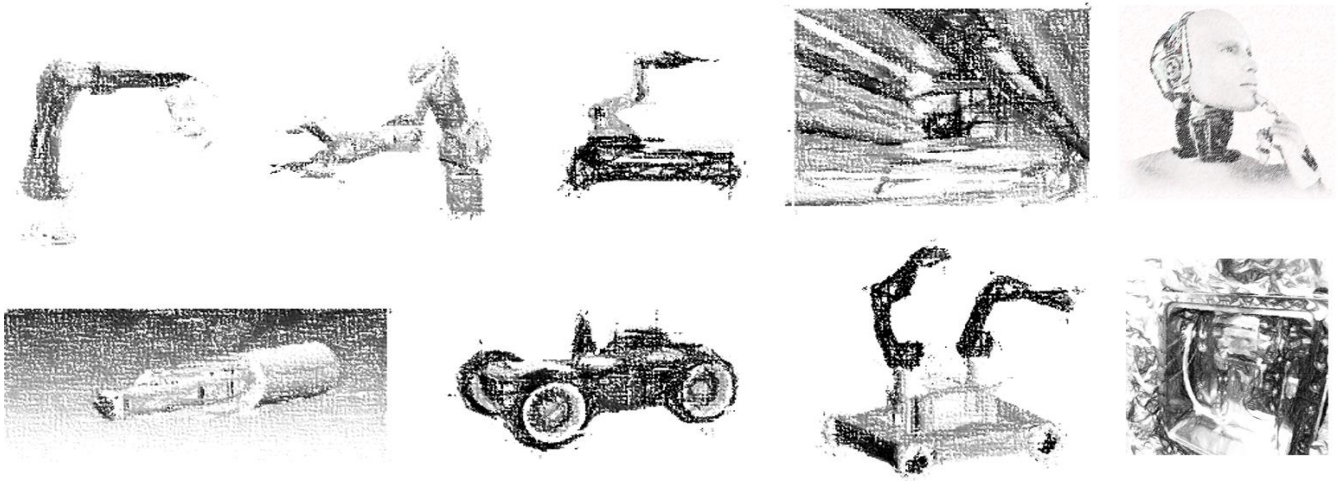

CERN

Robotic Solutions for Inspection and Remote Maintenance at CERN: Current Status and Upcoming Challenges

Mario DI CASTRO
CERN



CERN | EN ENGINEERING DEPARTMENT

Contents

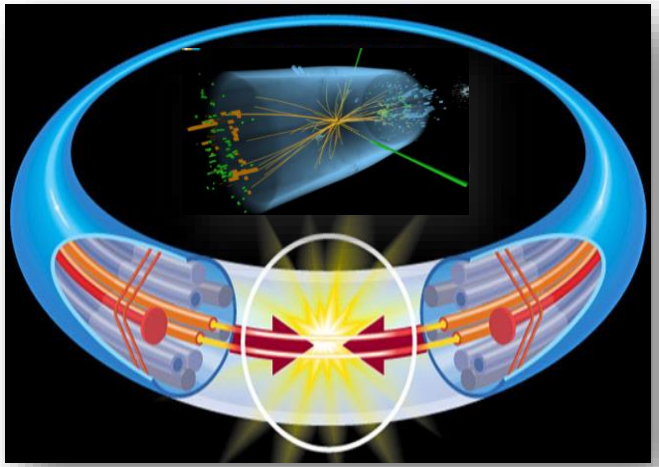
- Current Status
- Main Upcoming Challenges
- Needed Technological Skills of Suppliers
- Upcoming Procurements
- Summary

Robotics mandate at CERN

- The “mission” of tele-robotics at CERN may be resumed in the following:

Ensuring safety of Personnel

improving availability of CERN’s accelerators

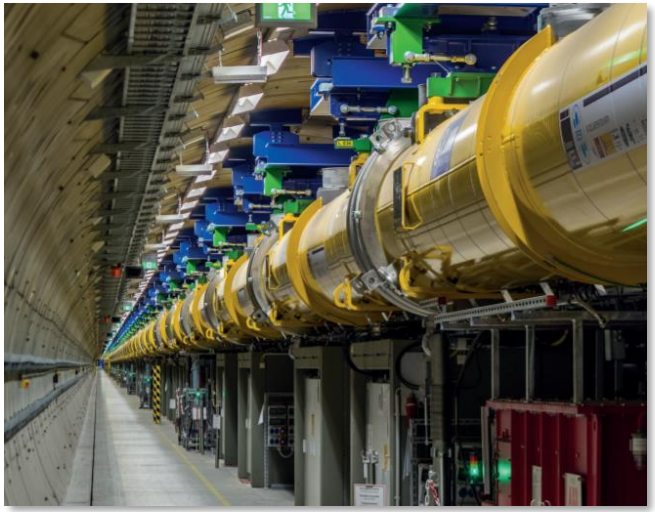


Main needs for robotics in Big Science Facilities

- Non-destructing testing and inspection, remote operation and maintenance of **dangerous equipment and zones**
- In many particle accelerator facilities, areas and objects are **not designed and built to be maintained remotely**
  - ✓ Any intervention may lead to **"surprises"**

The Thorium nuclear reactor

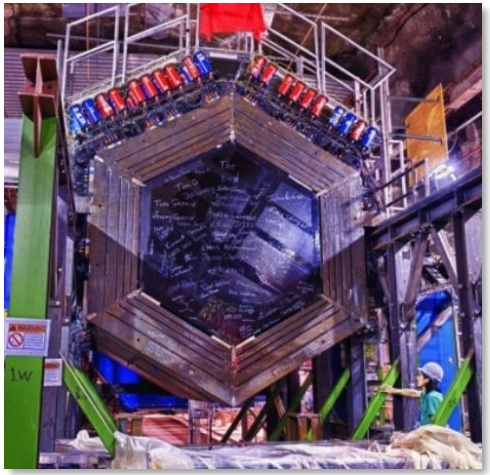
North Area experimental zone at CERN



The European XFEL accelerator tunnel

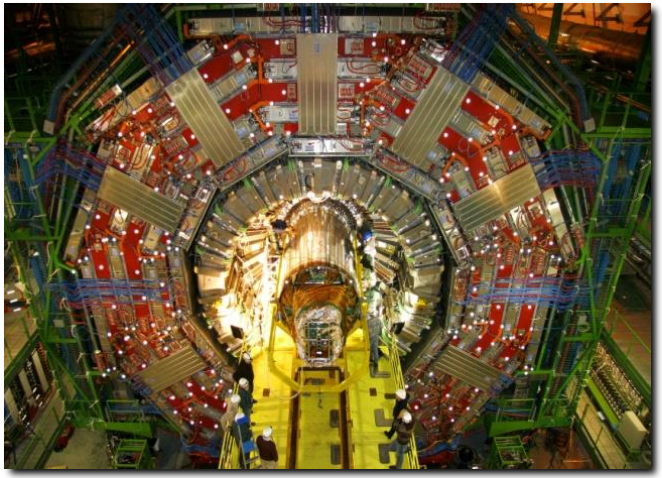
Main difficulties for robotics in Big Science Facilities

- **Accessibility**, radiation, magnetic disturbances, delicate equipment not designed for robots, big distances, temperature, explosive atmosphere, communication, **time for the intervention**, **highly skilled technicians required** (non robotic operators), etc.



Antineutrinos experiment at FERMILAB

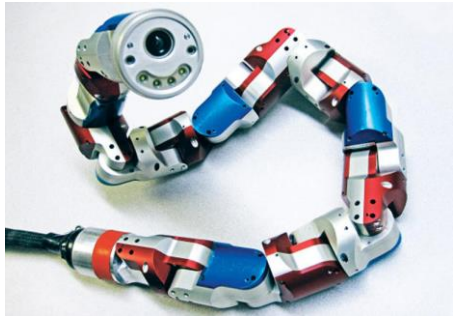
Clinton nuclear power plant



Compact Muon Solenoid experiment at CERN

Robotics for Big Science Facilities

- No single robotic solutions can fulfill the needs
- Mobility and manipulation capabilities are required
  - ✓ A “fusion” of several type of robot is needed



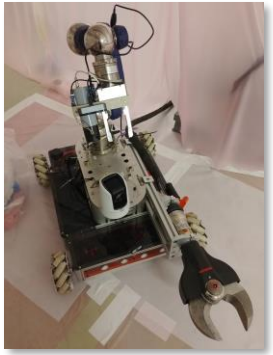
Robotics technologies are mainly used at CERN for:

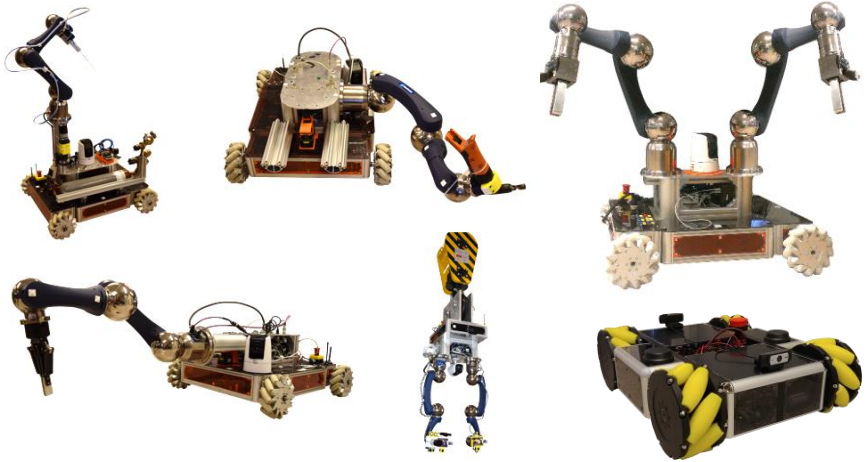
- Safety
- Human intervention procedures preparation
- Environmental measurements and inspection
- Maintenance
- Quality assurance
- Post-mortem analysis
- Reconnaissance
- Search and rescue
- ….

Robotic Support for CERN

Telemax robot

Train Inspection Monorail (CERN made)





CERNBot in different configurations (CERN made)

Teodor robot

EXTRM robot (CERN made)

[Mario Di Castro, Alessandro Masi, Luca Rosario Buonocore, Manuel Ferre, Roberto Losito, Simone Gilardoni, and Giacomo Lunghi. Jacow: A dual arms robotic platform control for navigation, inspection and telemanipulation. 2018.]

[Di Castro, Mario, et al. "i-TIM: A Robotic System for Safety, Measurements, Inspection and Maintenance in Harsh Environments." 2018 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR). IEEE, 2018..]

Robotic Support for CERN

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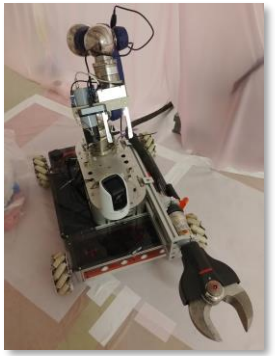
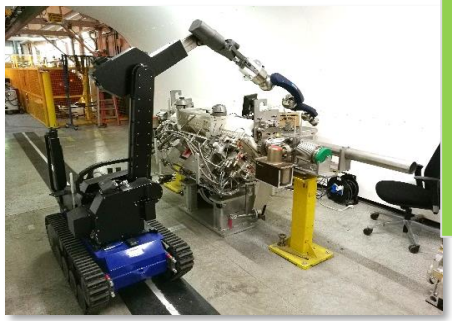


More than 20 robots in operation

- AUTONOMOUS INSPECTIONS
- OPERATOR DRIVEN INSPECTION
- ASSISTED INSPECTION
- TELEOPERATIONS
- ASSISTED TELEMANIPULATION
- AUTONOMOUS REMOTE OPERATION
- SAFETY, SEARCH AND RESCUE



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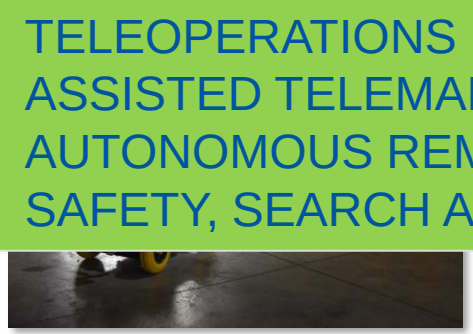

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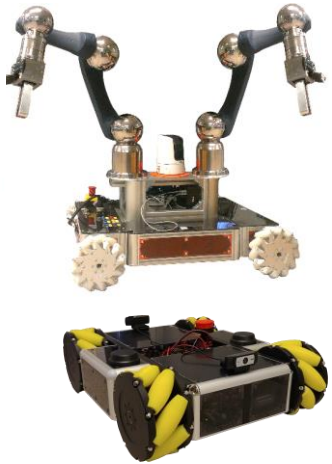

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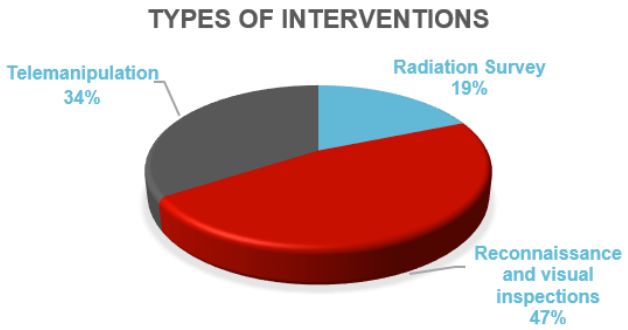
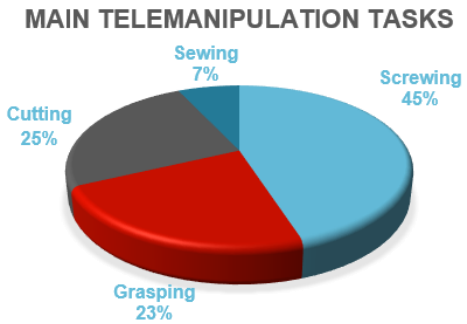
Robotic Operation at CERN

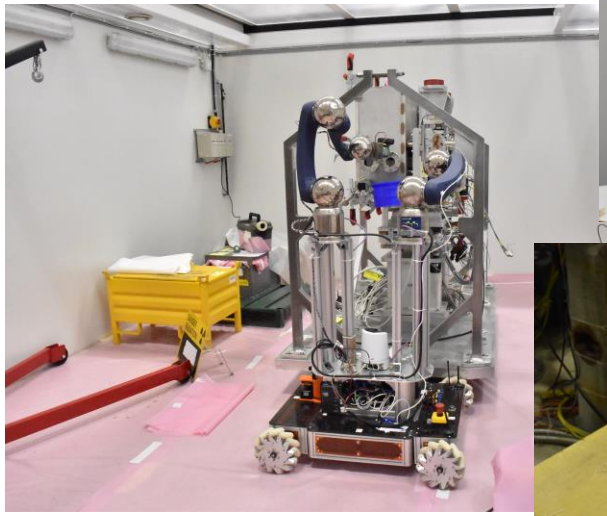
Nr. of Interventions in the last 48 months	Nr. of tasks performed in the last 48 months	Robot operation time in harsh environment [h]
140	250	~ 300

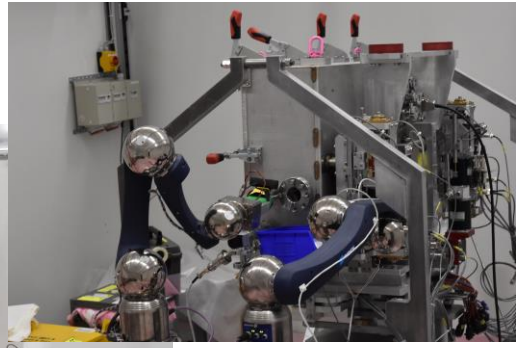


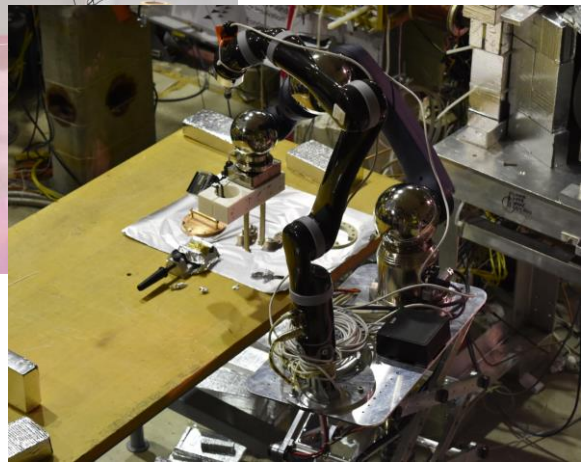


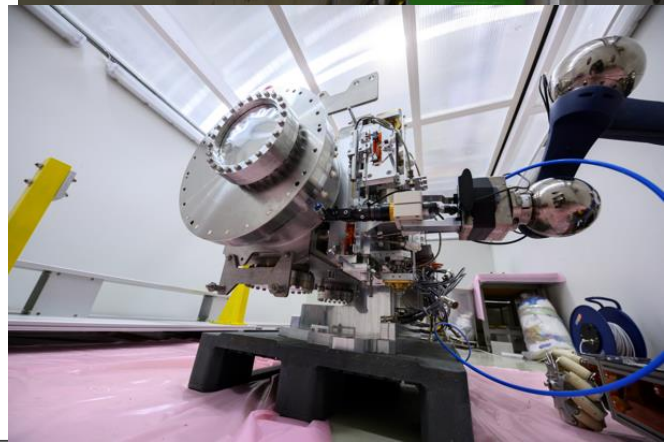
Continuing developing best practice for equipment design and robotic intervention procedures including recovery scenarios

Challenging Teleoperations









Robotic remote preventive maintenance

SPS MKP oilers refill

Remote surveys

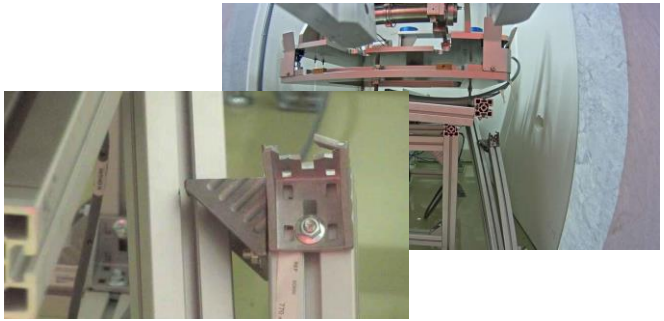
Cabling status inspection

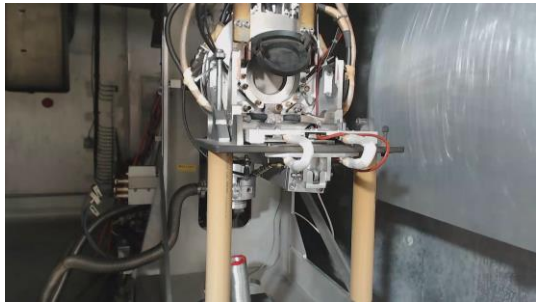
Temperature sensor installation on AD target

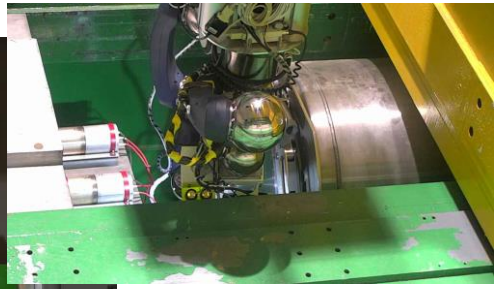
Tunnel structure monitoring

Remote Vacuum Leak detection

Fast reaction to reliability issues

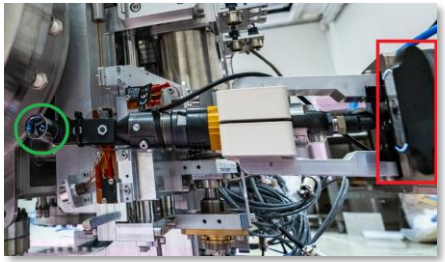


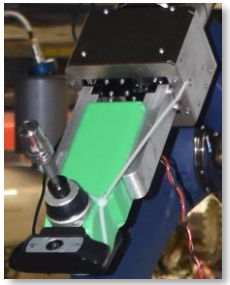


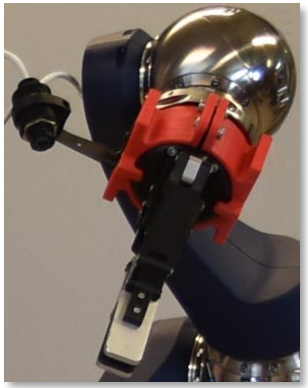
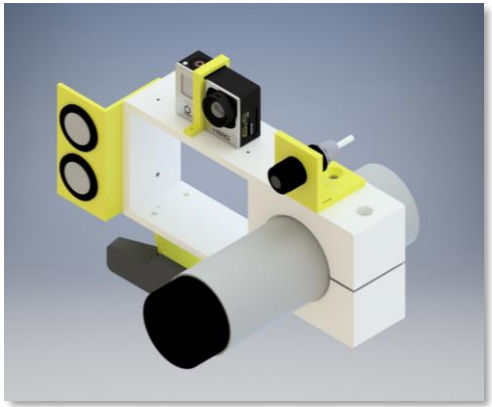
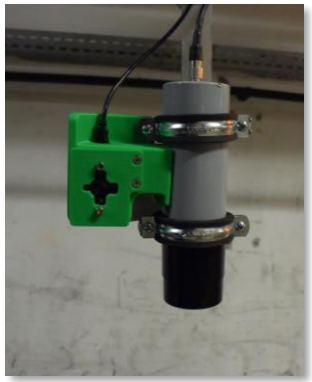


Procedures and Tools

- Several tools and sensors integrated for various tasks, also in emergency
  - ✓ Intervention procedures, recovery scenarios, tools and mock-ups are important as the robot/device that does the remote intervention




Robots at CERN: TIM

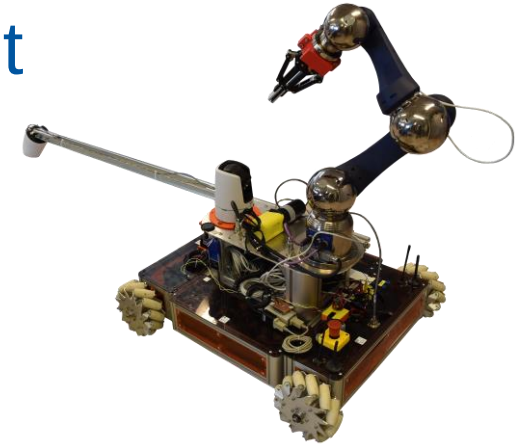
Built at CERN, used for inspection, radiation mapping of the LHC and survey. Operational Experience and technology could be useful for general tunnels inspections

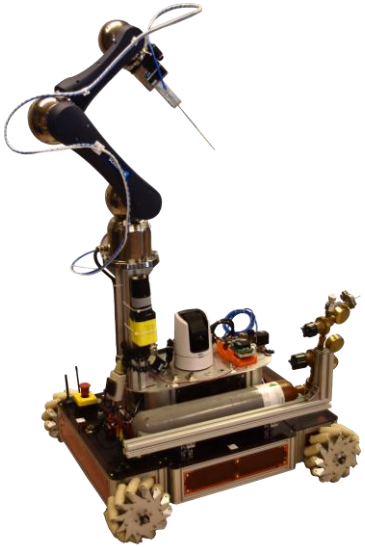
Robots at CERN: TIM

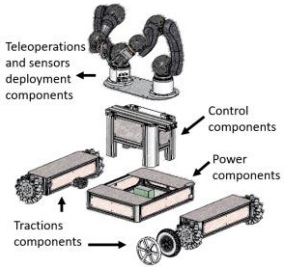
Robots at CERN: CERNbot

- **CERNbot robotic base**

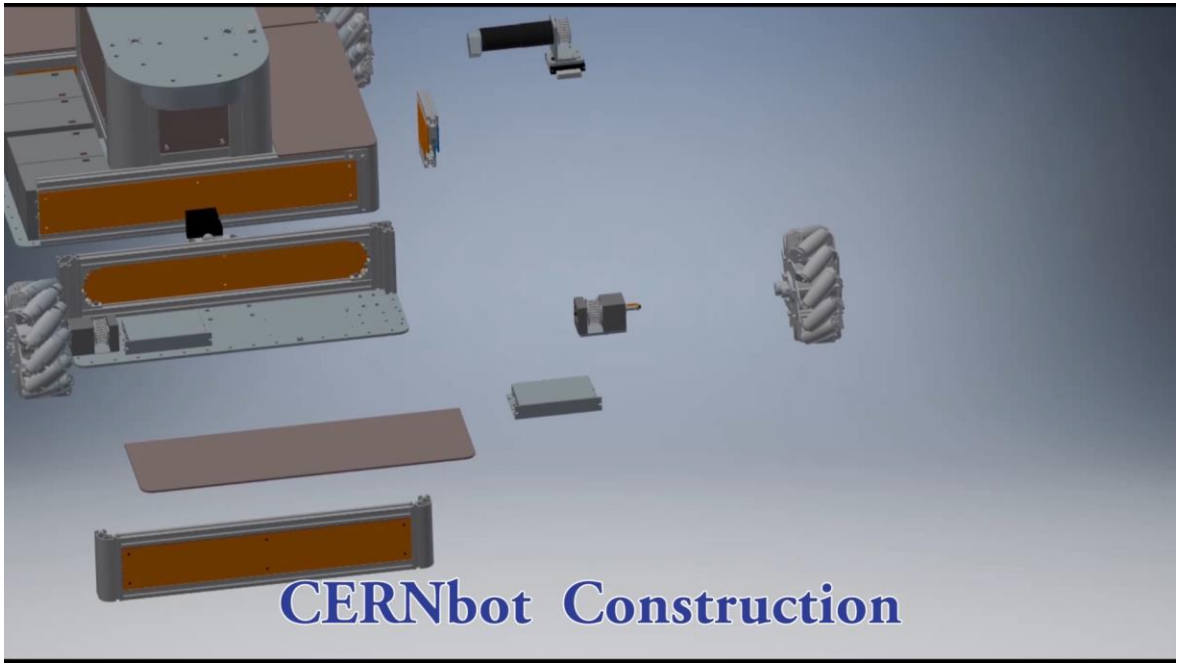
- ✓ Hardware and control software completely developed in-house
- ✓ Weight ~ 50 kg
- ✓ Continuous operation ~ 4 hr
- ✓ **Payload ~ 150 kg**
- ✓ **Arm Payload ~15 kg (can host 2 arms)**
- ✓ Max speed = 10 km/h
- ✓ Runs over Wifi/3G/4G
- ✓ **Entirely controllable from surface**
- ✓ User friendly human-robot interface
- ✓ **Can be fully autonomous**
- ✓ Embedded novel energy management system
- ✓ Inspection, helium sniffer for vacuum leak detection, RP survey, telemanipulation (cutting, grasping, screwing, sewing etc.)





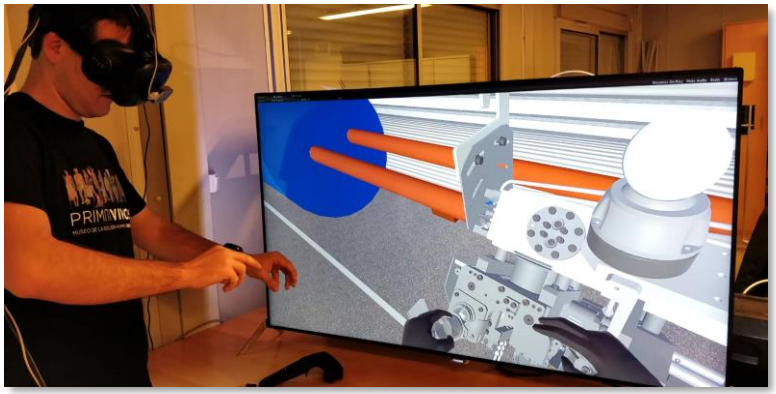


Robots at CERN: CERNbot



Virtual and Augmented Reality

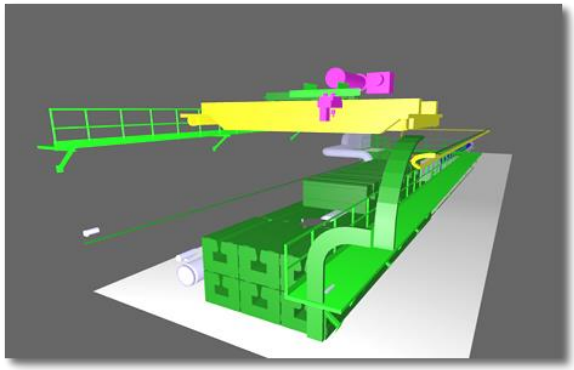
- Virtual and augmented reality in harsh environment is needed for:
  - Simulation of robotic interventions
    - ✓ Integration of robots in the environment and choice of robots
    - ✓ Intervention procedures
    - ✓ Tools design and test
    - ✓ Machines risk assessment
    - ✓ Robots training by demonstration
    - ✓ Operators training
    - ✓ Risk analysis
    - ✓ Steering new machine designs (robot-friendly)
    - ✓ Recovery procedures
  - Simulation of human intervention
    - ✓ Human intervention procedures
    - ✓ Live radiation levels and cumulated dose while training in VR (Augmented reality in virtual reality)
    - ✓ Intervention training
    - ✓ Risk analysis

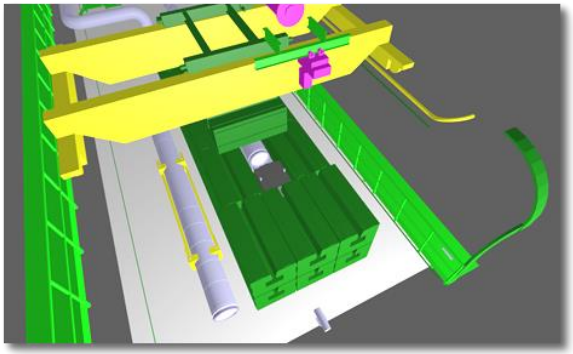


Intervention Examples

- LHC TDE inspection

CERNbot v1.0 core




Intervention Examples

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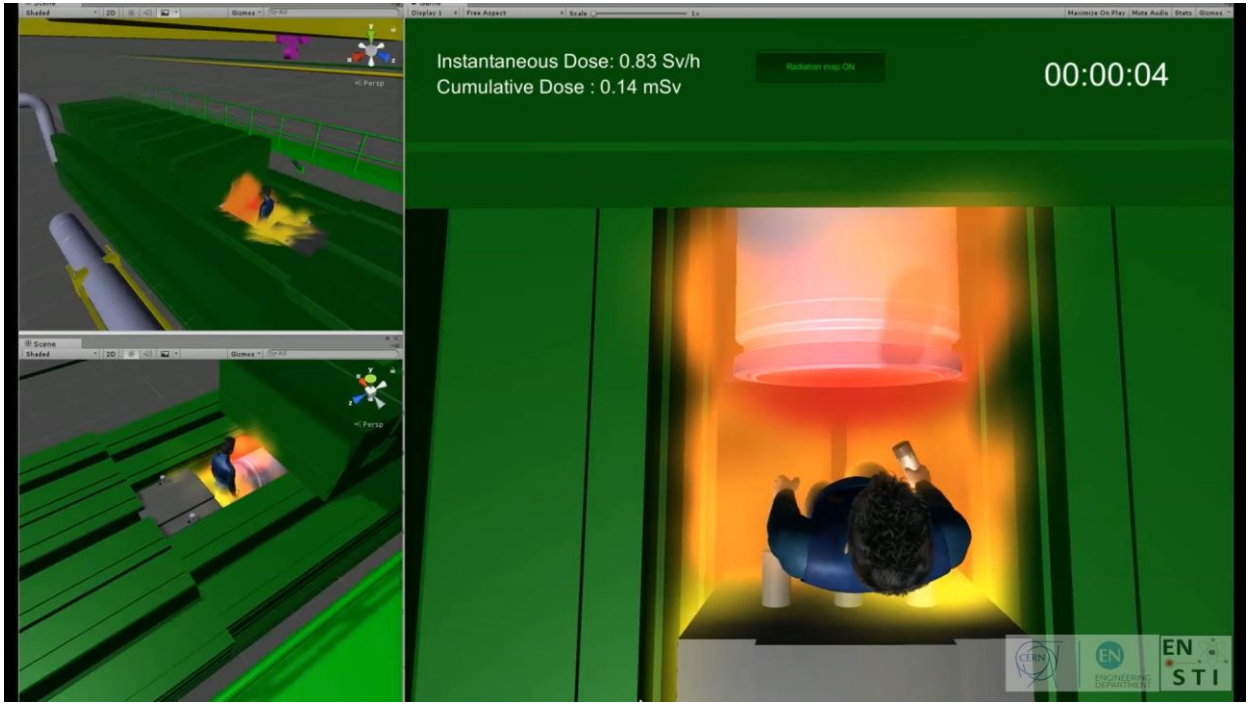
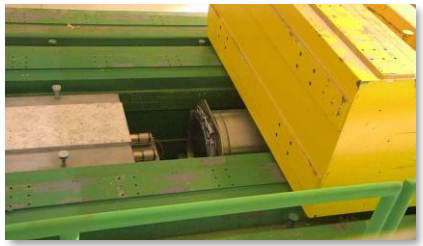
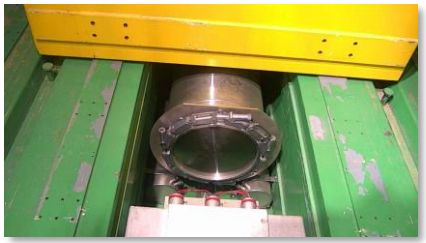
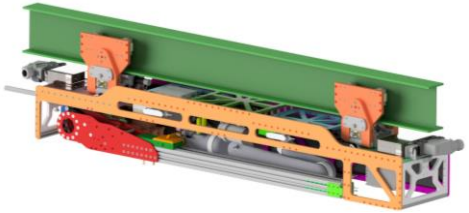






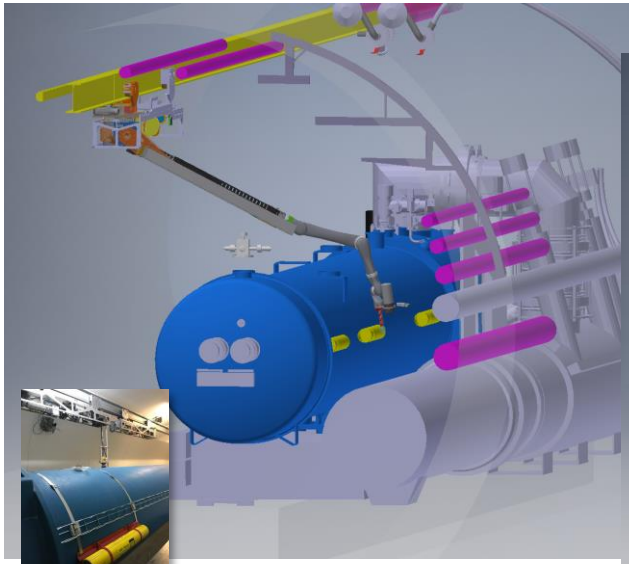
Contents

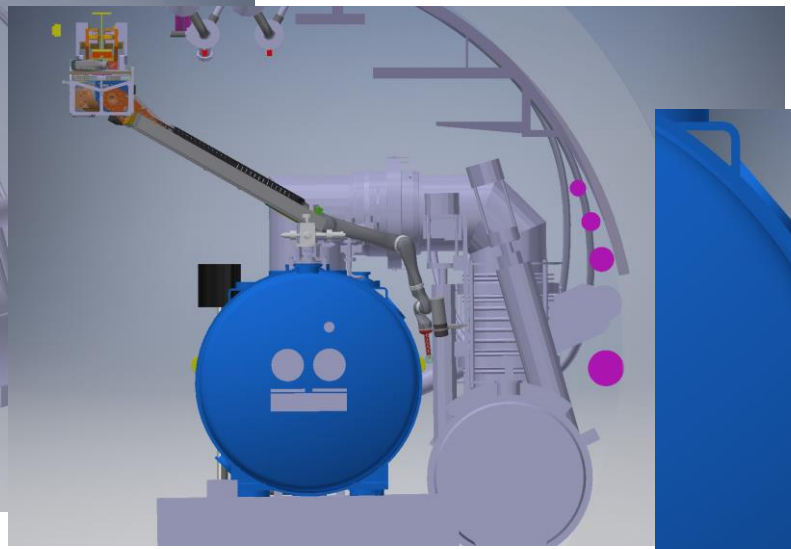
LHC Beam Loss Monitors Validation using TIM

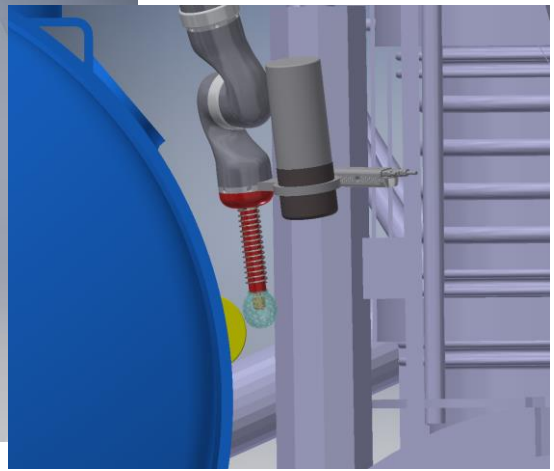


Proof of concept tests done

Automatic BLM recognition using machine learning



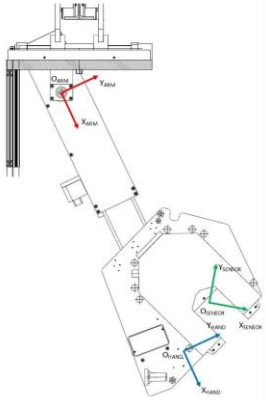




Robotic arm approaching the BLM located on the opposite site of the tunnel passage

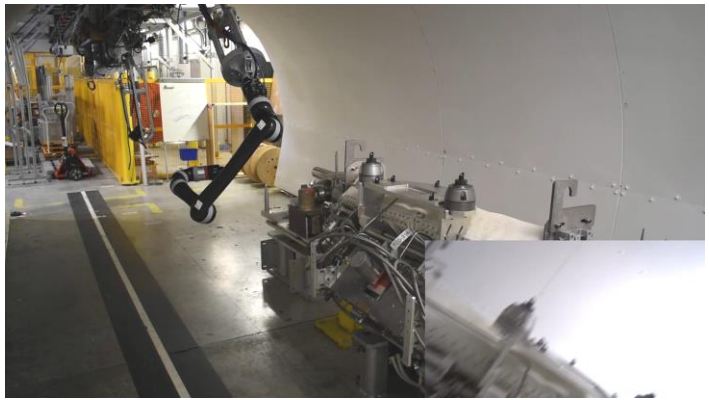
Source positioning close to the BLM

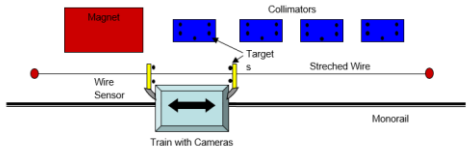
TIM Survey Wagon alignment to fiducials



Current robotic arm of the TIM survey wagon

TIM robotic arm for survey on LHC collimator

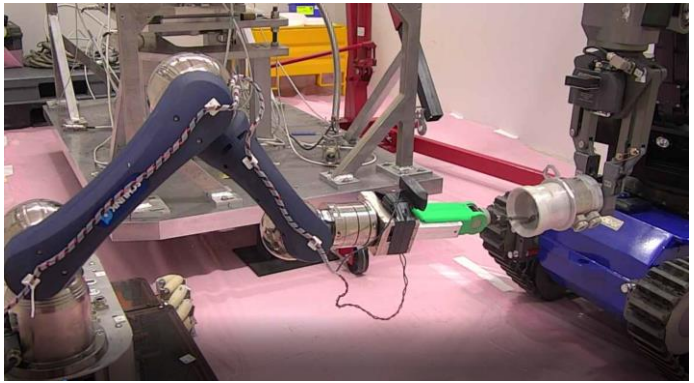


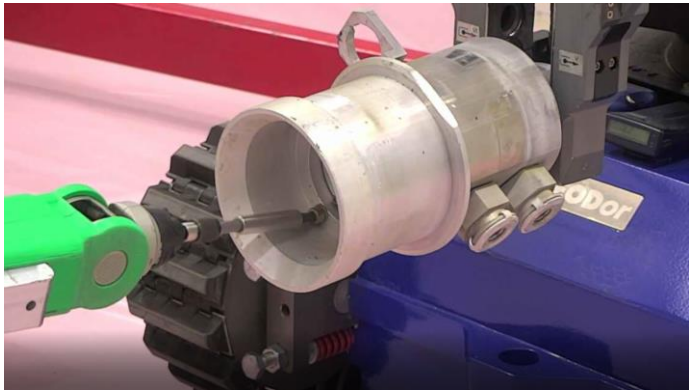


Working principle of the TIM survey wagon

TIM robotic arm equipped with HD camera

Operator Interface Performance

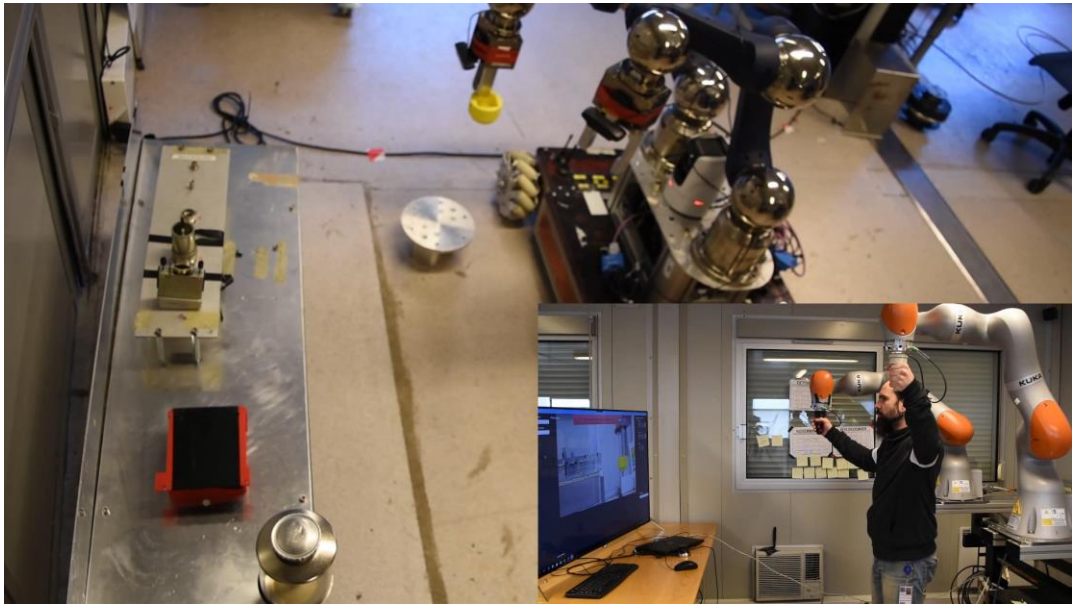




- Manipulation of radioactive targets
  - ✓ CERNTAURO intervention preparation, procedure, tooling and recovery scenarios
  - ✓ Force-feedback based bilateral control

Teleoperation Factors: Haptic Feedbacks and Master Device

- **Master-Slave Haptic-Based Teleoperations**
- In house **user friendly** and portable telemanipulation system to allow equipment owners and/or expert technicians to use robot in a “transparent way”
  - ✓ **No need of expert robotic operators**

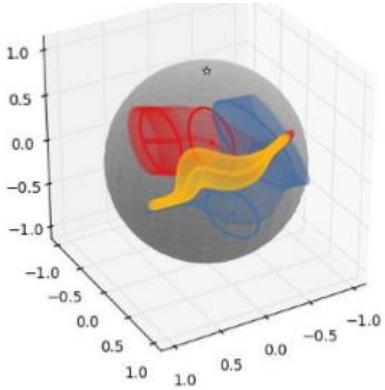


[Di Castro, Mario, et al. "Tracking-Based Depth Estimation of Metallic Pieces for Robotic Guidance." 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). IEEE, 2018.]

[Almagro, C. V., Di Castro, M., Lunghi, G., Marin, R., Ferre, M., and Masi, A. "Monocular Robust Depth Estimation Vision System for Robotic Tasks Interventions in Metallic Targets". Sensors 19.14 (2019): 3220]

Learning by Demonstration

- **Machine imitation learning**
  - ✓ Generate movement trajectories using Gaussian Mixture Model (GMM) on a Riemannian manifold from several human demos and Dynamic Movement Primitives (DMP)
- **Learning Benefits**
  - ✓ Robots adapted to the tasks and the environment
  - ✓ Fully autonomous task implementation possible
  - ✓ Assistive robotic technology supporting remote operators



Blue: robot moves in its base frame
Red: robot moves in target's frame
Orange: generated/reproduced movement for rob

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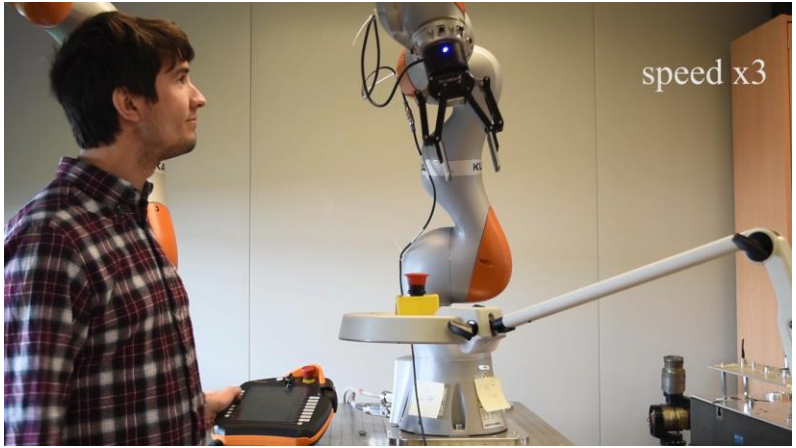
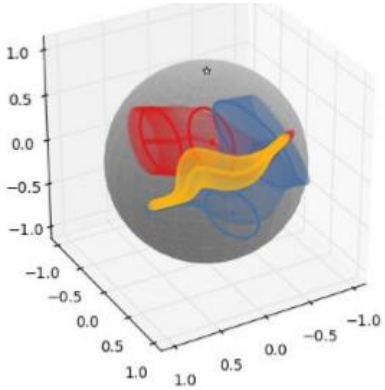
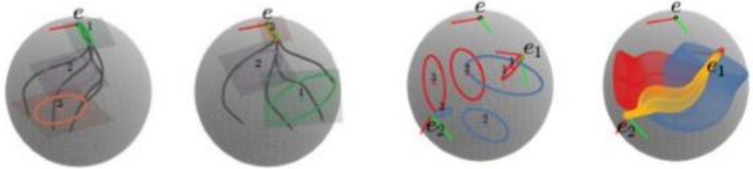
  - ✓ Fully autonomous task implementation possible
  - ✓ Assistive robotic technology supporting remote operators



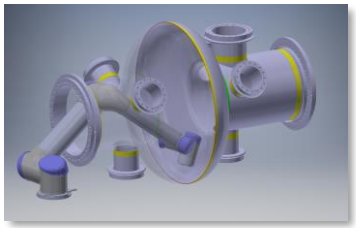


Blue: robot moves in its base frame
Red: robot moves in target's frame
Orange: generated/reproduced movement for robo

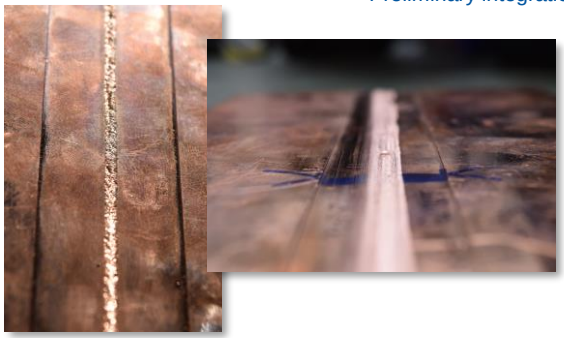


Welded joints polishing using a robotic arm (learning by demonstration techniques)

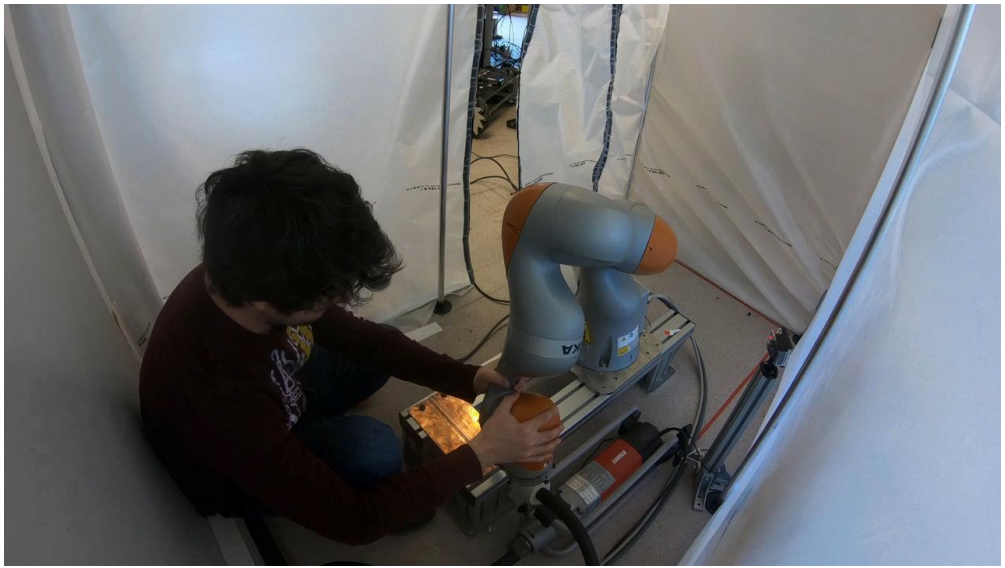
Picture of a cavity



Preliminary integration



Preliminary results of a polish on a welded joint.
Before polishing (left) and after polishing (right)



Contents

Needed Competences and Capabilities of Suppliers #1

- Teleoperation devices/sensors
  - Lightweight arms/manipulators where we can access low level communication protocols in order to embed them/our own controllers on our mobile platforms
  - Variable payload requirements, in kg range

- Haptics
  - Primary devices e.g. gloves, handheld devices
  - Secondary devices e.g. pressure sensors, lightweight FT sensors

Needed Competences and Capabilities of Suppliers #2

- Tooling, fabrication of complex mechanical pieces
- Sensors for embedded applications
  - Cameras
  - LIDAR/RADAR
- When applicable, an understanding of radiation environments and required radiation hardening mitigation steps required for hardware setups

Needed Competences and Capabilities of Suppliers #3

- Mechatronic, integration and dynamic simulations
- Modeling
  - Modelling of physical spaces in simulation from sensor data e.g. point clouds/stitched images
  - Representation of robotic systems in standard format for simulation visualization e.g. Unified Robot Description Format (URDF)
- Communication
  - Robust/reliable/configurable communication protocol understanding over different networks and delays

Strategy during the last 5 years

- Work performed by several stages, bachelor, master and PhD students

Plenty of collaboration opportunities with industries

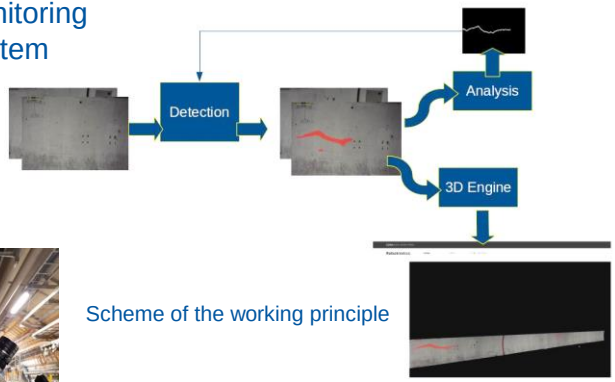
- ✓ Terabee
- ✓ Ross robotics
- ✓ National Grid
- ✓ Vacom
- ✓ CREATE
- ✓ ….
- ✓ CERN incubator program

Contents

Online Tunnel Structure Monitoring

- 360 HD and high speed camera system to allow image taken while robot is running at 6km/h for tunnel reconstruction (structure from motion)

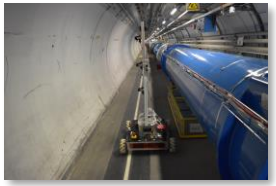
Structural Health Monitoring System



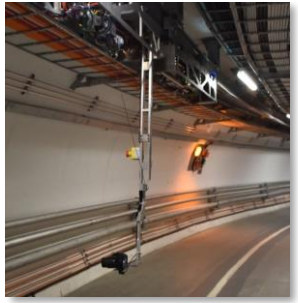
Scheme of the working principle

Example of water leak found by TIM2 during TS3 2018

HD camera system for tunnel dome view



System integrated also on other robots



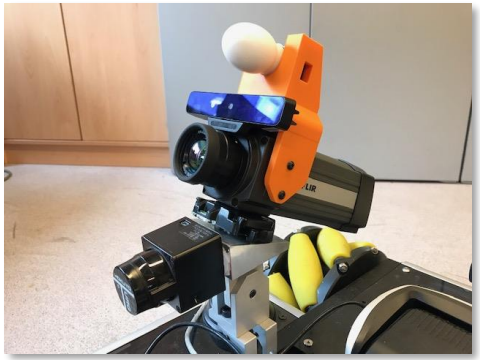
HD cameras mounted on TIM

Example of crack found using vision based machine learning techniques

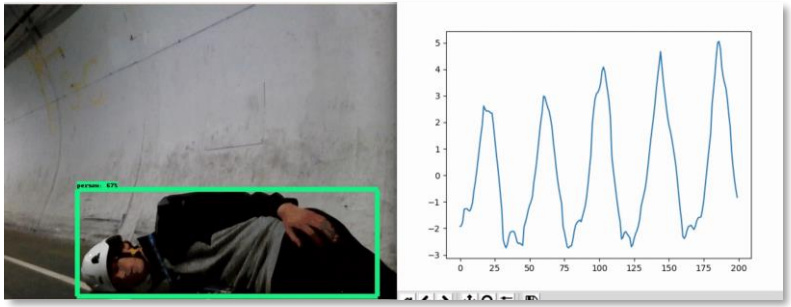
Attard, Leanne, Carl James Debono, Gianluca Valentino, and Mario Di Castro. "Vision-based change detection for inspection of tunnel liners." Automation in Construction 91 (2018): 142-154.
Attard, Leanne, Carl James Debono, Gianluca Valentino, and Mario Di Castro. "Tunnel inspection using photogrammetric techniques and image processing: A review." ISPRS journal of photogrammetry and remote sensing 144 (2018): 180-188.
Attard, Leanne, Carl James Debono, Gianluca Valentino, and Mario Di Castro. "Image mosaicing of tunnel wall images using high level features." In Proceedings of the 10th International Symposium on Image and Signal Processing and Analysis, pp. 141-146. IEEE, 2017.
Attard, L., Debono, C. J., Valentino, G., di Castro, M., and Tambutti, M.L. B. (2018, October). "An RGB-D video-based wire detection tool to aid robotic arms during machine alignment measurement." In 2018 IEEE International Conference on Imaging Systems and Techniques (IST) (pp. 1-6). IEEE.
Attard, L., Debono, C. J., Valentino, G., di Castro, M., Osborne, J. A., Scibile, L., and Ferre, M. (2018, October). "A comprehensive virtual reality system for tunnel surface documentation and structural health monitoring." In 2018 IEEE International Conference on Imaging Systems and Techniques (IST) (pp. 1-6)

People recognition and vital monitoring

- New radar system to increase current system capabilities
  - People search and rescue is of primary interest in disaster scenarios



Vision system (2D Laser, radar, thermal and 2D-3D camera)



Online respiration monitoring

Online people recognition and tracking

Ivanovs, Arturs, et al. "Multisensor Low-Cost System for Real Time Human Detection and Remote Respiration Monitoring." *2019 Third IEEE International Conference on Robotic Computing (IRC)*. IEEE, 2019.

Impact

Industry

- Problems to solve (a “solution deficit”)
- Technology and experience
- A need for qualified staff
- Limited budgets

Universities

- A “problem deficit”
- Research expertise
- Training skills
- Well-qualified students looking for jobs

Summary

- To apply robotic solutions in unstructured or semi-structured Big Science Facilities, the adaptability of the deployed robotic systems is crucial

- Robotic operator training is expensive and time consuming, and for highly dexterous tasks experts technicians are needed → Needs to have user friendly and transparent human robot interfaces to increase operators proprioception and to allow expert technician to do dangerous tasks in remote

- Industry should have more “influence in driving” university R&D towards practicality and real-world problems/application

Thank you for your attention

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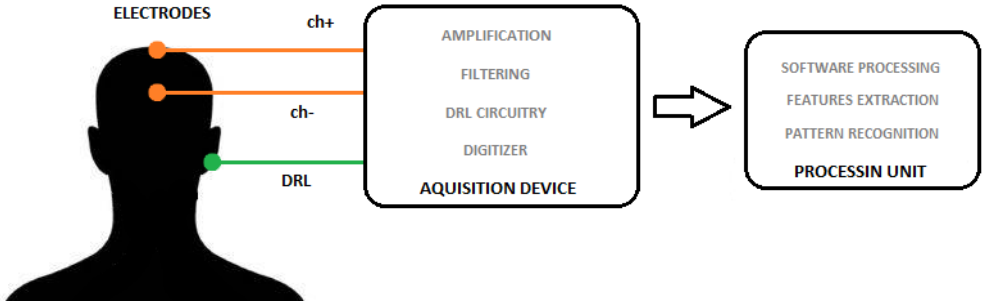
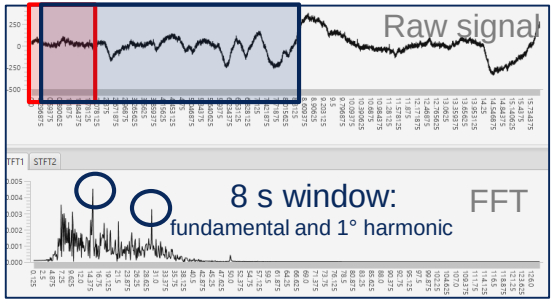
Brain-Robot Interface for robot arm control

- Online analysis of brain signal
- Augmented reality glasses used for commands display
- Eyes focus point detected by CNN processing Steady State Visual Evoked Potentials (SSVEP [15]) which are synchronous responses produced in the visual cortex area when observing flickering stimuli

Hardware used for the brain monitoring





Example of brain activity monitoring

Brain-Robot Interface for robot arm control