FUTURE
CIRCULAR
COLLIDER

Controls Electronics & Mechatronics

THE FCC ROBOTIC SYSTEM FOR SAFETY AND AVAILABILITY

Acknowledgements: O. Rios, T. Otto, G. Roy, R. Losito, M. Nas, F. Valchkova-Georgieva

Content

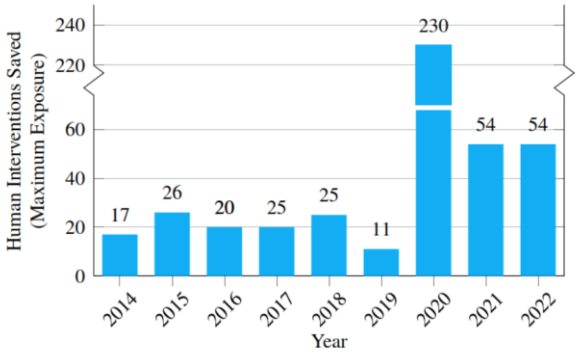
Acronyms

FCCRS … FCC Robotic System
RMIS … Remote Maintenance & Inspection System
SES … Surveyance & Emergency Shuttle
CRF … CERN Robotic Framework

Review – Robotic Service at CERN

Main Objectives of the current Robotic Service:

1. Increase **Operational Safety** by …
   - Protecting workers from dangerous interventions
2. Increase **Availability** by …
   - Corrective & preventive maintenance increasing maintainability



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

- Availability has two components: Reliability & Maintainability
- @ const. machine reliability, maintainability drives availability

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

M. Di Castro, FCC Week 23: https://indico.cern.ch/category/9071/

Review – Robotic Service at CERN

- Infrastructure not designed to host robotics
- Need to adapt robots to environment
- Highly versatile systems / relatively low efficiency

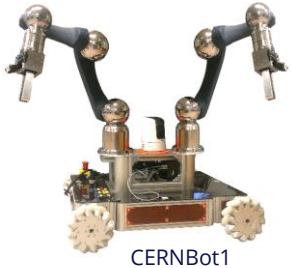

Unitree Go1


Train Inspection Monorail - TIM


Telerob Teodor

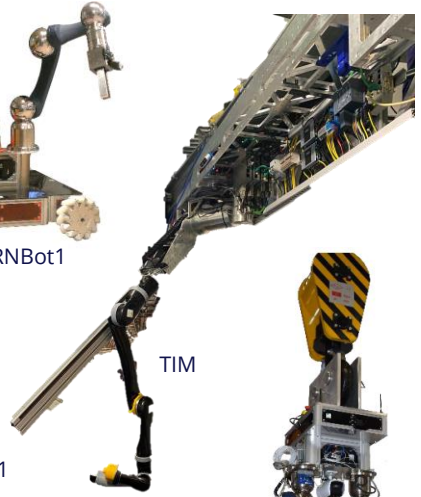

CERNBot1


Telemax

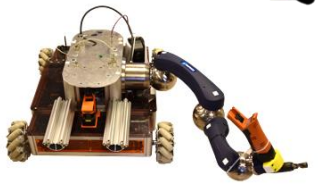

CERNBot1


Teodor


Unitree Go1


TIM

CERNBotCrane




Flyability Elios


CERNBot1


CERNBotSPS


CERNBot2

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

Review – Robotic Application Categories

Universal Systems


Tesla Optimus


Flyability Elios

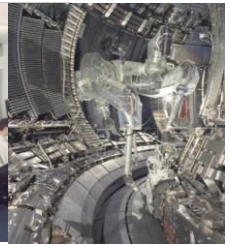

Telerob Telemax


Unitree Go1

Task Specific Systems

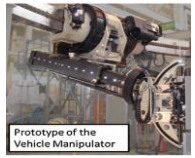

SNS – Oakland National Laboratory


JET – Primary (RACE)


JET – Secondary (RACE)


CERN - TIM

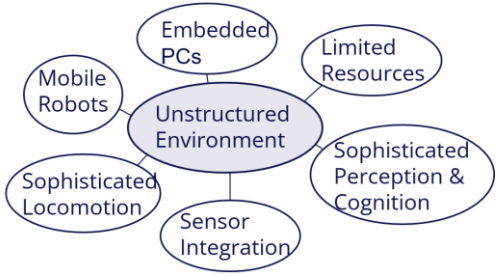

ISS – Canada Arm



ITER – RACE

Industrial Automation S.

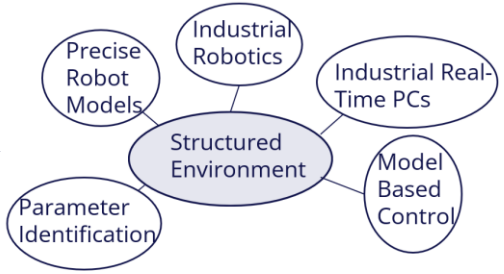

KUKA W8 center



High Versatility / Low Efficiency

LHC
SPS
NA
...

FCC

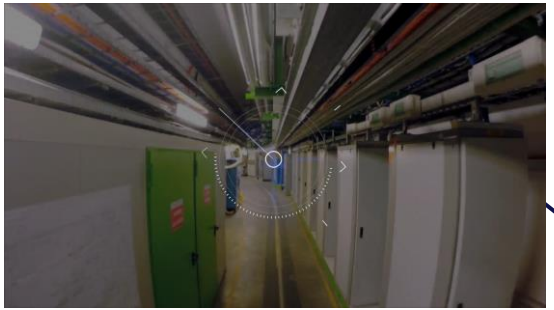


Low Versatility / High Efficiency

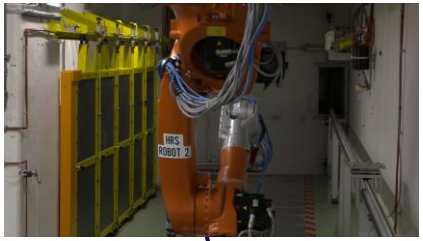
Review – Robotic Service at CERN

M. Di Castro Robotic solutions for the remote inspection and maintenance of particle accelerators https://indico.jacow.org/event/41/contributions/792/

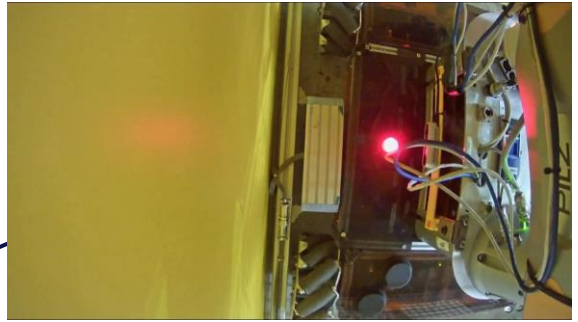
- Efforts to increase robotic efficiency in the current facilities by adapting the environment:



4x TIM operated by TI

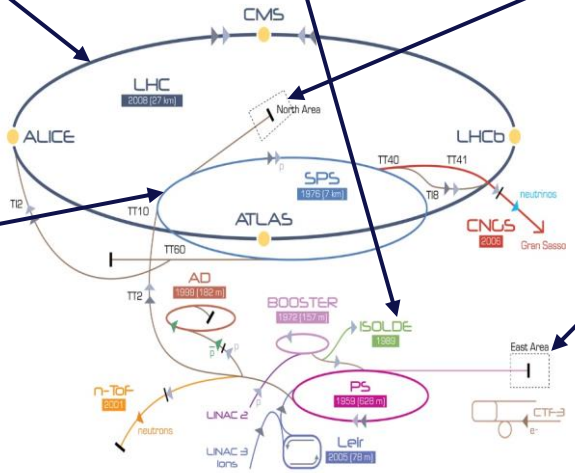


3x Kuka Robots in ISOLDE-Medicis



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

2x SPS robot



CHARM robot

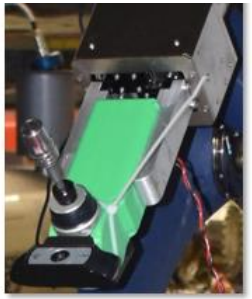
Review – Robotic Service at CERN

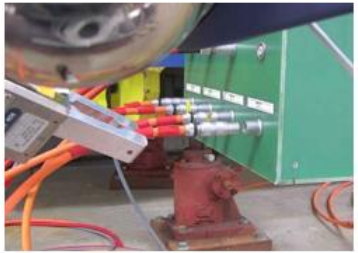
M. Di Castro Robotic solutions for the remote inspection and maintenance of particle accelerators https://indico.jacow.org/event/41/contributions/792/

- **Large Variety of tools and procedures designed to cope with non standardized machine interfaces**
- Standardization of interfaces and intervention procedures, reduce costs and intervention time
- For increased efficiency, infrastructure must be compliant with **automation**







Content

Acronyms

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RMIS … Remote Maintenance & Inspection System
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The FCC Robotic System (FCCRS) - Objectives

[1] J. Heron, et al. - Machine Protection and Availability in the FCC-ee-CERN-ACC-NOTE-2023-0019
FCC Week 2024 Presentation: https://indi.to/LmRvX

Review Study

FCCRS

Integration

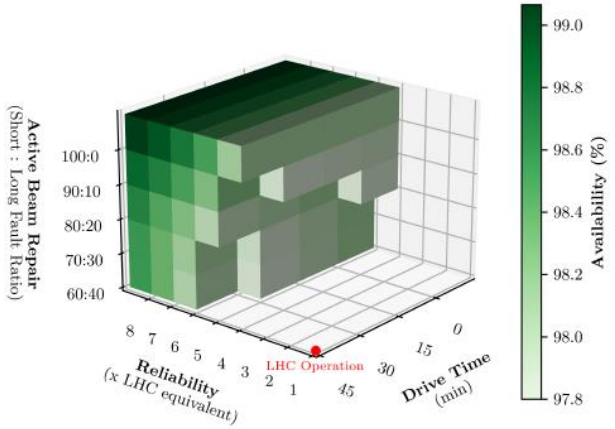
1. Operational Safety

- Protect workers from dangerous interventions (radiation exposure, …)

2. Availability

- Corrective & preventive maintenance increasing maintainability
- Predictive maintenance increasing reliability

Reliability	Maintainability	Availability
Increase ⬆	Increase ⬆	Increase ⬆⬆

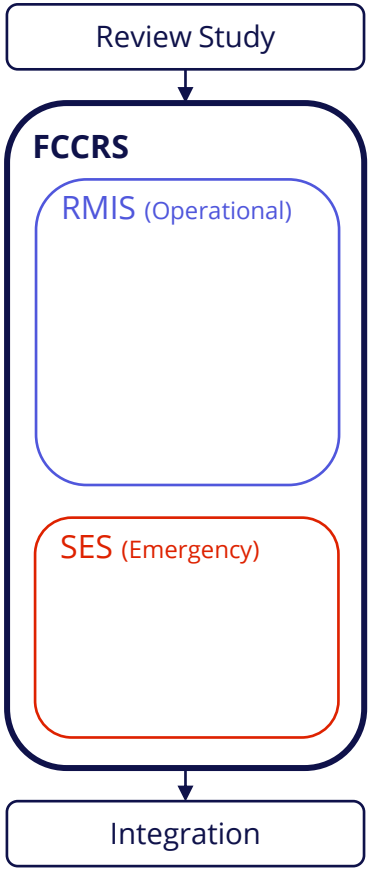


FCC Week 23 talk by J. Heron: https://indi.to/3TndY

- Machine Availability >= 80%[1]
- => 15-fold increase of mean time between failures of critical infrastructure
- Remote maintenance allows to relax this requirement by factor 3

FCC Week 2024 Presentation J. Heron: https://indi.to/LmRvX

The FCC Robotic System (FCCRS) - Objectives



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

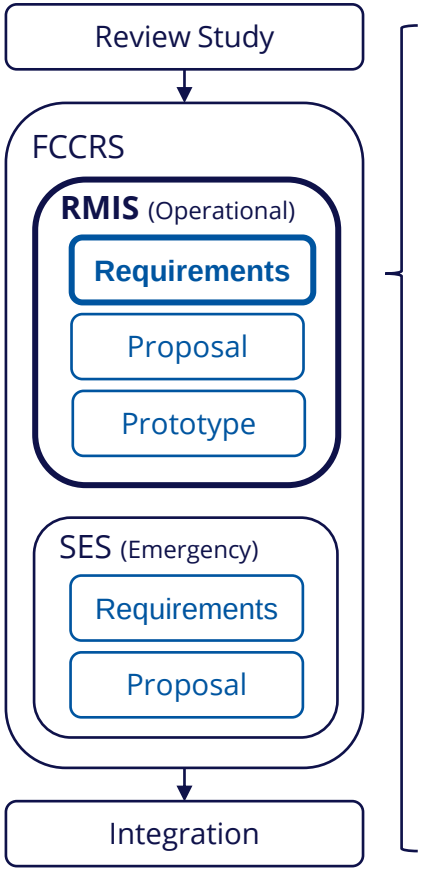
- Technical/Medical Emergencies
- Situation Awareness
- Detect and engage hazards

⇒ standby-ready
⇒ Quick

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

Robotics for Machine Availability & Operational Safety

H. Gamper, A Robotic System for CERN's Future Circular Collider, PhD Thesis, EDMS 232634

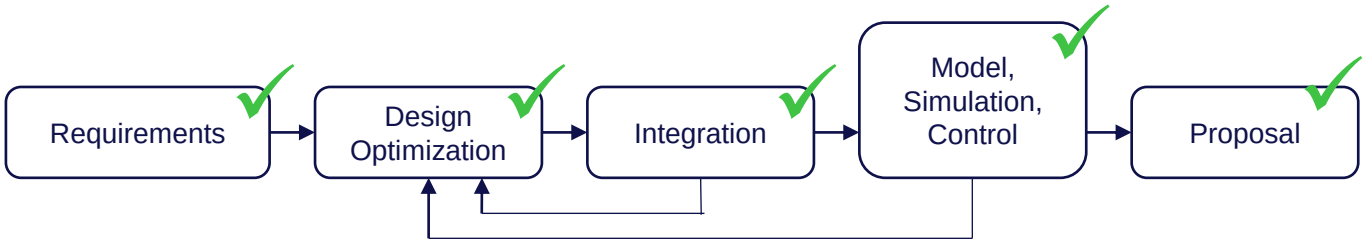


Collection of **Required Tasks**:

- Tunnel Health Monitoring
- Alignment Survey
- BLM Calibration
- Radiation Measurements
- Vacuum Leak Detection
- Measure Air Quality
- Perform Alignment
- Audio Inspection
- Safety Patrols
- ...

Derived **Quantified Requirements on the Robotic System**:

- Payload
- Workspace
- Perception Systems
- ...



Robotics for Machine Availability & Operational Safety

H. Gamper, A Robotic System for CERN's Future Circular Collider, PhD Thesis, EDMS 232634

Review Study

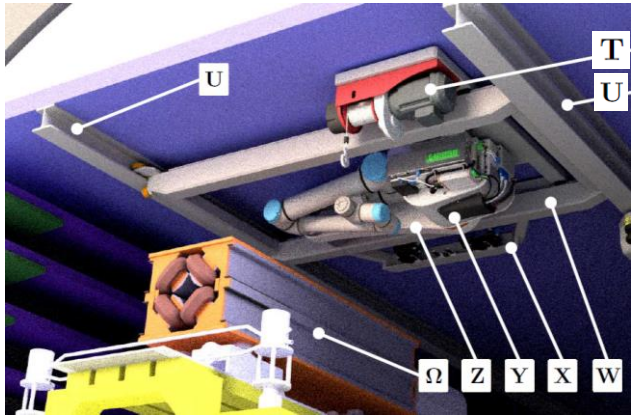
FCCRS

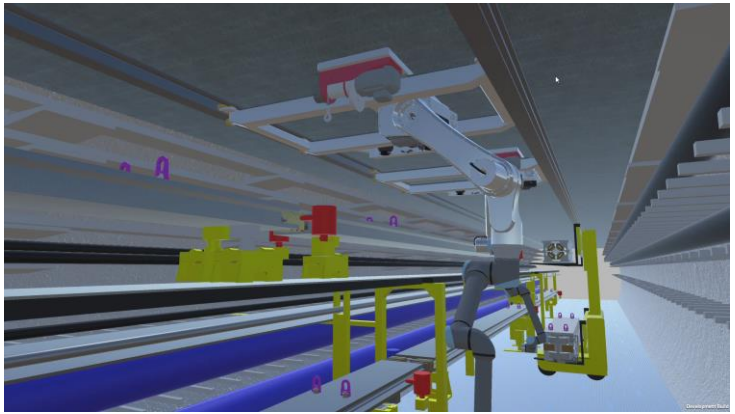
RMIS (Operational)
- Requirements
- **Proposal**
- Prototype

SES (Emergency)
- Requirements
- Proposal

Integration

RMIS Key Features:
- Rail guided system (U) for precision and robustness
- Ceiling mount allows for optimal access to infrastructure
- Highly redundant manipulator (Z) for reduced footprint and adapt manipulation
- Tool changing system (X)
- Winch (T) for high payload operations





Robotics for Machine Availability & Operational Safety

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- FCCRS
  - **RMIS** (Operational)
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    - Proposal
    - **Prototype**
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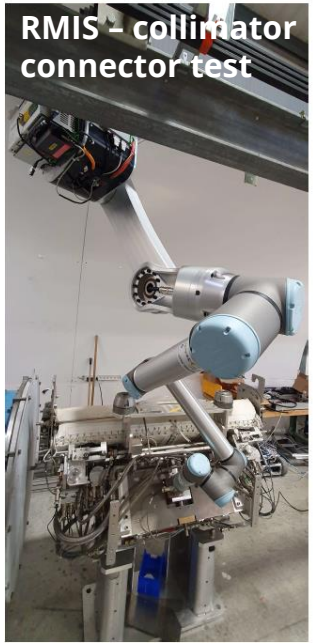
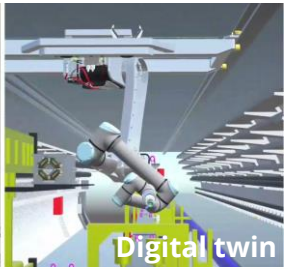
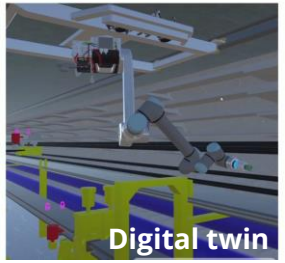
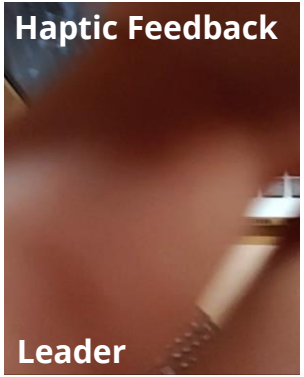
- Integration

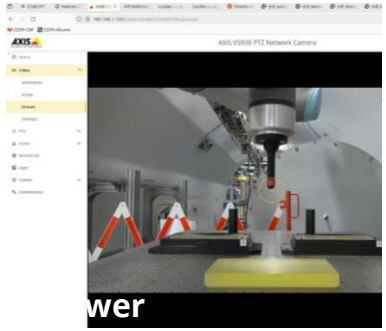
- Installation in LHC Mock-Up in Bldg. 927
- Proof of concept studies
- Biggest Challenge: Software & Control











Robotics for Machine Availability & Operational Safety

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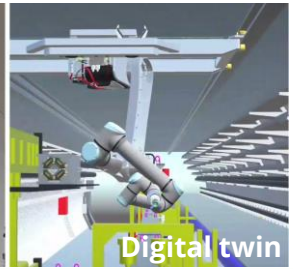


Dev. in software and control

Kinematic Model Pruning Algorithm:

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

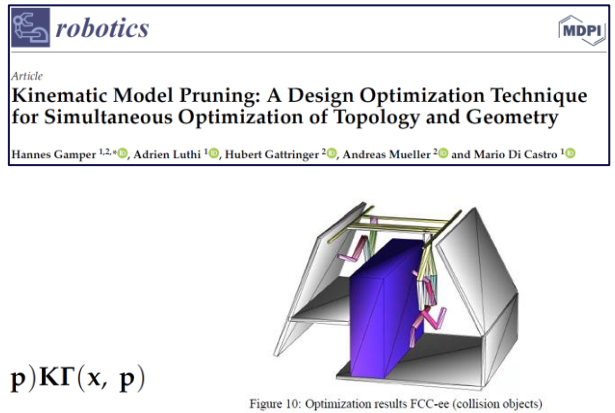
$$J(\mathbf{x},\,\mathbf{p}_l) = \mathbf{k}^T\mathbf{g}(\mathbf{p}) + \boldsymbol{\Gamma}^T(\mathbf{x},\,\mathbf{p})\mathbf{K}\boldsymbol{\Gamma}(\mathbf{x},\,\mathbf{p})$$

Definition 1 (Pruning Function). *A vector function* $\mathbf{g} = [g_1(l_1) \;\; g_2(l_2) \;\; \dots \;\; g_N(l_N)] : \mathbb{R}^N \to \mathbb{R}^N$ *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

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


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]

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

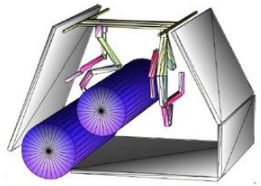


Figure 11: Optimization results FCC-hh (collision objects)

Robotics for Machine Availability & Operational Safety

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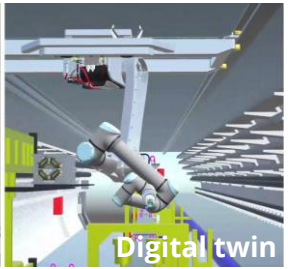
- Proof of concept studies
- Biggest Challenge: Software & Control



Dev. in software and control

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

An Inverse Kinematics Algorithm With Smooth Task Switching for Redundant Robots

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

Final Redundancy Resolution Law:

$$\dot{\mathbf{q}} = \mathbf{J}_1^{\dagger}\left(\dot{\mathbf{z}}_{ref,1} + \mathbf{K}_1\boldsymbol{\theta}_1\right) + \sigma_\theta(t)\,\underbrace{\left(\mathbf{I} - \mathbf{J}_1^{\dagger}\mathbf{J}_1\right)}_{\mathbf{N}_1}\mathbf{J}_2^{\dagger}\left(\dot{\mathbf{z}}_{ref,2} + \mathbf{K}_2\boldsymbol{\theta}_2\right) + \sigma_\tau(t)\,\underbrace{\left(\mathbf{I} - \mathbf{J}_{1,2}^{\dagger}\mathbf{J}_{1,2}\right)}_{\mathbf{N}_{1,2}}\mathbf{W}^{-1}\frac{\partial\tau}{\partial\mathbf{q}}$$

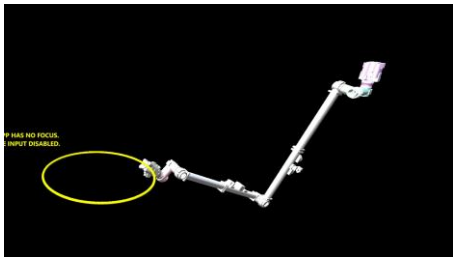
Switching Parameter

$$\ddot{\sigma}_B(t) = \begin{cases} 0 & t < 0 \\ a_{max}\sin(\frac{2\pi}{t_S}t)^2 & 0 \le t < \frac{t_S}{2} \\ -a_{max}\sin(\frac{2\pi}{t_S}t)^2 & \frac{t_S}{2} \le t < t_S \\ 0 & t_S \le t, \end{cases}$$

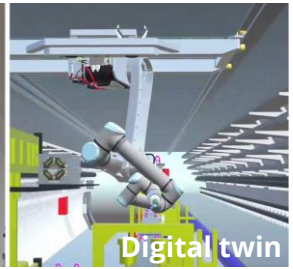
$$\sigma(t) = \sigma_S + \sigma_B(t)(\sigma_E - \sigma_S)$$

Open-source publication:
- lgpl-3.0-or-later
- CERN github
- ESA interest

ESA Operator Training on ISS Canada Arm:



Robotics for Machine Availability & Operational Safety



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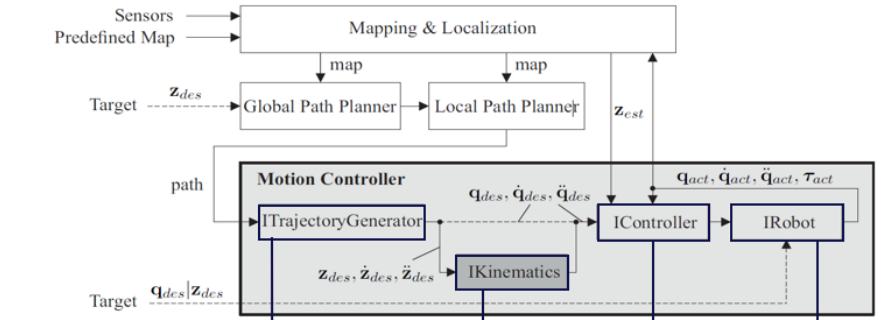
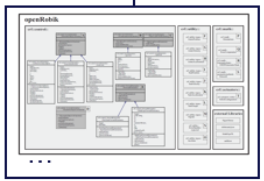
Dev. in software and control

Motion controller and navigation stack:



Cubic splines
NURBS
Sinusoid
...



Impedance
Teleoperation
Gravity Comp.
...

Robotics for Emergency Safety

O. Rios, “Safety Concept of the FCC”: https://indi.to/ndJ5q

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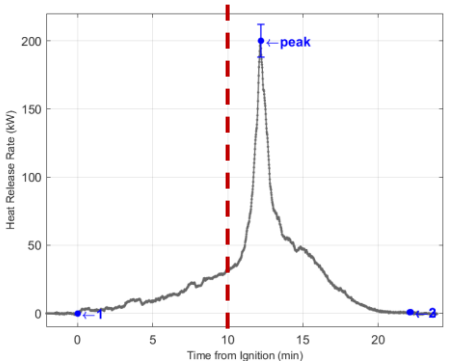
- Emergency Safety Requirements updated in 2024
- Study ongoing in collaboration with HSE

- **Required Interventions** in Case of Emergencies:
  - Guide, Follow & Monitor People
  - Search for Life
  - Situation Awareness
  - Locate and approach Fire
  - Fire Fighting (most challenging so far…)

Fire Fighting

- 99% of fires are contained to max. 5 MW in the first 10 min
- Existing studies: 23 l of CAF (Compressed Air Foam) can suffocate a 5 MW fire (studies at CERN ongoing to verify this data)
- LI batteries oppose a specific challenge to the robot and the CAF system.

SES Intervention



Kim, A.K., Crampton, G.P. Evaluation of the Fire Suppression Effectiveness of Manually Applied Compressed-Air-Foam (CAF) System. Fire Technol 48, 549–564 (2012). https://doi.org/10.1007/s10694-009-0119-3

On the power of fires - https://www.nist.gov/el/fcd/transient-combustion-calorimetry-tcc

T. Otto – Emergency Interventions and Fire Fighting in FCC – EDMS 2922606

Robotics for Emergency Safety

O. Rios, “Safety Concept of the FCC”: https://indi.to/ndJ5q

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Emergency Response Procedure by CFRS

1. Trained workers on site
2. **Emergency response robots**
   - **I. Situation Awareness**
   - **II. First intervention (Fire Fighting, Search & Rescue)**
3. Professional human responders
   - I. Verify Situation
   - II. Second intervention (Finalize Sit. Aw. & Fire Fighting, specific damage control)

M. Nas – Emergency Response in FCC - https://indico.cern.ch/event/1369396/

Covered by the SES

Ongoing Studies by CFRS considering robotic support for rescue teams

Example of specific fire fighting robots: Angatec TEC800

Acknowledgement: G. Roy, O. Rios, M. Nas, T. Otto

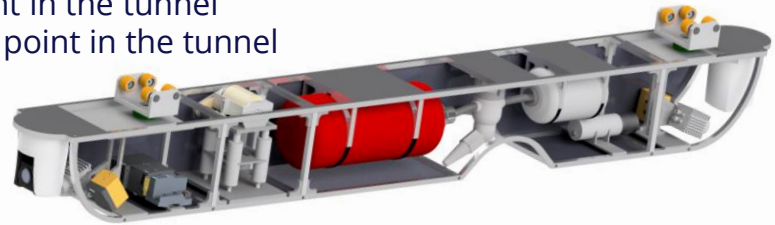
T. Otto – Emergency Interventions and Fire Fighting in FCC – EDMS 2922606

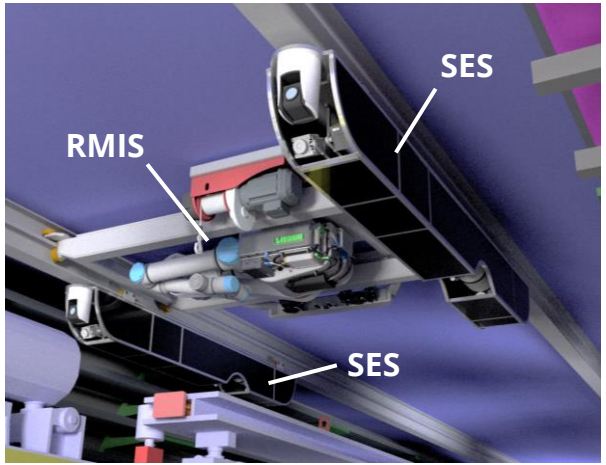
Robotics for Emergency Safety

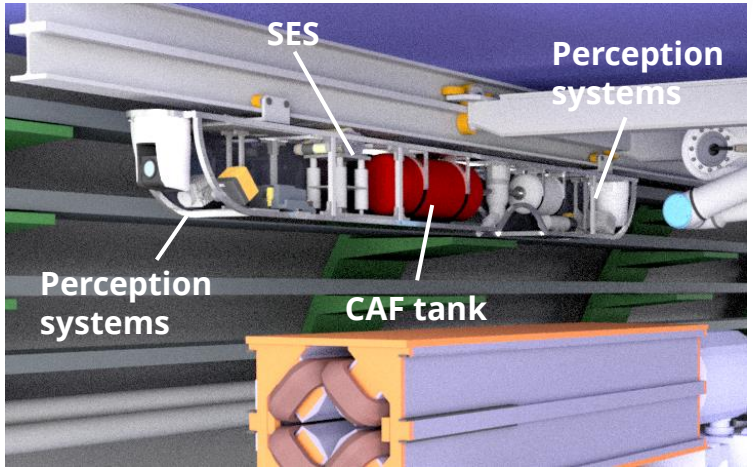
- Review Study
- FCCRS
  - RMIS (Operational)
    - Requirements
    - Proposal
    - Prototype
  - **SES** (Emergency)
    - **Requirements**
    - **Proposal**
- Integration

SES Key Features:

- 1 SES per rail for redundancy
- 36 km/h => within 10 min at every point in the tunnel
- Or 100 km/h? => within 4 min at every point in the tunnel
- Able to bypass RMIS
- >= 25 l CAF tank
- SA perception systems







Robotics for Emergency Safety

Review Study

FCCRS

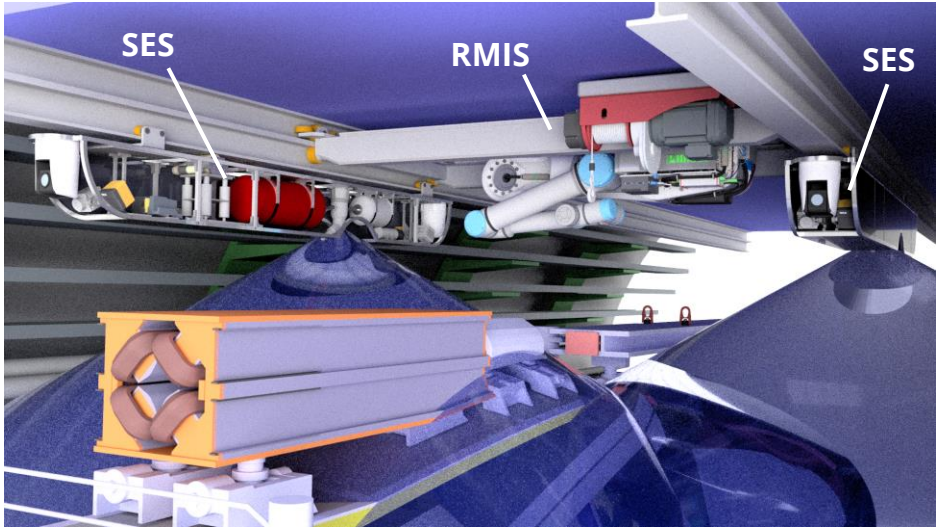
RMIS (Operational)
- Requirements
- Proposal
- Prototype

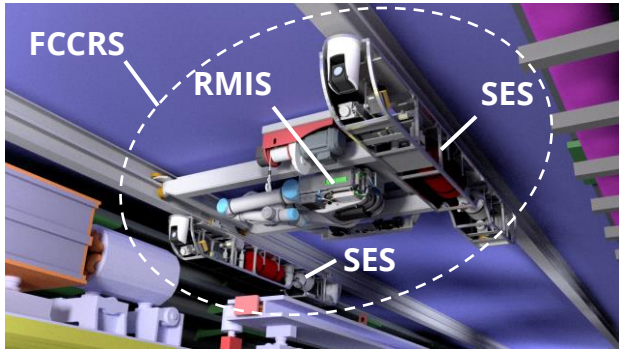
SES (Emergency)
- Requirements
- Proposal

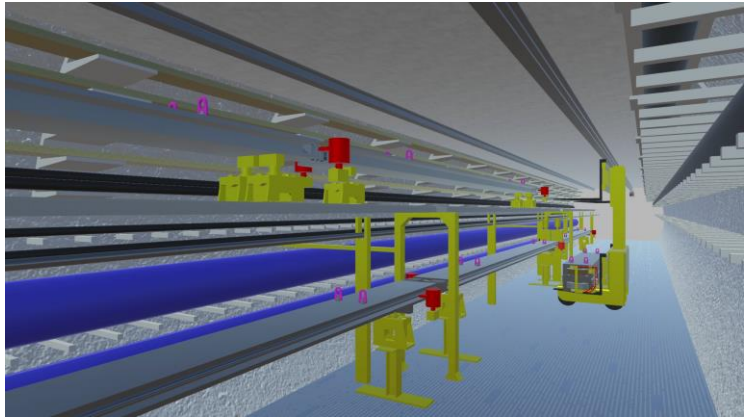
Integration

FCCRS

- High speed, standby-ready SES
- SES can bypass RMIS
- Highly redundant RMIS manipulator
- Always ensure a free passage for SES (additional enclosure?)







Robotics for Emergency Safety

Review Study

FCCRS

RMIS (Operational)
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SES (Emergency)
- Requirements
- Proposal

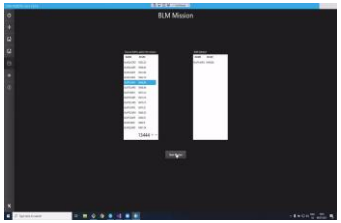
Integration

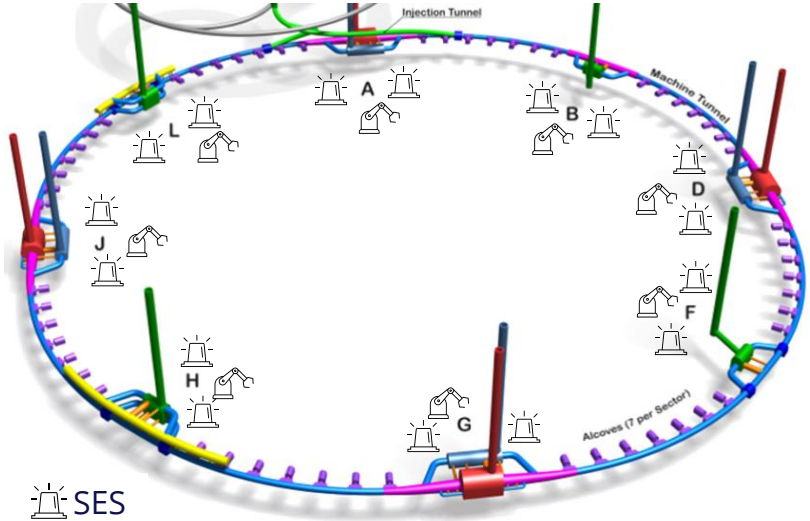
- Radiation safe parking spots in Service Caverns:
  - Protect hardware
  - Allow for maintenance work on FCCRS
- System per Service Cavern:
  - >= 1 RMIS in different configurations for different interventions
  - >= 2 SES
- Total amount of Systems for FCC:
  - >= 8 RMIS
  - >= 16 SES
- FCC with more complex task with respect to LHC
  => Invest in Automation and Standardization to increase robotic efficiency!
- Collaboration with HSE on emergency response!

RMIS SES

Today

- **4 TIMs for 27 km in LHC**
- Most complex task: radio active source handling



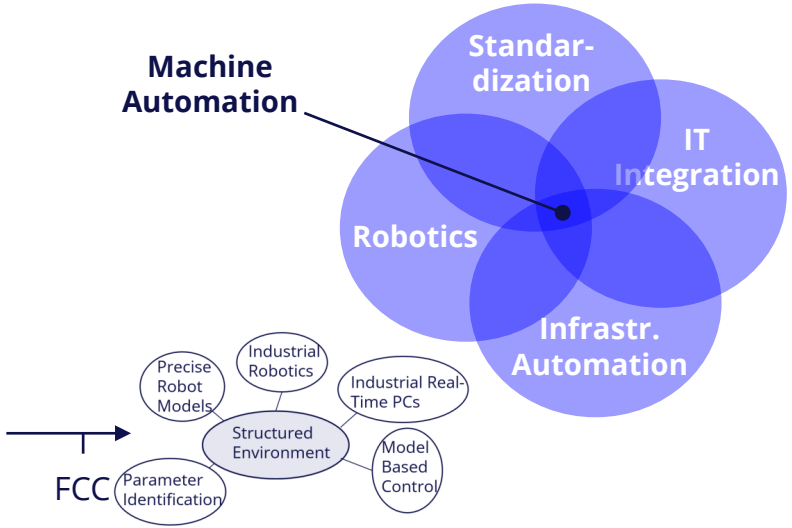


Conclusions

FCC Impact

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

- Required to **consider robotic maintenance from an early design phase onwards**
- Standardized infrastructure design, interfaces and intervention procedures
- Consider robotics as **one** component in machine automation
- Push the FCC infrastructure design towards a **structured environment** to facilitate high robotic efficiency



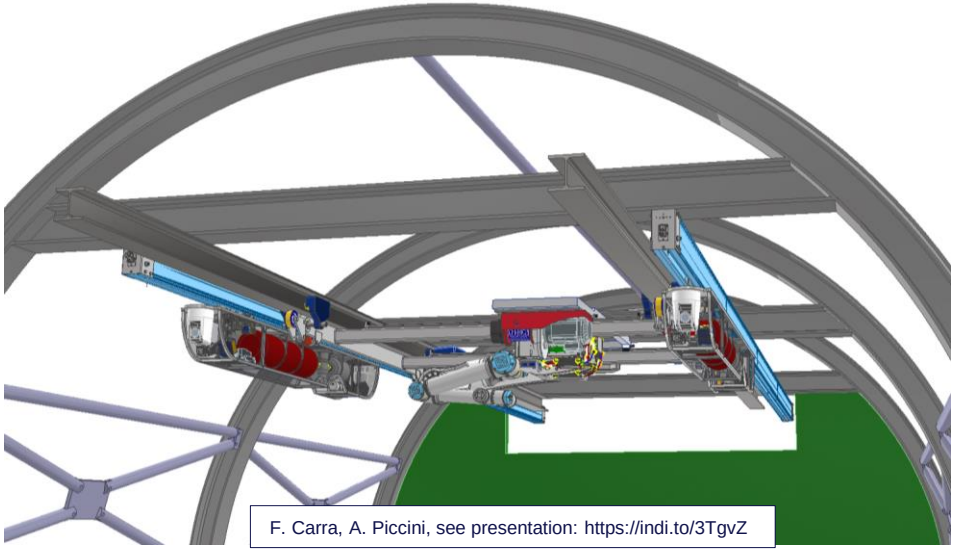
FCCRS

- Task specific system
- Rail guided solution
- Independent maintenance (RMIS) and emergency (SES) system
- Parked in Service Caverns
- >= 8 RMIS
- >= 16 SES

DERIN – Design for Remote Maintenance working group

Outlook

- Prototype (RMIS) installation in FCC main tunnel Mock-Up in beginning of 2025
- Integration of FCCRS into service caverns



F. Carra, A. Piccini, see presentation: https://indi.to/3TgvZ

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 FCCRS developments
- **Thank you for the various fruitful collaborations within CERN!**

Established within the FCCRS project

Thank you for your attention!