19th Int. Conf. Accel. Large Exp. Phys. Control Syst. ICALEPCS2023, Cape Town, South Africa JACoW Publishing
ISBN: 978-3-95450-238-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2023-MO3A007

CONTROL DESIGN OPTIMIZATIONS OF ROBOTS FOR THE MAINTENANCE AND INSPECTION OF PARTICLE ACCELERATORS

A. Díaz Rosales*†[1,2], H. Gamper*[1,3], M. Di Castro[1]
[1] European Organization for Nuclear Research (CERN), 1211 Meyrin, Switzerland
[2] Department of Cognitive Robotics, Delft University of Technology, 2628 Delft, The Netherlands
[3] Johannes Kepler University, Linz, 4040 Linz, Austria

Abstract

Automated maintenance and inspection systems have become increasingly important over the last decade for the availability of the accelerators at CERN. This is mainly due to improvements in robotic perception, control, and cognition and especially because of the rapid advancement in artificial intelligence. The robotic service at CERN performed the first interventions in 2014 with robotic solutions from external companies. However, it soon became clear that a customized platform needed to be developed in order to satisfy the needs and in order to efficiently navigate through the cluttered, semi-structured environment. This led to the formation of a robotic fleet of about 20 different robotic systems that are currently active at CERN. In order to increase the efficiency and robustness of robotic platforms for future accelerators it is necessary to consider robotic interventions at the early design phase of such machines. Task-specific solutions tailored to the specific needs can then be designed, which in general show higher efficiency than multipurpose industrial robotic systems. This paper presents the latest developments and techniques for designing and developing robotic systems that are specific to certain tasks, such as maintenance and inspection in particle accelerators. We explore the necessary requirements for a robotic system, including the control strategies that are applied, and the optimization of the system's topology and geometry.

INTRODUCTION

The fourth industrial revolution, the current trend of automation and data interconnection in industrial technologies, is leading to a boost for maintenance and availability for space applications, warehouse logistics, particle accelerators, and harsh environments [1]. The main pillars of Industry 4.0 are the Internet of Things (IoT), Wireless Sensors, Cloud Computing, Artificial Intelligence (AI) and Robotics. Core to success and future growth in this field is the use of robots to perform various tasks, particularly repetitive, unplanned, or dangerous tasks, which humans either prefer to avoid or are unable to carry out due to hazards, size constraints, or the extreme environments in which they take place.

During the last decade at the European Organization for Nuclear Research (CERN) [2], robotic technologies have been developed and integrated within the accelerators to support maintenance tasks reducing human exposure to hazards and boosting machines availability [3]. The advancements in robotic perception, control, and cognition, particularly in artificial intelligence, have contributed to this development. The CERN robotic service initially used external company solutions for interventions but later had to create customized platforms to meet their specific requirements and navigate the cluttered and semi-structured environment efficiently. This led to a robotic fleet of about 20 different robotic systems [4,5]. In order to increase the efficiency and robustness of robotic platforms for future accelerators it is necessary to consider robotic interventions in the early design phase of new machines. Task-specific solutions tailored to particular needs can then be designed, which in general show higher efficiency than universal robotic systems [6, p. 284].

This approach is currently applied to the design of the new robotic manipulators at CERN. This paper presents the latest progress in producing a task-specific robotic system designed for maintenance and inspection. We will use the 100 km long main tunnel of the Future Circular Collider as an example, along with a system for examining Radio Frequency cavities. The requirements for such a robotic system are described in the Section on *Requirements and Restrictions*. Based on these findings a design optimization concerning the topology and geometry of the robotic system was performed and used as a starting point for the mechanical design of the different components (Section *Design Optimization*). The structure of the control strategies used on these robots is discussed in the Section on *Control Strategies*, while the Section on *Software Architecture* explains the workflow of the software developments and their deployment on the robots. The two different use cases are then explained in their own sections before concluding with opportunities for future work.

RELATED WORK

We initially compared universal systems to task-specific solutions. Universal systems excel in unstructured environments demanding advanced locomotion, perception, and cognition, but they can become complex and less robust due to numerous components. In contrast, task-specific systems excel in structured environments, optimizing efficiency, availability, and robustness.

Considering the semi-structured nature of most of the environments found at CERN, we decided to focus on task-specific systems tailored to specific needs. We conducted a study looking at relevant examples from other facilities:

Joint European Torus (JET): JET's task-specific robotic system [7] excels in the challenging tokamak chamber, per-

---

* Equal contribution of authors.

† alejandro.diaz.rosales@cern.ch

Content from this work may be used under the terms of the CC BY 4.0 licence (© 2023). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI

Content from this work may be used under the terms of the CC BY 4.0 licence (© 2023). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI

forming critical tasks and enhancing operational efficiency and safety. It is highly tailored to JET's specific operations.

International Thermonuclear Experimental Reactor (ITER): ITER's task-specific robotic system [8–12] contributes to safe and efficient fusion reactor operations. Each robot is designed for specific tasks, from maintenance within the plasma chamber to complex component assembly.

Spallation Neutron Source (SNS): SNS's specialized robots [13] handle experiments in high-radiation environments with precision. They enable safe and efficient sample manipulation for neutron scattering experiments, supporting research across multiple scientific domains.

European Spallation Source (ESS): ESS's task-specific robots [14] will operate in high-radiation and extreme temperature conditions, positioning samples for neutron scattering experiments. They will enhance research precision and safety across various scientific disciplines.

These examples emphasize the need for efficient and robust task-specific solutions in demanding facilities like the Large Hadron Collider (LHC) or the Future Circular Collider (FCC).

REQUIREMENTS AND RESTRICTIONS

To begin building a robotic system, it is essential to comprehend its requirements and limitations. At CERN, before constructing a new system, all departments involved in its operation gather and provide input on the robotic system's requirements. Based on a decade of experience in remote interventions, the robotic section at CERN categorizes these requirements into three groups: General, Maintenance, and Emergency. The first category contains those requirements that are common among most of the designs, such as:

- Fully Autonomous Interventions.
- Detect Hazards.
- Robust Control.
- Low Maintenance.
- Reliable/Redundant Power Supply.
- Robust Communication.
- Intuitive Human-Robot Interface (HRI).
- Dexterity in Maneuverability.
- No Further Contamination by Robot.

DESIGN OPTIMIZATION

The requirements of the robotic system are expressed in a way that allows them to be used in an optimization problem. This helps to find the best possible design for the system. Specifically, the focus of the optimization is on creating the most optimal manipulator design in terms of topology and geometry. During this phase a novel algorithm for simultaneous optimization of topology and geometry was developed and presented in [15, 16]. The algorithm departs from a predefined design space $\mathbf{p}$ on which model pruning

$$\begin{aligned} \min_{\mathbf{x},\,\mathbf{p}} \quad & J\left(\mathbf{x},\ \mathbf{p}\right) \\ \text{s.t.} \quad & \mathbf{f}(\mathbf{x},\ \mathbf{p}) - \mathbf{z}_d = \mathbf{0} \\ & -\mathbf{c}\left(\mathbf{x},\ \mathbf{p}\right) \leq \mathbf{0} \\ & \mathbf{ub}\left(\mathbf{x},\ \mathbf{p}\right) \leq \mathbf{0} \\ & \mathbf{lb}\left(\mathbf{x},\ \mathbf{p}\right) \leq \mathbf{0} \end{aligned} \tag{1}$$

will be applied. The objective function $J\left(\mathbf{x},\ \mathbf{p}\right)$ then resembles a pruning function, see [15]. $\mathbf{p}$ contains the N geometric parameters or link lengths of the candidate linkage and $\mathbf{x}$ represents the points of interest the manipulator has to reach. The equality constraint ensures that the desired end position will be reached, while the first inequality constraint implements collision avoidance and the last two inequality constraints contain the joint limits.

The results of the design optimization are used as a starting point for an iterative process where robot links are designed and motors and power supply are selected. First, a dynamic model of an initial robot design was generated and fed into numerical simulation tools that allowed the required motor torques and eigenmodes for the current mechanical design to be found. The CAD model was then updated according to this data using Finite Element (FE) methods in combination with generative design methods and considering design parameters like eigenmodes and elasticity (maximum displacement at the end-effector).

Throughout the various stages and iterations of the design process, it may be necessary to make adjustments for solutions that have a high manufacturing cost. For example, finding a compromise between the benefits of improving the robot's structural payload/weight ratio and the price can be crucial.

CONTROL STRATEGIES

Proper control is needed to be able to use a robot and its accessories to their maximum potential. The software used in a robot is specifically designed for an environment and a set of tasks, and must consider all its characteristics and be robust, expandable, and adaptable to CERN's needs. Designing and choosing the wrong control technique for a specific task can negatively affect the overall performance of the system.

The method of designing robots explained in the previous section has resulted in the construction of robots with more complex topologies, for example with highly redundant manipulators. There are two ways in which we control the motors for these robots at a low level. If the design is custom-made and built in-house, we use the CANopen protocol over CAN or EtherCAT to communicate with the motor drivers. However, if we integrate commercial arms as an extension of our robots, we use the manufacturer's API to control them. To effectively operate these manipulators in real time, a new control system is required. This highlights the necessity for a versatile robot motion controller at CERN that can adapt to any future robotic system setup.

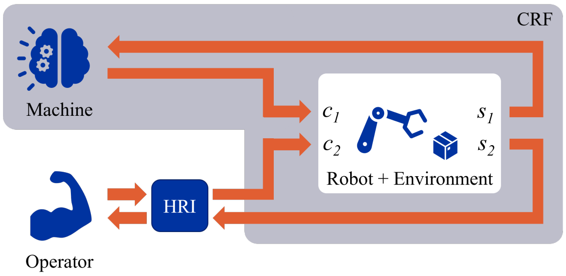


Figure 1: Semi-Autonomous Control strategy, where the CERN robotic framework [3] is taking care of all the autonomous signals and the communications towards and from the robot actuators and sensors. The HRI processes and gives feedback to the human operator. Image adapted from [20].

Certain CERN tasks can be anticipated, allowing operators to choose the appropriate tools and control methods, and occasionally test the process in a secure location. These tasks may therefore be accomplished with greater autonomy, sometimes referred to as *Supervised Autonomy*. However, unforeseen emergency interventions require immediate action. In such cases *Direct Teleoperation* is often imposed. This is due to the fact that many unplanned or emergency interventions still necessitate human perception and cognition to comprehend complicated situations and decide how to intervene. Regardless of the accelerator, this classification is expected to apply even to future facilities, such as the FCC.

The control of the robot must be able to adapt to what the human operator believes is pertinent. This is known as Shared Control, where both the robot and the human operator can influence its movements, with varying degrees of influence from each party [17–19]. There are three types of control strategies [20], namely Semi-Autonomous Control (SAC), State-Guidance Shared Control (SGSC), and State-Fusion Shared Control (SFSC). At CERN, SAC is the most commonly used strategy during interventions. This approach separates the signals controlled by the autonomous system and the human operator (Figure 1).

Gaofeng Li [20] classified the SAC strategy into two types: low-level autonomy and parallel autonomy. Low-level autonomy involves human operators making decisions and issuing commands for higher-level variables, while an autonomous controller manages low-level constraints that may not be intuitive to humans. On the other hand, parallel autonomy involves both human operators and autonomous controllers concurrently controlling separate variables.

A low-level autonomy feature that is needed for the controller of some CERN robots is a Kinematics Library that can handle this highly redundant mechanical structure. The new inverse kinematics algorithm includes a Jacobian-based redundancy resolution with task prioritization and additional optimization of arbitrary deterministic measures based on the robot configuration. The novel contribution of the developed algorithm is that it allows for smooth switching between lower-priority tasks. This was a required feature by the robot operators at CERN, who for example wanted to turn on and off the collision avoidance, lock a certain joint, enable cyclicity, or move a robot only using the wheel or only using the arm motors. The complete algorithm can be written down as

$$\begin{aligned}\dot{\mathbf{q}} &= \mathbf{J}_1^{\dagger}\left(\dot{\mathbf{z}}_{ref,1} + \mathbf{K}_1\theta_1\right) \\ &\quad + \sigma_{\theta_2}(t)\underbrace{\left(\mathbf{I} - \mathbf{J}_1^{\dagger}\mathbf{J}_1\right)}_{\mathbf{N}_1}\mathbf{J}_2^{\dagger}\left(\dot{\mathbf{z}}_{ref,2} + \mathbf{K}_2\theta_2\right) \\ &\quad + \sigma_{\tau}(t)\underbrace{\left(\mathbf{I} - \mathbf{J}_{1,2}^{\dagger}\mathbf{J}_{1,2}\right)}_{\mathbf{N}_{1,2}}\mathbf{W}^{-1}\frac{\partial\tau}{\partial\mathbf{q}},\end{aligned} \tag{2}$$

with the gains σ_{θ_2} and σ_{τ} for smooth en- or disabling of the tasks θ and τ. This has already been proven very valuable for efficiency and can reduce the stress on operators.

The details of the Kinematics Library will be published in a different article. This library relies on two files, a custom configuration file and a URDF description of the robot that provides all the necessary information about the robot and its surrounding environment. These files also enable the real-time controller to execute a wide range of tasks, from simple point-to-point motion trajectories to complex movements that take advantage of the robot's characteristics.

One example of parallel autonomy that is being explored and tested is Variable Impedance Control (VIC), where the objective is to adapt the contact forces to the task characteristics [21, 22]. This control method imitates the way humans naturally adjust the stiffness of their muscles when they interact with objects that have varying rigidity. The impedance can be represented using a mass-spring-damper model [23]

$$F = M\ddot{x} + D\dot{x} + Kx \tag{3}$$

where the interaction force is defined by F. The vector $x \in \mathbb{R}^6$ is the displacement. $M \in \mathbb{R}^{6\times 6}$, $D \in \mathbb{R}^{6\times 6}$ and $K \in \mathbb{R}^{6\times 6}$ are the inertia tensor, damping, and stiffness matrices, respectively.

As the variety of interventions increases, more features and control schemes are being considered during the development of this motion controller, while ensuring the stable and robust behavior of the system.

SOFTWARE ARCHITECTURE

The onboard control of the entire robotic fleet at CERN is achieved using a Single Board Computer (SBC) running the CERN Robotic Framework (CRF), with the majority of the software being written in C++, complemented by some modules in Python [3]. In certain instances, the safety of the robots relies on Programmable Logic Controllers (PLCs).

When it comes to the human-robot interface (HRI), the focus is on making it user-friendly for the operator. To achieve this, an enhanced augmented reality visual HRI has been created in Unity, utilizing the Microsoft HoloLens2 [24–26]. The robot models are projected into the room, displaying the environment in which it operates, as well as its current state and configuration. This allows for a clear and intuitive understanding of the situation. Figure 2 depicts an example of this technology in use.

Content from this work may be used under the terms of the CC BY 4.0 licence (© 2023). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI

Content from this work may be used under the terms of the CC BY 4.0 licence (© 2023). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI

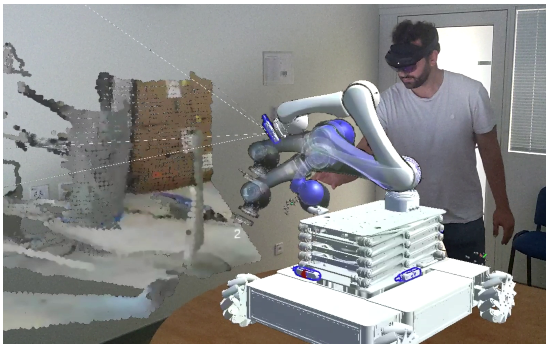


Figure 2: Operator using the CERN human-robot interface based on AR featuring a mobile platform with an attached robotic arm [26].

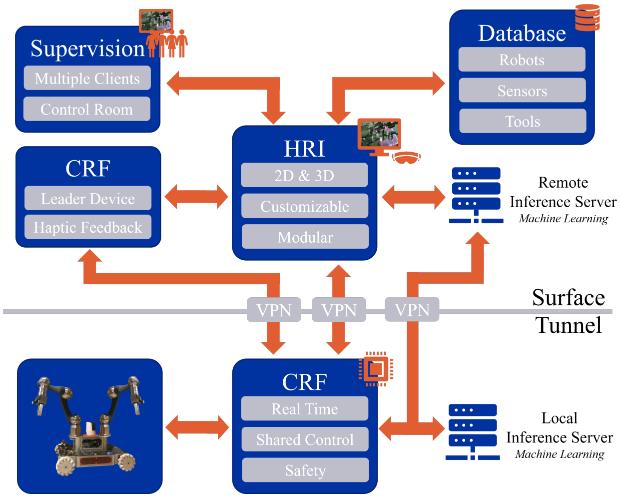


Figure 3: Architecture of some of the systems involved in the control of the robots.

In Figure 3, all the components that contribute to the control of a CERN robot are shown. The only aspect not displayed in the picture is the safety feature managed by the PLC, as it is not present in all the robots.

When undertaking a new project or intervention, it may be necessary to utilize or create new robots, sensors (such as cameras, lidars, IMUs, radiation sensors, and force-torque sensors), or actuators (such as grippers and screwdrivers). Some of these devices may be designed in-house, like the manipulators created with the method described in this paper, while others may need to be purchased, such as cameras or other sensors.

The initial step involves integrating the device into the CRF in accordance with predefined guidelines and a set style. This will enable the device to be easily used in any other robotic systems currently deployed. To accomplish this, one must ensure that any external library or API required is compatible with those already running on the robots. If there are no compatibility issues, the device will be accepted for integration. Subsequently, it will be integrated into an existing module within the CRF if it fits. If not, a new module will be created with a proper interface defining all the functions. Each functionality will be adequately tested and added to the unit and integration testing. This is a standard procedure in many IT companies to ensure that any new device will work correctly without affecting any already implemented module or being affected by any future device. Once all these requirements are met, the code to control the new device will be deployed to all the robots. Figure 4 shows the described workflow.

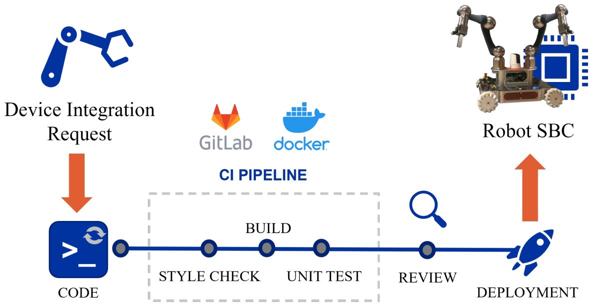


Figure 4: General workflow of the integration of any new device within the CRF, where tools like GitLab and Docker are used.

Table 1: Maintenance and Emergency Requirements of the FCC Manipulator

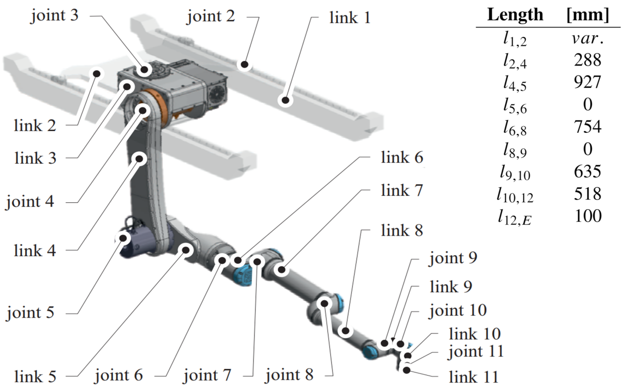
	Requirements
Maintenance	Cover full work space
	Stable movement along tunnel axis
	Pass Fire Doors
	Robust Collision Avoidance
	High Dexterity Manipulator
	Autonomous operation
	Operate in cluttered work space
	Specific Tools
	Tool Changer
	Fast Interventions
	Modularity
	Teleoperation with Haptic Feedback
	End-effect payload ~ 15 kg
	Material transport Payload ~> 50 kg
Emergency	Not Blocking Emergency Ways
	Specific Tools (Infrared Camera, Radar, Locate & extinguish fire)
	Move in Harsh Cluttered Environment
	Robot Speed ~ 34.2 km/h

CASE STUDY: FCC MANIPULATOR

During an initial study the environment for the robotic system, based on the current baseline of the FCC tunnel, was analyzed. This led to a clear definition of the workspace for the robot with a cross-section of roughly 5.5 × 3.4 m. The table of requirements is presented in Table 1.

Applying the model pruning technique to the initial design space leads to the optimal design. Figure 5 shows the optimal topology and geometric parameters, which in this

ISBN: 978-3-95450-238-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2023-MO3A007



Length	[mm]
$l_{1,2}$	*var.*
$l_{2,4}$	288
$l_{4,5}$	927
$l_{5,6}$	0
$l_{6,8}$	754
$l_{8,9}$	0
$l_{9,10}$	635
$l_{10,12}$	518
$l_{12,E}$	100

Figure 5: Optimized Geometry and Topology (11*DoF*) [15].

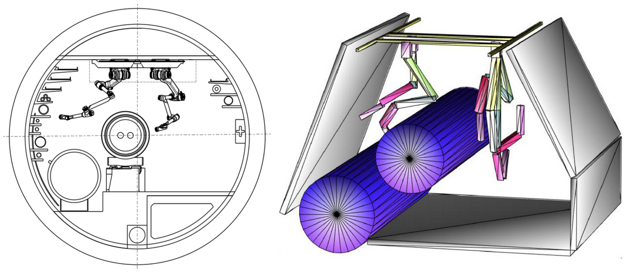


Figure 6: First visualization of the optimal manipulator in the FCC-hh cross-section, based on the design optimization results. The image on the right shows the collision objects used for the optimization [15].

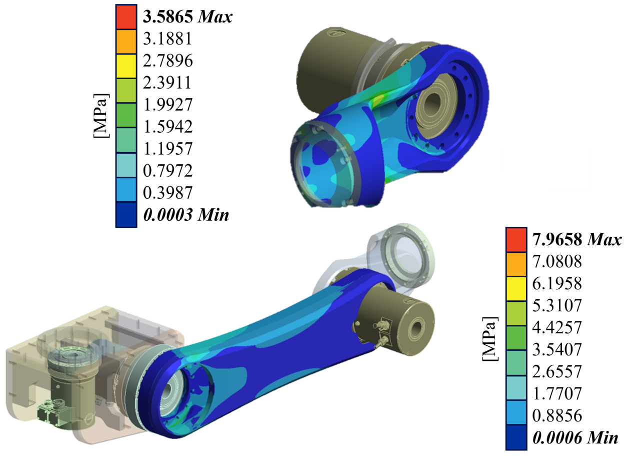


Figure 7: FE analysis and topology optimization results.

case are the link lengths of the manipulator, with e.g. $l_{2,4}$ the link length between joint 2 and joint 4. Figure 6 shows the environment used during the optimization.

Figure 7 shows the result of the FE analysis in combination with the generative design methods for the first two robot links. The generative design algorithms were tuned to converge to results, which can be manufactured using 6DoF milling and turning machines. More sophisticated topologies and increased payload to robot weight ratios have been generated during the design process but were discarded due to the high manufacturing costs.

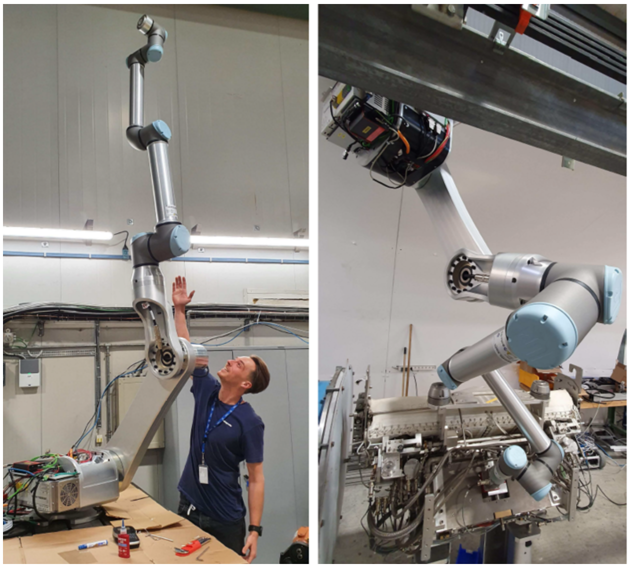


Figure 8: Prototype in the mock-up of the LHC tunnel.

The final design of the FCC robot prototype is shown in Figure 8. In order to quickly produce a working prototype for proof of concept studies, the last 6 joints of the whole robot were replaced by a commercial solution from Universal Robot, namely the UR10e. The choice for the UR10e was made because it resembles a lightweight design with a high payload to robot weight ratio of ~0.3 and the access to low level control of the motors can be done using a Real Time Data Exchange - RTDE protocol.

This prototype has been installed in a tunnel mock-up for proof of concept studies (Figure 8), investigating the efficiency of interventions in an accelerator environment when conducted in a fully autonomous or teleoperated fashion.

CASE STUDY: RF CAVITY INSPECTION ROBOT

The second use case demonstrates the design of an inspection arm for Radio Frequency (RF) cavities used in particle accelerators. Figure 9 shows the geometry of the RF cavity. The inspection arm has to follow the surface at a constant distance and take high resolution pictures that will be stitched together such that a computer vision algorithm can detect the smallest imperfections that could lead to poor performance of such cavities.

Figure 10 shows the topology and geometry that defined the design space for the inspection arm. The design space showed five DoFs and a somewhat reasonable guess for the link lengths.

The design space from Figure 10 was the starting point for the design optimization using the model pruning technique. Figure 11 shows the final optimal result of the topology and geometry of the inspection arm. The optimal design results in 3DoF with correspondingly optimized link lengths.

Thus it is clearly visible that the model pruning technique removed unnecessary joints and adjusted the link such that

Content from this work may be used under the terms of the CC BY 4.0 licence (© 2023). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI

Content from this work may be used under the terms of the CC BY 4.0 licence (© 2023). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI

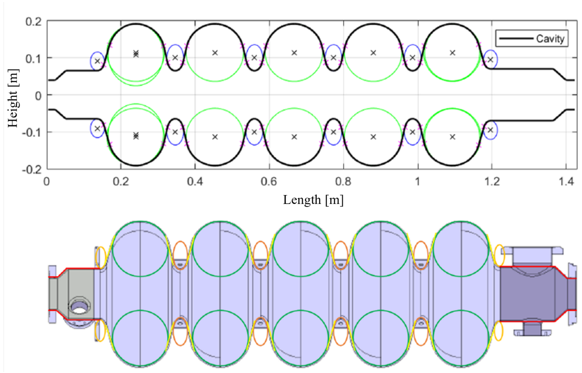


Figure 9: The operation environment of the cavity inspection arm. The inner surface geometry of the Radio Frequency (RF) cavity of LINAC [16].

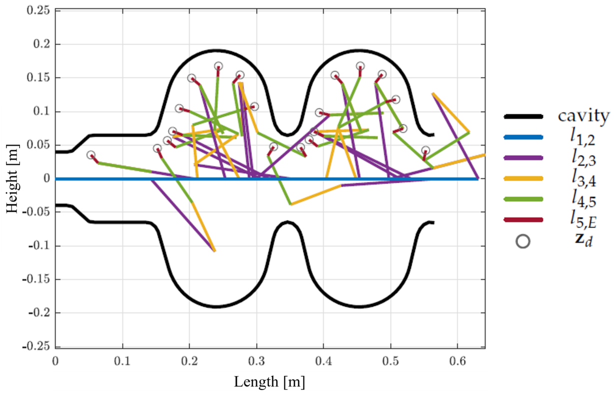


Figure 10: Initial guess for the topology and geometry of the cavity inspection arm [15].

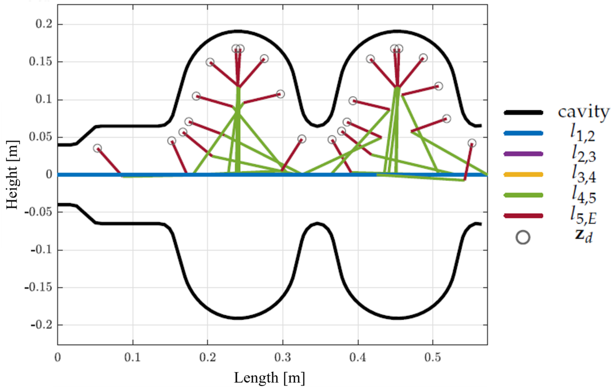


Figure 11: The optimal topology and geometry of the cavity inspection arm after applying the model pruning technique [15].

an optimal configuration according to the applied deterministic measures could be found. This optimal design of the inspection arm was the starting point for the mechanical design of the robotic system. Figure 12 shows the final mechanical design of the robotic arm with $L_{cam} = l_{5,E}$ and $L_{arm} = l_{4,5}$.

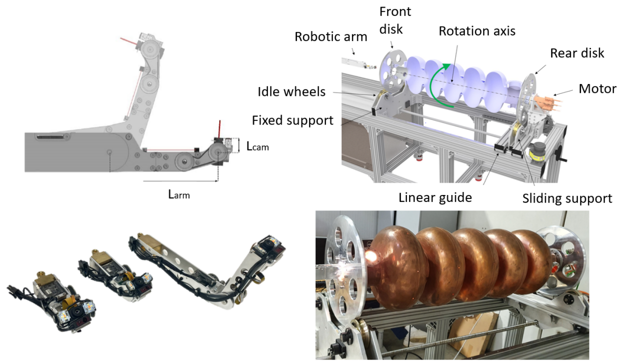


Figure 12: The mechanical design of the robotic arm and its realization based on the optimized design space (left). The 3D model of the RF cavity test stand and a picture of a cavity installed (right) [16].

FUTURE WORK

These case studies are now in their test phase at CERN. The FCC robot prototype is already deployed in the mock-up of the FCC main tunnel, while the RF Cavity Inspection robot is in its final phase of completion. Various studies are being conducted to verify and validate:

- The new real-time motion controller module.
- The new kinematics library.
- The new augmented reality human-robot interface.
- The efficiency in complex interventions and the expected reduction of downtime of the accelerator machine.

CONCLUSION

This paper emphasizes the significant impact of Industry 4.0 technologies, specifically robotics, on improving maintenance and inspection in challenging environments such as those found in particle accelerators.

The evolution of robotic technologies over the past decade, driven by advancements in perception, control, and artificial intelligence, has paved the way for the development of task-specific robotic systems. These systems, tailored to operational needs, have demonstrated superior efficiency, robustness and adaptability, particularly in semi-structured environments like those found at CERN.

The ongoing development of a task-specific robotic system for the FCC exemplifies the transformative potential of this approach. By considering robotic interventions during the early design phase of new machines, we can optimize solutions to meet the specific requirements of complex environments. This proactive strategy not only ensures higher efficiency but also contributes to the safety and availability of the accelerator.

In this pursuit of automation excellence, adherence to a remote maintenance code of practice becomes indispensable. Furthermore, we emphasize the importance of a holistic approach that encompasses all Industry 4.0 tools. This comprehensive perspective allows us to harness the full potential of these technologies for improved maintenance practices in critical industrial and scientific domains.

REFERENCES

[1] F. Chen *et al.*, "Framework of teleoperated and stereo vision guided mobile manipulation for industrial automation," in *Conference on Mechatronics and Automation*, pp. 1641–1648, 2016.

[2] A. Pol, R. Heuer, and P. Stamm, *Inside CERN: European Organization for Nuclear Research*, Lars Müller Publishers, 2013. `https://www.lars-mueller-publishers.com/inside-cern`

[3] M. Di Castro, M. Ferre, and A. Masi, "CERNTAURO: A modular architecture for robotic inspection and telemanipulation in harsh and Semi-Structured environments," *IEEE Access*, vol. 6, pp. 37506–37522, Jun. 2018. `doi:10.1109/ACCESS.2018.2849572`

[4] M. Di Castro, A. Masi, E. Matheson, and L. R. Buonocore, "Robotic solutions for the remote inspection and maintenance of particle accelerators", presented at the IPAC'23, Venice, Italy, May 2023, paper THOGA2, unpublished.

[5] H. Gamper *et al.*, "Adaptive Radiation Survey Using an Autonomous Robot Executing LiDAR Scans in the Large Hadron Collider," *Robotics Research*, 2023, pp. 295–303. `doi:10.1007/978-3-031-25555-7_20`

[6] M. Di Castro, "Novel Robotic Framework for Safe Inspection and Telemanipulation in Hazardous and Unstructured Environments," Ph.D. thesis, CERN, 2019.

[7] A. C. Rolfe, "Remote handling: JET experience," *Commission of the European Communities*, 1999. `https://api.semanticscholar.org/CorpusID:113826471`

[8] D. McGarrigle, E. Flynn, C. Kennedy, A. Loving, and S. Budden, "Analysis of Existing and Proposed Maintenance Deployment Systems Toward DEMO MPD Development," *IEEE Transactions on Plasma Science*, vol. 50, no. 11, pp. 4485-4490, Nov. 2022. `doi:10.1109/TPS.2022.3163466`

[9] L. Gargiulo *et al.*, "Operation of an ITER relevant inspection robot on Tore Supra tokamak," *Fusion Engineering and Design*, vol. 84, no. 2–6, pp. 220–223, Jun. 2009. `doi:10.1016/j.fusengdes.2008.11.043`

[10] H. Wang, W. Chen, Y. Lai, and T. He, "Trajectory planning of tokamak flexible in-vessel inspection robot," *Fusion Engineering and Design*, vol. 98–99, pp. 1678–1682, Oct. 2015, `doi:10.1016/j.fusengdes.2015.05.028`

[11] M. Nakahira, Y. Matsumoto, S. Kakudate, N. Takeda, K. Shibanuma, and A. Tesini, "Design progress of the ITER blanket remote handling equipment," *Fusion Engineering and Design*, vol. 84, no. 7–11, pp. 1394–1398, Jun. 2009. `doi:10.1016/j.fusengdes.2009.03.006`

[12] R. Buckingham and A. Loving, "Remote-handling challenges in fusion research and beyond," *Nature Physics*, vol. 12, no. 5, pp. 391–393, 2016. `10.1038/nphys3755`

[13] V. B. Graves and M. J. Dayton, "Core Vessel Insert Handling Robot for the Spallation Neutron Source," in *ANS Topical Meeting on Emergency Management and Robotics for Hazardous Environments*, Jan. 2011. `https://www.osti.gov/biblio/1042830`

[14] E. Boman and L. Smisovsky, "Remote Handling within the Active Cells Facility at the European Spallation Source, Using Digital Reality Techniques," Master's Thesis, Lund University, 2016.

[15] H. Gamper, A. Luthi, H. Gattringer, A. Mueller, and M. Di Castro, "Kinematic Model Pruning: A Design Optimization Technique for Simultaneous Optimization of Topology and Geometry," *Robotics*, vol. 11, no. 2, p. 31, 2022. `doi:10.3390/robotics11020031`

[16] A. Macpherson, L. R. Buonocore, M. Di Castro, H. Gamper, and A. Luthi, "Camera Placement in a Short Working Distance Optical Inspection System for RF Cavities", in *Proc. SRF'21*, East Lansing, MI, USA, Jun.-Jul. 2021, p. 503. `doi:10.18429/JACoW-SRF2021-TUPTEV010`

[17] D. A. Abbink, M. Mulder, and E. R. Boer, "Haptic shared control: smoothly shifting control authority?" *Cognition, Technology & Work*, vol. 14, no. 1, pp. 19–28, Mar. 2012. `doi:10.1007/s10111-011-0192-5`

[18] A. D. Dragan and S. S. Srinivasa, "A policy-blending formalism for shared control," *The International Journal of Robotics Research*, vol. 32, no. 7, pp. 790–805, Jun. 2013. `doi:10.1177/0278364913490324`

[19] M. Selvaggio, M. Cognetti, S. Nikolaidis, S. Ivaldi, and B. Siciliano, "Autonomy in Physical Human-Robot Interaction: A Brief Survey," *IEEE Robotics and Automation Letters*, vol. 6, no. 4, pp. 7989–7996, Oct. 2021. `doi:10.1109/LRA.2021.3100603`

[20] G. Li, Q. Li, C. Yang, Y. Su, Z. Yuan, and X. Wu, "The Classification and New Trends of Shared Control Strategies in Telerobotic Systems: A Survey," *IEEE Transactions on Haptics*, pp. 1–17, 2023 `doi:10.1109/TOH.2023.3253856`

[21] E. Burdet, R. Osu, D. W. Franklin, T. E. Milner, and M. Kawato, "The central nervous system stabilizes unstable dynamics by learning optimal impedance," *Nature*, vol. 414, no. 6862, pp. 446–449, Nov. 2001. `doi:10.1038/35106566`

[22] P. Song, Y. Yu, and X. Zhang, "A Tutorial Survey and Comparison of Impedance Control on Robotic Manipulation," *Robotica*, vol. 37, no. 5, pp. 801–836, May 2019. `doi:10.1017/S0263574718001339`

[23] N. Hogan, "The mechanics of multi-joint posture and movement control," *Biological Cybernetics*, vol. 52, no. 5, pp. 315–331, Sep. 1985. `doi:10.1007/BF00355754`

[24] K. A. Szczurek, R. M. Prades, E. Matheson, J. Rodriguez-Nogueira, and M. Di Castro, "Mixed Reality Human–Robot Interface With Adaptive Communications Congestion Control for the Teleoperation of Mobile Redundant Manipulators in Hazardous Environments," *IEEE Access*, vol. 10, pp. 87182–87216, 2022. `doi:10.1109/ACCESS.2022.3198984`

[25] K. A. Szczurek, R. M. Prades, E. Matheson, R. Cittadini, and M. Di Castro, "Enhanced Human-Robot Interface with Operator Physiological Parameters Monitoring and 3D Mixed Reality", *IEEE Access*, vol. 11, pp. 39555-39576, 2023. `doi:10.1109/ACCESS.2023.3268986`

[26] K. A. Szczurek, R. M. Prades, E. Matheson, J. Rodriguez-Nogueira, and M. Di Castro, "Multimodal Multi-User Mixed Reality Human–Robot Interface for Remote Operations in Hazardous Environments," *IEEE Access*, vol. 11, pp. 17305–17333, 2023. `doi:10.1109/ACCESS.2023.3245833`

Content from this work may be used under the terms of the CC BY 4.0 licence (© 2023). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI