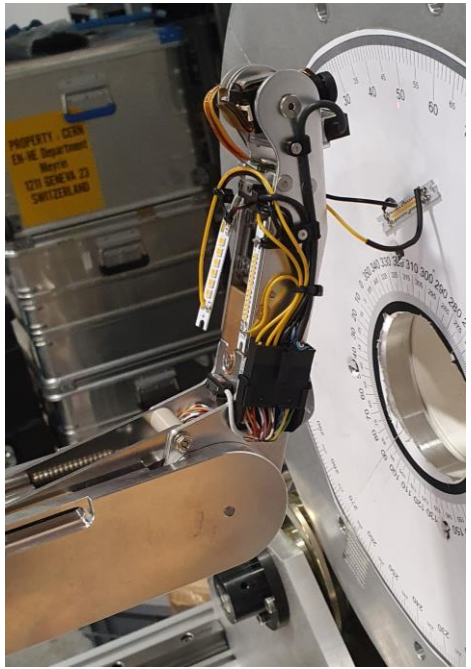
Control Concepts

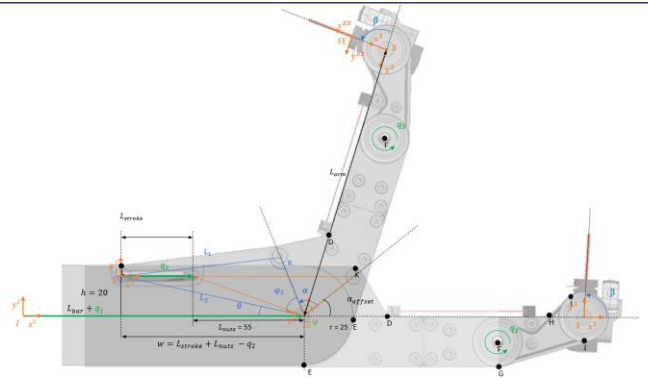
↓

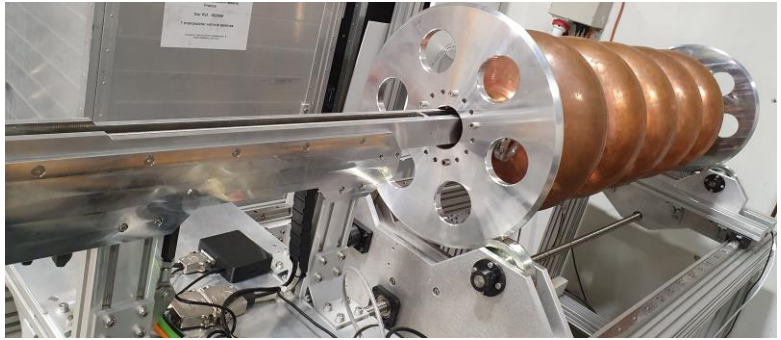
Prototype PoC

## Off topic: Cavity Design Optimization

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







# Development Process

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

## Mechanical Design

Update Topology & Parameters

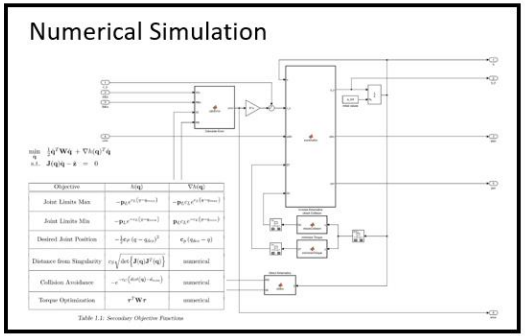
## Analytic Description

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

Update EoM

Update Torque

## Numerical Simulation



$$\min_{\mathbf{q}} \quad \frac{1}{2}\mathbf{q}^T\mathbf{W}\dot{\mathbf{q}} + \nabla h(\mathbf{q})^T\mathbf{q}$$
$$\text{s.t.} \quad \mathbf{J}(\mathbf{q})\mathbf{q} - \dot{\mathbf{x}} = 0$$

| Objective | $h(\mathbf{q})$ | $\nabla h(\mathbf{q})$ |
|---|---|---|
| Joint Limits Max | $-\mathbf{p}_L e^{c_L(\mathbf{q}-\mathbf{q}_{max})}$ | $-\mathbf{p}_L c_L e^{c_L(\mathbf{q}-\mathbf{q}_{max})}$ |
| Joint Limits Min | $-\mathbf{p}_L e^{-c_L(\mathbf{q}-\mathbf{q}_{min})}$ | $\mathbf{p}_L c_L e^{-c_L(\mathbf{q}-\mathbf{q}_{min})}$ |
| Desired Joint Position | $-\frac{1}{2}\mathbf{e}_P(\mathbf{q}-\mathbf{q}_{des})^2$ | $\mathbf{e}_P(\mathbf{q}_{des}-\mathbf{q})$ |
| Distance from Singularity | $c_{SI}\left(\det\left[\mathbf{J}(\mathbf{q})\mathbf{J}^T(\mathbf{q})\right]\right)$ | numerical |
| Collision Avoidance | $-e^{-c_C(\mathbf{d}(\mathbf{q})-\mathbf{d}_{min})}$ | numerical |
| Torque Optimization | $\mathbf{r}^T\mathbf{W}\mathbf{r}$ | numerical |

*Table 1.1: Secondary Objective Functions*

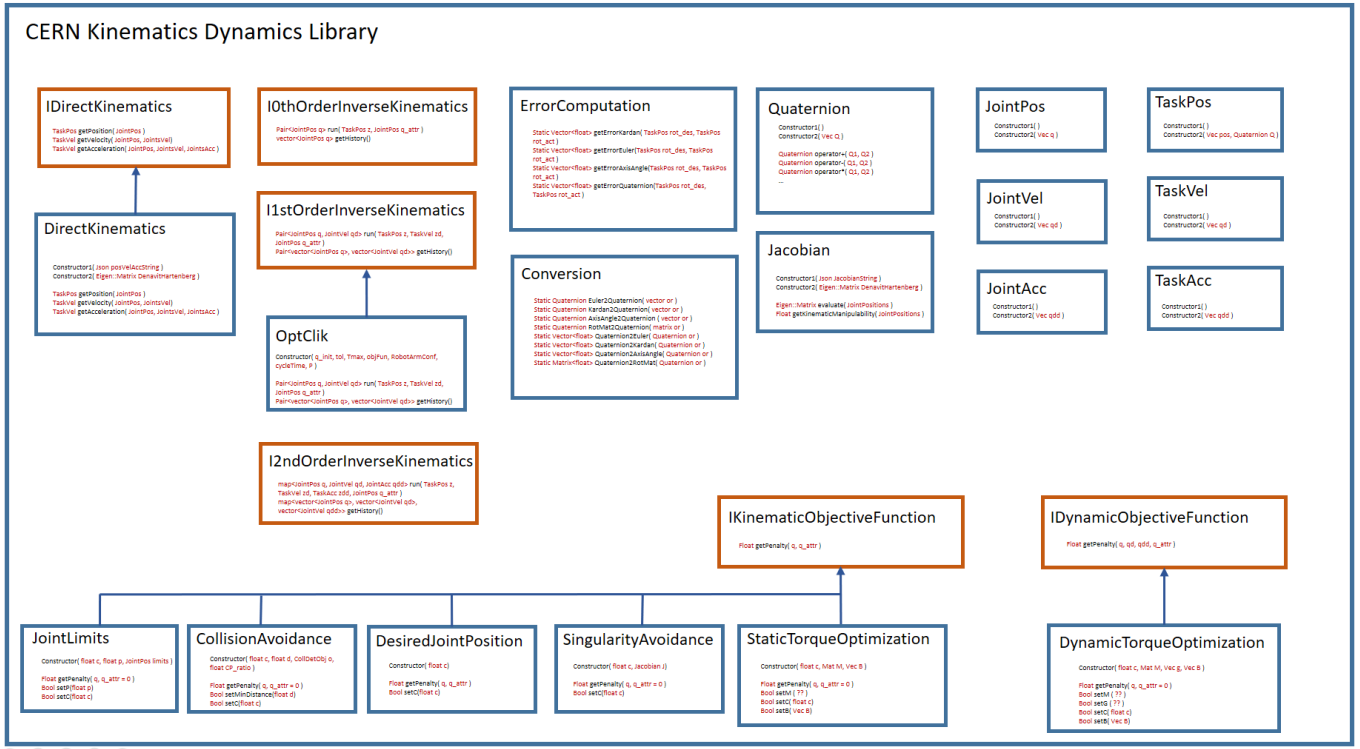
Deployment to CRF (C++ Framework) on Real-Time Linux Machines

- CERN Kinematics Library in C++
- IK for highly redundant systems

# Development Process

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

- CERN Kinematics Library in C++ (IK for highly redundant systems)




Alejandro Diaz Rosales, Laura Rodrigo Perez

# Development Process

- Initial Study
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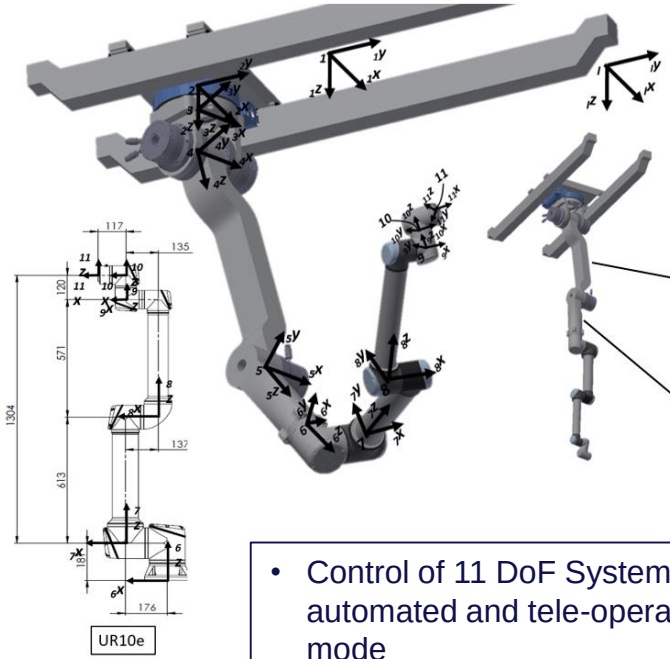


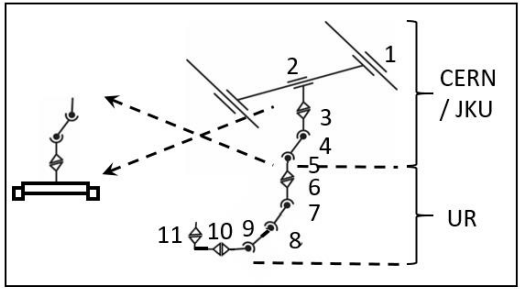


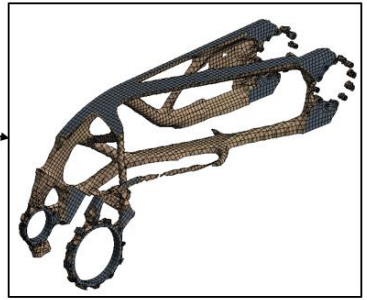

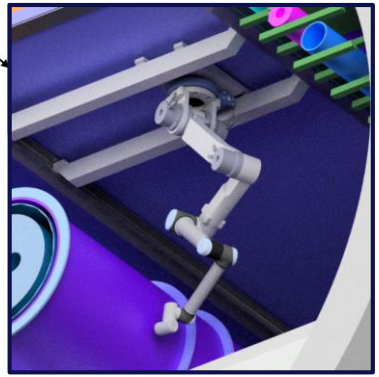

- Control of 11 DoF System in automated and tele-operated mode
- Proof of Concept for most critical tasks, based on experience from past and ongoing interventions

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# Content

# Remote Maintenance – Code of Practice

EDMS Nr. 2263542

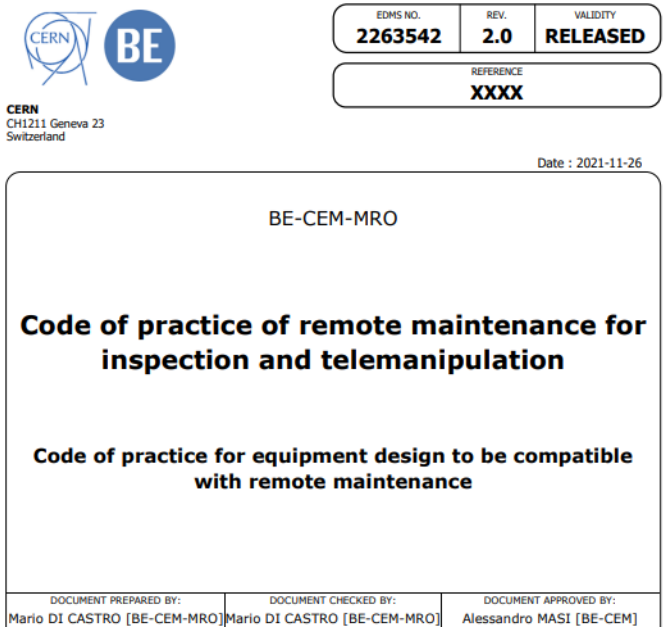
- Experience from over 200 interventions and over 1000 tasks
- Following the Code of Practice increases efficiency of remote maintenance and dismantling tasks

- The Code of Practice includes mainly:

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

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

**=> Decrease downtime of FCC machine and maintenance costs**



CERN
CH1211 Geneva 23
Switzerland

| EDMS NO. | REV. | VALIDITY |
|---|---|---|
| 2263542 | 2.0 | RELEASED |

REFERENCE
XXXX

Date : 2021-11-26

BE-CEM-MRO

**Code of practice of remote maintenance for inspection and telemanipulation**

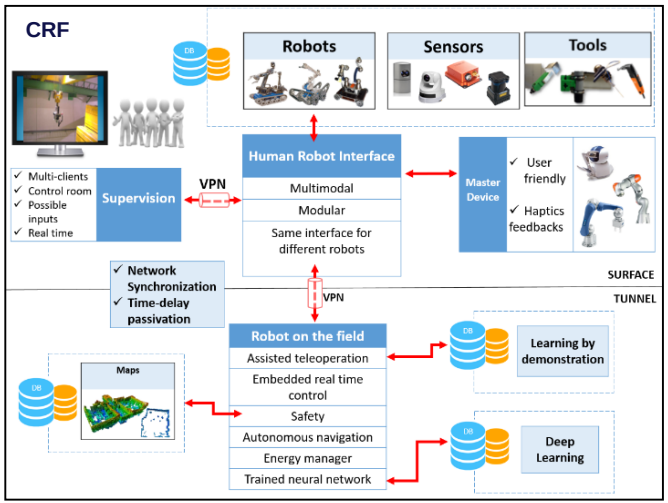
**Code of practice for equipment design to be compatible with remote maintenance**

| DOCUMENT PREPARED BY: | DOCUMENT CHECKED BY: | DOCUMENT APPROVED BY: |
|---|---|---|
| Mario DI CASTRO [BE-CEM-MRO] | Mario DI CASTRO [BE-CEM-MRO] | Alessandro MASI [BE-CEM] |

# 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
- Commitment from University for future R&D concerning the FCC prototype.

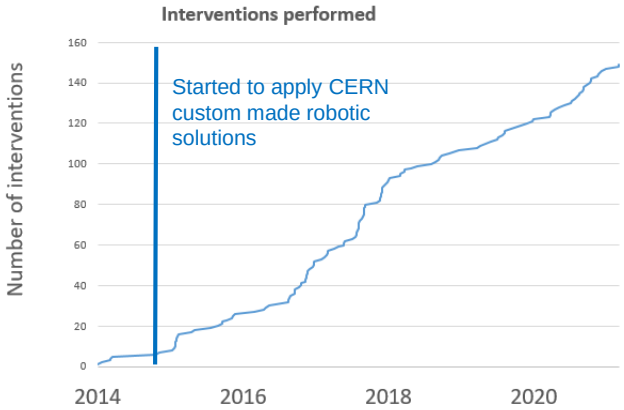



Contact: hannes.gamper@cern.ch

Mario Di Castro

# Conclusions

- Installation, maintenance and dismantling tasks must be taken into account at design phase
- Remote maintenance systems integrated within accelerator will increase maintainability and availability of machines
- Ready-to-use industrial solutions are often not available for the specific requirements in CERN facilities
- The proposed remote maintenance approach for FCC can be adapted to other accelerators and experimental zones



Controls Electronics & Mechatronics

BEAMS

# Thank you for your attention!