BE SEMINAR

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

1. What is Robotics?

2. Robotics in Big Science Facilities
   • State of the Art
   • Robotics at CERN

3. The Vision for FCC

4. Development Process
   • Requirements & Restrictions for a Robotic System
   • Integration and Logistics
   • Current Research

5. Remote Maintenance - Code of Practice

6. Collaborations
What is Robotics?

Robot

Mechanics

- Kinematics
  - Forward & Inverse Kinematics, parallel, serial, holonomic, …

- Dynamics
  - Lagrange, rigid, elastic Identification, Inverse Dynamics, …

Motion Control

- Linear, Non-Linear, Heuristic, Model Based, Machine Learning, …

Software Integration/Deployment

- (ROS, CRF, …)

Cognition

- AI, Machine Learning, State Machines, …

Motion Planning

- Localization & Mapping
- Path Planning
- Trajectory Planning

Actuation

- Motors, Drivers, Power Supply

Manipulators

- Grasping, Redundancy, …

Locomotion

- Gait Analysis, Stability, Poincare Cycles, …

Perception

- Sensors - Camera, Lidar, Force

Parameter Identification

- Precise Robot Models

Industrial Robotics

- Structured Environment

Industrial Real-Time PCs

- Model Based Control

Limited Resources

- Embedded PCs

Mobile Robots

- Unstructured Environment

Sophisticated Locomotion

- Sensor Integration

Sophisticated Perception & Cognition

- Embedded PCs

Motion Control

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Perception

- Sensors - Camera, Lidar, Force
What is Robotics?

- Example 1: The equation of motion

\[ L = -\frac{i}{4} F_{\mu \nu} F^{\mu \nu} + i D \psi + h.c \\
+ \gamma_i \gamma_j \gamma_k \phi + h.c \\
+ |D^2 \phi|^2 - V(\phi) \]

\[ L = T - V \]

\[ d \frac{\partial L}{\partial i} - \frac{\partial L}{\partial q} \frac{\partial R}{\partial i} = Q \]

\[ M(q)q + g(q, q) = Q \]

nonholonomic system

mechanical solution

RP measurements on old LHC TDE w/ CERNbot
What is Robotics? (Ex. 2)

• Example 2: Compliant Control

1. Mass spring damper system
   \[ M\ddot{x} = h - Cx - D\dot{x} \]

2. Discrete Frequency domain
   \[ G(z) = \frac{b_0}{1 + a_1 z^{-1} + a_2 z^{-2}} \]

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

4. Controller

   Problem:
   Solution:

   TIM Handling Radioactive Source for BLM Tests

   Low Damping:
   High Damping:
What is Robotics?

- Example 3: Inverse Kinematics

\[
\begin{align*}
  z &= f(q) \\
  \dot{z} &= \frac{\partial f(q)}{\partial q} \frac{\partial q}{\partial t} = J(q)\dot{q} \\
  \dot{q} &= J(q)^{-1}\dot{z}
\end{align*}
\]
What is Robotics?

Example 4: The CERN Robotic Framework - CRF

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   • Current Research
5. Remote Maintenance - Code of Practice
6. Collaborations
Robotics in Big Science Facilities - State of the Art

Universal Systems

Task Specific Systems

Figure 2 RESQ A

Figure 4 RESQ C

Figure 19 TALON equipped with od-mapping system ©TEPCO

Figure 24 Warrior ©TEPCO

Figure 22 BR0KK 90 ©TEPCO

JET – Primary (RACE)

JET – Secondary (RACE)

Spallation Neutron Source Target – Oakland National Laboratory

Prototype of the Vehicle Manipulator

ITER – RACE
Robotics in Big Science Facilities – Robotics at CERN

Telemax robot

EXTRM robot with single arm (CERN made)

The TIM (CERN made)

EXTRM robot (CERN made)

CRANEbot (CERN made)

CERNbot (CERN made)
Robotics in Big Science Facilities – Robotics at CERN

TIM (x5)

Kuka Robots (x3)

MIRA - CERNbot

BE-CEM-MRO

CHARMbot
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6. Collaborations
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 10 min (1 Robot ~300 km/h or 15 Robots ~20 km/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

1. **What is Robotics?**

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3. **The Vision for FCC**

4. **Development Process**
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5. **Remote Maintenance - Code of Practice**

6. **Collaborations**
# Development Process

<table>
<thead>
<tr>
<th>Task</th>
<th>Description</th>
<th>Derived Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Measuring Radiation</td>
<td>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.</td>
<td>Reach Beam level in front and behind pipe; Position accuracy for repeatable measurements: WSP: 3.2x3.6m</td>
</tr>
<tr>
<td>2. Take Pictures</td>
<td>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</td>
<td>Stable movement; carry a camera array</td>
</tr>
<tr>
<td>3. Test BLM Sensors</td>
<td>Rough map of sensors exists, go to rough sensor position and find exact position with DNN, 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</td>
<td>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 -&gt; every orientation)</td>
</tr>
<tr>
<td>4. Measure Oxygen</td>
<td>Industrial Oxygen measurement sensor; measured throughout the whole tunnel. Make sure its save for people to work down there</td>
<td>Reach different heights to measure oxygen; WSP: 3.2x3.6m</td>
</tr>
<tr>
<td>5. Measure Alignment</td>
<td>Strings are placed by STI on fixed mounted sockets in tunnel. TIM goes to strings as reference and measures some indicators on the Collimators &amp; Dipoles, same distance =&gt; align! New method will automatically place the strings; outer 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.</td>
<td>Version 1: (manually placed string) reach string with existing technology; stable movement; Version 2: (automatically placed string) head of two outer robots and one Inner robot with existing technology</td>
</tr>
<tr>
<td>6. Audio Inspection</td>
<td>Microphone is carried through whole tunnel, detect unusual noise (e.g., frequency domain -&gt; 100Hz peaks) To detect unusual noise which can indicate other problems (e.g.</td>
<td></td>
</tr>
</tbody>
</table>
Development Process

Initial Study
- Requirements
- Restrictions

Integration & Logistics

Design Optimization

Control Concepts

Prototype PoC

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<tr>
<td>Geometry Req.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power Supply</td>
<td></td>
<td></td>
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<tr>
<td>Communication</td>
<td></td>
<td></td>
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<tr>
<td>Maneuverability</td>
<td></td>
<td></td>
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<tr>
<td>Radiation</td>
<td></td>
<td></td>
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<tr>
<td>Control</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emergency</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Matrix:

- Mobile Robot (holonomic)
- Mobile Robot (non-holonomic)
- Rail Guided Robot (ceiling)
- Drone
- Legged Robot (ANYbotics,...)
- Legged Robot + Wheels (Boston Dynamics,...)
- Holonomic Robot travel in Hyperloop
- Rail Guided Robot w. robotic arm & hol. Robot
- Holonomic Robot w. Robotic Arm
- RailGuided Robot w. Snake Robotic Arm

Diagram:

- Development process flowchart
- Task importance ratings
- Task restrictions

Graph:

- Performance metrics
- Summed up rating in %
Development Process

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

Initial Study
- Requirements
- Restrictions

Integration & Logistics

Design Optimization

Control Concepts

Prototype PoC
Development Process

Initial Study
- Requirements
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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!

<table>
<thead>
<tr>
<th>Part</th>
<th>Mass [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Links, motors 6-11</td>
<td>34</td>
</tr>
<tr>
<td>2 x link</td>
<td>20</td>
</tr>
<tr>
<td>4 x motor 3-5</td>
<td>50</td>
</tr>
<tr>
<td>Linear link</td>
<td>80</td>
</tr>
<tr>
<td>2 x linear motor</td>
<td>30</td>
</tr>
<tr>
<td>Control, electronics, cable</td>
<td>30</td>
</tr>
<tr>
<td>Payload</td>
<td>15</td>
</tr>
<tr>
<td>Tools</td>
<td>0 ... 30</td>
</tr>
<tr>
<td>ESTIMATED TOTAL</td>
<td>259 ... 289</td>
</tr>
</tbody>
</table>

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
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

Fani Valchkova-Georgieva
Development Process

Initial Study

Requirements

Restrictions

Integration

&

Logistics

Design Optimization

Control Concepts

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

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

Development Process

Optimal Solution:
- Optimal Geometric Parameters (link lengths)
- Optimal Topology (11 DoF, Joint Configuration)
Development Process

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

Development Process

Initial Study
- Requirements
- Restrictions

Integration & Logistics

Design Optimization

Control Concepts

Prototype PoC

Mechanical Design

Update Topology & Parameters

Analytic Description

Numerical Simulation

Update Torque

Update EoM

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

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

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

CERN Kinematics Dynamics Library

- IDirectKinematics
  - CERN Kinematics Dynamics Library
    - 10thOrderInverseKinematics
    - 11thOrderInverseKinematics
  - ErrorComputation
  - Quaternion
  - JointPos
  - TaskPos
    - Conversion
    - Jacobian
    - TaskVel
    - JointVel
    - JointAcc
    - TaskAcc
- IKinematicObjectiveFunction
- IDynamicObjectiveFunction

Initial Study
- Requirements
- Restrictions

Integration & Logistics

Design Optimization

Control Concepts

Prototype PoC

Alejandro Diaz Rosales, Laura Rodrigo Perez
Development Process

Initial Study
- Requirements
- Restrictions

Integration & Logistics

Design Optimization

Control Concepts

Prototype PoC

- 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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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

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

=> Decrease downtime of FCC machine and maintenance costs
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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
Thank you for your attention!