

UNIVERSIDAD POLITÉCNICA DE MADRID
Escuela Técnica Superior de Ingenieros Industriales



New methods for remote handling robotic
procedures applied to environments under
radiation

DOCTORAL THESIS

Submitted for the degree of Doctor by:

Violeta Isabel Redondo Gallego

Master in Automation and Robotics

Madrid, 2025



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*If science fiction is the mythology of modern technology,
then its myth is tragic.*
Ursula K. Le Guin

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Abstract

This thesis focuses on remote handling (RH) applied to maintenance procedures in large scientific facilities under radiation environments. Remote handling consists of using robotic systems to execute tasks that could present any hazard to humans.

The contributions presented in this work are the result of a careful and deep study of the available state of the art and the ongoing collaboration with different scientific facilities such as CERN (European Organization for Nuclear Research) and IFMIF-DONES (International Fusion Materials Irradiation Facility DEMO Oriented Neutron Source). The topics of interest in this thesis are automation strategies in RH applications, radiation effects on electronic components and robotic tooling design because of their great importance for the advancement of this field.

Traditionally, RH procedures have been performed using teleoperation. This means that a person guided the robot manually throughout the whole operation process, often using a master-slave architecture. However, recently efforts are being done to increase the automation level of RH applications, getting to supervisory control. This control mode consists in the automation of the activities, but always maintaining a human in the loop responsible for validating the advance of the procedure and closing the control loops. This is a key aspect because when implementing a new RH procedure, it is vital to give the operator relevant feedback about the status of the working environment and establish meaningful validation tests to ensure the correct execution of the task. To reach this automation level it is necessary to previously carry out a failure analysis exploring mitigation strategies and courses of action in case of accidents. This thesis proposes a supervisory control diagram for the implementation of new RH procedures and applies it to different real life maintenance activities.

Studying the effects of radiation on electronic components is a key aspect for the maintenance of accelerators and other scientific facilities, because it is very important to guarantee the proper functioning of the equipment introduced in the working environment. Rescue and recovery operations can be complicated due to the restricted access to areas under radiation. For this reason, it is necessary to characterize in advance the radiation exposure limits of the equipment to be used and measure their absorbed dose while working. This thesis presents a detailed study of the available options and suitability depending on the radiation levels expected in the working environment. For this purpose, commercially available radiation hardened devices are analysed, along with the radiation resistance to expect for conventional commercial ones and different mitigation strategies. Theoretical analysis of robotic tools radiation resistance, are presented. And also, real radiation exposure tests performed on servomotors, controllers and a 3 degrees of freedom robotic arm.

Finally, it is important to remark that it is not possible to develop a generic robotic tool to be used in all RH procedures and facilities. It is always advised to use commercial components, however often requirements result in the development of specific custom tools for each task. For this reason, in this thesis a careful study has been done of the existing design methodologies and an innovative classification of the most common RH tasks in maintenance procedure is proposed. The goal of this classification is to remark on the common characteristics of the tools belonging to each group, finding generalities to take into account in the design of future tools. To illustrate this work, several examples of bolting and gripping tools are presented, including the development and laboratory tests for their validation.

In conclusion, this thesis proposes innovative methods for the implementation of new RH applications in environments under radiation, covering from the control architecture to the selection of components and tooling design. Thanks to the ongoing collaboration with different scientific facilities, it has been possible to apply the work developed to the problems they were facing. As a result, the solutions proposed have been validated and are presented in this document.

Resumen

Esta tesis se centra en la manipulación remota aplicada a los procedimientos de mantenimiento de instalaciones científicas con entornos radiactivos. La manipulación remota consiste en el uso de sistemas robóticos para la ejecución de tareas que pueden resultar peligrosas para las personas.

Las contribuciones presentadas en esta tesis son el resultado de un cuidadoso estudio del estado del arte y la colaboración con grupos de manipulación remota en diferentes instalaciones científicas como el CERN (Organización Europea por la Investigación Nuclear) o IFMIF-DONES (International Fusion Materials Irradiation Facility DEMO Oriented Neutron Source). Por su gran importancia para el avance de esta disciplina las contribuciones presentadas en esta tesis se apoyan en tres pilares fundamentales: las estrategias de automatización de procedimientos de manipulación remota, los efectos de la radiación sobre los componentes electrónicos y el diseño de herramientas robóticas.

Tradicionalmente, los procedimientos en los que se ha usado manipulación remota han sido teleoperados. Es decir, la persona a cargo guiaba al robot manualmente en todo momento, normalmente a través de una arquitectura de maestro y esclavo. Sin embargo, recientemente hay un interés creciente por la evolución hacia el control supervisado, caracterizado por la automatización de las tareas, pero manteniendo a la persona a cargo para validar el avance y cerrar los correspondientes lazos de control. Esto es un aspecto clave, ya que para implementar estos sistemas es necesario devolver a la persona información relevante y establecer criterios de validación significativos, garantizando así la correcta ejecución de las tareas. Para llegar a este nivel de automatización es necesario un estudio previo de los posibles fallos y situaciones de emergencia que pueden ocurrir, para elaborar procedimientos de mitigación y gestión. En esta tesis se propone un esquema de control siguiendo la arquitectura de control supervisado y se aplica a diferentes procedimientos reales.

Respecto al efecto de la radiación sobre los componentes electrónicos, es un aspecto clave para el mantenimiento en aceleradores y otras instalaciones científicas, ya que se debe garantizar el buen funcionamiento de los equipos introducidos en el entorno remoto. El acceso a este entorno para el rescate de los equipos puede resultar muy complicado y peligroso, por lo que es necesario conocer con anterioridad sus límites de exposición y medir la dosis que absorben. Esta tesis presenta un estudio detallado de las opciones disponibles y más convenientes según el nivel de radiación esperado en el entorno de trabajo. Para ello analiza las diferentes opciones comerciales de dispositivos diseñados para resistir radiación, la resistencia que se puede esperar en los elementos convencionales y diferentes estrategias para aumentar la tolerancia en ambos casos. Se presentan tanto estudios teóricos de resistencia a radiación de herramientas robóticas, como pruebas reales de exposición de controladores, motores y un robot de tres grados de libertad.

Finalmente, es importante destacar que en los procedimientos de manipulación remota es imposible desarrollar una herramienta genérica que pueda ser utilizada en todas las tareas e instalaciones. Siempre se aconseja priorizar el uso de componentes comerciales, pero en muchos casos los requisitos de la planta y del procedimiento son tan exigentes que desembocan en el desarrollo de una herramienta específica para cada caso. Por este motivo, esta tesis realiza un profundo estudio de las metodologías de diseño existentes y propone una clasificación de las tareas más habituales, con el fin de destacar las características más comunes de cada grupo y

encontrar generalidades a tener en cuenta en el diseño de futuras herramientas. Para ilustrar este trabajo se presentan numerosos ejemplos de herramientas de atornillado y manipulación desarrolladas, incluyendo las pruebas de laboratorio llevadas a cabo para su validación. En conclusión, en esta tesis se proponen métodos innovadores para la implementación de nuevas aplicaciones de manipulación remota en entornos con radiación, abarcando desde la arquitectura de control hasta la selección de componentes y diseño de herramientas. Gracias a la colaboración con diferentes proyectos científicos, estos métodos han podido aplicarse a problemáticas existentes aportando soluciones que han sido validadas y se exponen en este documento.

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Abbreviations and acronyms

ARIEL Advanced Rare IsotopE Laboratory

ATE Absolute Trajectory Error

AV Accelerator Vault

BD Beam Dump

BDTL Beam Dump Transport Line

CB Control Board

CCD Charge Coupled Device

CE Cumulative Effects

CERN European Organization for Nuclear Research

CFETR China Fusion Engineering Test Reactor

CMOS Complementary metal–oxide–semiconductor

COT Components of the shelf

DD Displacement Damage

DEMO DEMOnstration power plant

DMR Double Modular Redundancy

DoF Degrees of Freedom

EDAC Error Detection And Correction

ENEA Italian National Agency for New Technologies, Energy and Sustainable Economic Development

EPROM Erasable Programmable Read-Only Memory

FAT Factory Acceptance Test

FMEA Failure Mode Effect Analysis

HEBT High Energy Beam Transport

HFTM High Flux Test Module

IFMIF-DONES International Fusion Materials Irradiation Facility DEMO Oriented Neutron

Source

ITER International Thermonuclear Experimental Reactor

JET Joint European Torus

KIT Karlsruhe Institute of Technology

LHC Large Hadron Collider

LOA Level of Automation

MOS metal-oxide-semiconductor

NASA National Aeronautics and Space Administration

NASREM NASA/NBS Standard reference model for telerobot control system architecture

NIEL Non-ionizing Energy Loss

NMR N Modular Redundancy

PWM Pulse-Width Modulation

QDS Quick Disconnection System

Rad-hard Radiation hardened

RH Remote Handling

RHBD Radiation Hardening By Design

RHE Remote Handling Equipment

RIR Radiation Isolation Room

SAT Site Acceptance Test

SEE Single Event Effect

SEU Single Event Upset

SM Servo motor

TC Test Cell

TCP Tool Centre Point

TID Total Ionizing Dose

TMR Triple Modular Redundancy

UPM Universidad Politécnica de Madrid

Chapter 1

Introduction

1.1 Overview

Remote handling (RH) consists in using robotic systems to perform activities that could present a threat for humans (Siciliano & Khatib, 2016). In the literature most of the definitions remark that it always involves a human in the loop, as the majority of the tasks need the intuition and intelligence of human beings (EUROfusion, n.d.). The goal of RH is extending the sensing and manipulative capability of the human operator into a remote and often hostile and unstructured environment to carry out a wide variety of tasks (Bicker et al., 2004).

The term RH is widely used in the nuclear sector, in other fields is more common to refer to it as telemanipulation or telerobotics. The difference between these two often relates to the automation level of the system. If the control is purely manual it is called telemanipulation, whereas for more automated systems usually telerobotics is preferred.

According to Siciliano and Khatib (2016), RH was first used in the 1940s, when Raymond C. Goertz developed the first system to enable humans protected by shielded walls to handle radioactive material. It quickly became a research field of high interest in the nuclear industry resulting in the creation of more complex and capable systems. However, as RH started to be developed it became attractive to other applications, such as underwater robotics (Xia et al., 2023), space teleoperation (Fong et al., 2013) or surgical robotics (Evans et al., 2018).

A nuclear related field where RH became a key aspect is the maintenance of large scientific facilities, for example, particle accelerators or fusion research centres. The pioneer scientific facility for RH maintenance is JET, where in 1998 the first ever fully remote operations were achieved successfully (Rolfe, 2007). The goal was to replace the divertor of the facility.

Since then, RH has greatly spread worldwide, and it is now a key aspect in the maintenance of large scientific facilities (Buckingham & Loving, 2016; David et al., 2009). In some of them RH has been introduced after the construction of the plant, gradually adapting maintenance tasks to be performed by robots. Several examples of this can be found at CERN, where now is used MIRA robot to perform radiation surveys in the tunnel (Forkel, 2024), among many other RH interventions.

A different scenario can be found in large scientific facilities currently under development, as RH is being taken into account since the design phase. This means that requirements for the robotic maintenance are being considered in the design of plant components and the necessary robotic interfaces are being included. Some examples of this are IFMIF-DONES (Miccichè et al., 2019), ITER (Lyytinen et al., 2021) and CFETR (Zhao et al., 2020). In Di Gironimo and Grazioso (2021) is detailed how taking into account RH since the design of the facility impacts the layout of the systems and components, as it is necessary to guarantee the accessibility of the RHE to enable the maintenance. Additionally, Wolff et al. (2017) relates to the impact made by the variation of the aspect ratio and number of toroidal field coils to the RH system of DEMO.

As mentioned before, it is very useful to consider RH since the design phase of the facility, another key aspect of RH applications is to carry out a continuous improvement of the system. For example, in Dayton (2018) the author explains the changes made to the equipment throughout the years to improve the safety of the operators and the reliability of the maintenance activities. Also, the lessons learnt by RH teams over the years and how their philosophy towards the maintenance procedures has evolved. Now they have become more conscious about the importance of equipment flexibility and the crucial role of recovery plans among

other aspects.

Remote handling plays a very important role in guaranteeing the safety (Maekawa et al., 2015), reliability (Rathod et al., 2024), maintainability (Di Gironimo & Grazioso, 2021) and availability (Hall et al., 2024) of large nuclear scientific facilities. It protects workers from radiation exposure and enables maintenance in areas with access constraints. Furthermore, it increases the availability of the plant as it minimizes the operation time for the maintenance procedures (Gitardi et al., 2022). In addition to this, RH also aims to increase the automation level of the system getting to a supervised control architecture.

Remote handling requires careful planning, which means the modelling of the task that will be performed. This implies selecting the most suitable control architecture, the robotic system to be used and integrating or developing the necessary tools. For this purpose, several modelling methodologies have been developed, they are very useful to assist throughout the whole lifecycle of the RH procedure, from the development of the necessary components to the performance analysis to identify potential improvements, including the training for the operators (Di Castro, 2019).

Besides the lifecycle of a RH activity, it is necessary to implement a control architecture based on the specific needs of the task. In RH is very common to use supervisory control (Sheridan, 1992), where, even though some steps of the procedure are automated, the operator still plays a very important role in the execution of the task, being able to take full control of the system when needed and having to approve the advancement to the following stage throughout the whole procedure.

In previous paragraphs it has been mentioned that this thesis will focus on the RH tasks carried out in radiation areas. This is relevant because humans need to be protected from radiation, and also the exposure of electronic components to ionizing radiation has severe consequences for them (Holmes-Siedle, 2007). Damages caused by radiation can be temporary or permanent, and can be caused by the cumulative radiation absorbed or by stochastic events (Faccio, 1999). For this reasons it is very important to explore radiation mitigation strategies that enable the use of electronics in radiation environments, and also, study the behaviour of this type of components under harsh working conditions. This enables predicting reliably their life span and avoiding critical failures.

As can be deduced from the literature cited about the inclusion of RH since the design phase, designing specific tooling for the different maintenance procedures is crucial for the success of the operation. **RH in large scientific facilities results in the development of very specialized tools to fulfil the particular requirements of a precise task**, for example spatial constraints are usually very demanding, but vary widely from one task to another even within the same facility. To facilitate the design procedure there are several RH handbooks, usually each facility develops their owns. These documents gather common useful strategies to help in the design phase, not only for the tooling but also for the plant systems. They can be combined with a design methodology to provide careful assistance throughout the whole tooling development phase. Handbooks often offer design guidelines, such as using positioning systems (Tesini, 2009; Tripodo, 2024), but design methodologies also include the different stages of the design as carrying out several iterations of the design or creating simulations and mock-ups to preliminarily test the integration of the tool in the RHE.

Even though each RH task has its specific requirements, tools designed for analogous purposes often present some similarities. For example, the pipe cutting tools can use a different cutting

method, or can be deployed from the inside or the outside of the pipe (Ren & Skilton, 2024), but for the design of all of them, some systems will have to be considered, for example, the positioning system, the swarf collection system or the cooling one.

1.2 Motivation

Since the beginning, the goal of telerobotics has been making maintenance procedures safer for people. In particular in facilities under radiation environments, as it was first introduced for the handling of activated components in nuclear power plants (Siciliano & Khatib, 2016). Thereafter, it has become a research field by itself, as it offers plenty of advantages not only for the safety of operators, but also for the functioning of facilities. The variety of tasks carried out by RH has widely spread, nowadays it is possible to perform very complex activities by RH, as cutting and welding of pipes (Thomson et al., 2017) or tightening of bolts (Noguchi et al., 2021). To achieve this level of maturity, RH has faced critical challenges as the teleoperation in real time (Geng et al., 2023) or the human-robot interaction (Rastogi & Srivastava, 2019; Schreiter et al., 2022). And, of course, there are still many other challenges pending to be solved, for instance the adaptability requirements (Benito & Barrientos, 2024) or the demanding mechanical requirements for the tools (Bai et al., 2020; Williams, 2018). Also, the achievable automation level for the systems has gradually increased thanks to RH. An example of this can be found in the development of more efficient vision algorithms (Fahim et al., 2020), the integration of augmented reality (King & Hamilton, 2009; Martínez et al., 2014) and the advancements in many other technological fields (David et al., 2023; Ribeiro et al., 2020). As a result of the improvements made in RH techniques the automation level of the maintenance systems can increase and other industries are becoming interested in it, for example, research facilities.

As science advances towards fusion power plants, or other scientific experiments are designed, there is an increasing need for larger research facilities. For example, at CERN there is an ongoing project to build a larger particle accelerator (Gamper et al., 2024) where remote handling will be a fundamental part for its maintenance. Regarding fusion power plants, they are considered a feasible solution to generate clean and safe energy to satisfy the future energetic needs of our society (Kerekeš et al., 2023). However, they are still under development and many technological breakthroughs are needed in different disciplines in order to achieve it (Kembleton, 2023). This turns out to be extremely challenging for example to material science, as the reactor conditions are highly restrictive (Alba et al., 2022; Duffy, 2010), but also to RH because its performance will have a huge impact, not only in the safety, but also in the availability and economical viability of the facility (Buckingham & Loving, 2016).

So, as RH is constantly advancing and consolidating as a key strategy for the maintenance of these scientific facilities and any other with difficult access or hazardous environments, this thesis aims to contribute to this discipline as a way of enabling science to advance faster towards transforming our society and creating a safer and more sustainable reality.

1.3 Methodology

As explained in the previous section, the motivation for this thesis is to contribute to the field of remote handling as it is considered a key aspect for the advancement of science and therefore society. To achieve the desired contribution it is fundamental to apply an iterative methodology combining simulation tests and experiments using real robots. This enables profiting from the safety and flexibility given by the simulation environments and the reliability and validation provided by the real life tests.

An iterative methodology consists in performing successive design-test-analyse loops to a developed design in order to improve the design with each iteration. As the design advances the type of experiments performed can advance too. For example, at the beginning simulation is very useful to test the feasibility of the idea, and as the design advances real life experiments start to be necessary.

The iterative methodology described above follows the scientific method as it proposes a design, tests it, analyses the results and improves the initial design based on the results obtained. This enables the evolution from the conceptual design to the final one which solves the issues detected during the experiments.

It is important to remark that the tests can be only for a certain feature of the design, not necessary the whole system has to be tested in all phases. Prototypes can be created for this purpose.

In the final iterations of the design the goal of the tests is to validate the prototype. This means defining a validation threshold to certify that the prototype meets the requirements. Usually it also involves comparison analysis, because the final goal is to improve the existing equipment. For example, when developing a new teleoperation architecture it is important to evaluate its performance compared to existing ones. Also it is a key aspect to validate the system in different operation conditions, paying attention not only to normal operation conditions, but also to failure management and emergency scenarios.

Regarding the different types of tests that can be performed, simulating consists in using robotic simulators to model virtually the robotic equipment, the tasks and the environment. The main advantages of this type of testing are related to the easy replication of the experiments and the data recording. Referring to replicating the experiments, they can be repeated many times under similar circumstances even by different people. And regarding data recording, simulation enables registering ground truth data and the use of sensors that could not be feasible in real life experiments. Simulations are useful to validate procedures developed as well as tooling designed, they help in the iteration process improving the designs. Whereas real life experiments consist in performing tests using real physical robotic equipment. Usually this type of experiments are used once the procedures and designs are validated in simulation. They can be carried out using mock-ups or the definitive components. The goal of this tests is to analyse the behaviour of the system in real life, including aspects that could not be included in the simulation such as communication delays. It is required to develop a test bench taking into account the necessary safety aspects and the equipment calibration. Using a combination of all the described approaches results in the development of reliable and validated designs and procedures. The iterative methodology is a continuous improvement strategy that can perform another iteration whenever a new requirement or improvement is identified.

Besides this, the results obtained have been published to get the contributions beyond the projects and help other researchers in the scientific community.

1.4 Objectives and contributions

The main goal of this thesis is to contribute to the progress of remote handling by exploring useful applications and proposing innovative solutions. In particular, this thesis focuses on maintenance procedures in environments under radiation. The methodology followed for achieving this, has been a careful study of the state of the art related to remote handling, identifying the immediate needs of the topic and finally developing and proposing solutions, that have been applied to the maintenance of IFMIF-DONES, CERN and other facilities. The contributions made by this thesis to remote handling are related to three main topics considered key aspects for the success of remote handling applications. These will be explained in the following paragraphs:

- Modelling maintenance procedures for implementing RH activities. After analysing different control architectures, it is proposed a diagram for modelling RH procedures following the supervised control strategy. A relevant aspect of this diagram is that it proposes a solution for the operator to manage a procedure which is not fully automated. On the one hand, it presents the possibility for the operator to take full control of the system whenever it is needed. And, on the other hand, it requires that the operator approves each stage before advancing to the following one. This model has been applied to different real maintenance procedures. Besides, the importance of considering the failure and emergency scenarios is remarked, in particular the need of developing appropriate strategies to handle these situations, and including them in the general diagram of the task.
- Selecting robotic equipment for RH tasks carried out in environments under radiation. The different types of ionising radiation and their effects on electronic components have been extensively studied. Including theoretical estimations of the radiation resistance of different robotic tools. Based on these estimations and the existing literature, examples of robotic system selection are presented. These selections are made according to the radiation levels in the working area. And one of the examples corresponds to the RHE selection for the maintenance of the accelerator system in IFMIF-DONES. In addition to this, the results of radiation exposure tests carried out on several microcontrollers and a custom-made three degree of freedom (DoF) robotic arm are described. Along with these results, the effectiveness of different radiation mitigation strategies is analysed and some recommendations are made based on this.
- Designing tooling to be used in the RH procedures. The existing design guidelines are analysed and a novel design methodology is proposed. The key aspects of this new methodology are that it follows a continuous improvement philosophy, and that it remarks the importance of training the operators with mock-ups, while the new components are manufactured to speed up their commissioning and minimize the eventual failures

due to the unfamiliarity of the person with the new system. Additionally, the different tasks performed are analysed for a better understanding of the corresponding design requirements and available design strategies. Several examples of tools designed following the proposed methodology are detailed and these tools are proposed for specific remote handling procedures at IFMIF-DONES and CERN.

Finally, it is relevant to mention that the contributions in this thesis are backed up by several scientific publications, listed at the end of this document.

1.5 Outline

This thesis includes six chapters presenting different aspects of remote handling robotic procedures:

- Chapter 1. Introduction.
This chapter starts by giving a brief overview on the topic and commenting the motivation for this research, including the objectives of the thesis and the contributions made.
- Chapter 2. State of the art.
Introduces the state of the art necessary for the understanding of the remote handling robotic procedures.
- Chapter 3. Procedure modelling for remote handling tasks.
Focuses on the modelling of remote handling procedures. It explains in detail the aspects to be considered for the modelling of new RH tasks, including the different control strategies and failure scenarios. In addition to this, this chapter presents two examples where all these ideas are applied to IFMIF-DONES.
- Chapter 4. Robots and equipment for environments under radiation.
The subject of this topic is the behaviour of robotic systems when exposed to ionizing radiation. The consequences will be explored as well as strategies to mitigate the potential damages. Also, in this chapter the estimation of the radiation resistance of a custom made bolting tool and the analysis of the behaviour of several electronic components when exposed to ionizing radiation will be presented.
- Chapter 5. Design of tooling for remote handling.
Centres in the design of tools to be used in RH procedures. Proposes a design methodology and a classification of RH tasks according to the type of tool used. Moreover, it details several examples of tools developed throughout this thesis.
- Chapter 6. Conclusions.
Finally, this chapter remarks the main conclusions obtained from the work carried out during this thesis. In addition, some ideas for future works are proposed.

Chapter 2

State of the art

2.1 Automation considerations

This section aims to identify the characteristics a procedure should meet to be automated, as well as the desirable characteristics for automating the procedures. Taking into account the existing bibliography on this topic, the first thing to mention is that according to Sheridan (1992), a procedure is automated when it is automatically controlled by mechanical or electronic devices that take the place of the human in terms of observation, decision, and/or effort.

As explained in Parasuraman et al. (2000), there are four stages of human information processing, which are information acquisition, information analysis, decision-making, and actions. They can all be automated, but the interest in doing so will depend on the specific case. In addition, the level of automation for each stage may vary, depending on the needs of the system. In Calhoun (2022), ten different levels of automation (LOAs) are detailed, going from the lowest, where the human should take all decisions and actions, to the highest, which corresponds to the computer deciding everything, acting autonomously and ignoring the human, Table 2.1.


Levels of automation of decision and action selection		
	10	The computer decides everything, acts autonomously, ignoring the human
	9	The computer informs the human only if it decides to
	8	The computer informs the human only if asked
	7	Executes automatically, then necessarily informs the human
	6	Allows the human a restrictive time to veto before automatic execution
	5	Executes if the human approves to
	4	Suggests one alternative to the human
	3	Narrows the selection down to a few
	2	Offers to the human a complete set of decision/action alternatives
	1	The computer offers no assistance: Human must take all decisions and actions

Table 2.1: Levels of automation. (Calhoun, 2022).

There are two different ways of analysing when a procedure should be automated and to what level. In Parasuraman et al. (2000), the human-centred automation is presented, proposing several aspects to consider. First, the consequences for human performance, including mental workload, awareness of the situation, complacency, and skill degradation. Second, reliability of automation and cost of decision/action outcomes. This means that when automatising a procedure, the objective shall be to achieve the mental workload of the human to be adequate for the system tasks to be performed, while maintaining the situation awareness of the person and preventing complacency that can lead to the operator not finding failures and skill degradation. Whereas in Endsley and Kaber (1999), technology-centred automation is explained, in this case the analysis considers optimising the technological capabilities and the cost reduction.

So, keeping all of this in mind, to reach a high level of automation in a procedure, it is important that it involves straightforward activities that take place in a very structured environment. An example of this is a screwing procedure, as this is a very routine activity, it can free the mental workload of the operator, without decreasing their situation awareness, or affecting negatively their complacency or degrading their skills. In addition to this, existing technology can achieve this task. However, it might be necessary to develop specific tooling to adapt to the particular conditions of the environment, such as be the spatial constraints or the accessibility conditions. It is also important to analyse the most suitable LOA, as this task is very repetitive and is usually part of a bigger procedure. The automation can consist in screwing the bolt and then informing the operator, which corresponds to level seven of the previously mentioned LOAs. However, keeping in mind that depending on the criticality of the task, it might be preferable to choose that the human has a restricted time to veto before the operation is automatically executed, which corresponds to level 6 of automation.

2.2 Evolution from telemanipulation to supervisory control

In some cases, such as the maintenance of scientific facilities involving radiation, procedures have been automated to protect humans from harsh environmental conditions (Allan et al., 2011; Di Gironimo & Grazioso, 2021). At first, these procedures were always teleoperated, which means that the robotic equipment was always guided by the human operator. But nowadays, efforts are being made to achieve higher levels of automation in certain tasks, leading to a faster and safer maintenance (Buckingham & Loving, 2016). However, the human is never taken out of the loop, because of the high cost of automation failure.

This current stage, where some tasks have a high automation level but still need a human operator, uses supervisory control. This term and how it affects the procedure and the operator, will be explained in further detail in this section.

2.2.1 Supervisory control

In Sheridan (1992) supervisory control is defined as the type of control where "one or more human operators are continually programming and receiving information from a computer that interconnects through artificial effectors and sensors to the controlled process or task environment". It can also be understood as an intermediate step between teleoperation and full automation.

Supervisory control can correspond to an automation level between five and seven. The human operator is always taken into the loop, and is possible for them to take full control of the procedure at all times. Using this type of control is attractive for situations where the environment can be predictable, and the complexity and completion time is not too high or too low, see Fig. 2.1. Throughout the whole procedure, the operator checks the correct functioning of the system, and intervenes if necessary.

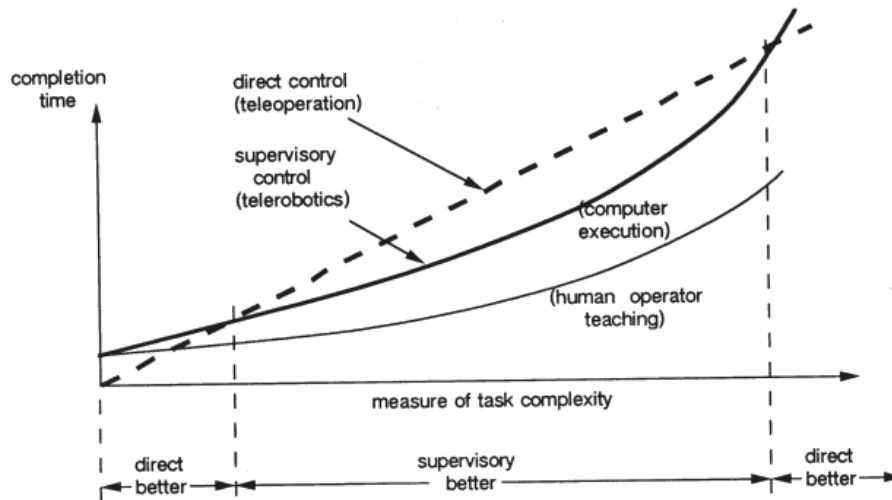


Figure 2.1: Recommended type of control based on the task complexity and the completion time. (Sheridan, 1992)

Some examples of the use of supervisory control can be found in Reniers and Thuijsman (2020), which presents an application of this type of control to product lines. And also in Xu et al. (2021), a method is proposed to apply supervisory control to optimise fuel consumption in hybrid cars.

2.2.2 NASREM

Throughout this work, NASREM has been used as a reference. As explained in Albus et al. (1989), it is a telerobot control architecture developed by NASA to achieve the following results:

- Define the functional architecture of the primitive and servo levels.
- Suggest software and hardware architectures and software development environments.

As seen in Fig. 2.2, NASREM is a hierarchical diagram composed of several rows and columns. Each row corresponds to a different complexity level, starting with the movement of the actuators in the bottom row and moving up to the service management. Referring to the columns, the one on the left corresponds to the sensing, this means reading the information from the sensors, and comparing it with the predicted values. The central column is the model of the world developed for the automation of the task, and it also includes the evaluation of the state of the world combining the memory of the previous states, the sensory information, and the expectation for future states. And finally, the other column involves the task decomposition, including temporal and spatial decomposition, this consists of planning and executing the high level goals into low level actions.

Linking this subsection with the previous one about keeping the human in the loop, it is important to remark that the NASREM architecture includes the operator interface connected to all the different levels in the hierarchy, enabling the operator to take control at any necessary

level. So, they can intervene not only at the higher levels such as the tasks but also at the lowest ones and directly move the actuators.

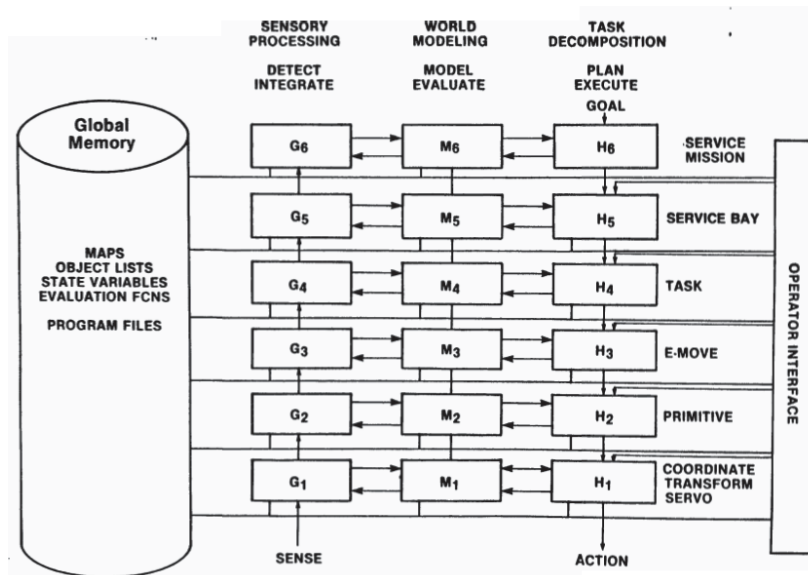


Figure 2.2: NASREM Diagram, telerobot control system architecture. (Albus et al., 1989)

2.2.3 Operator role

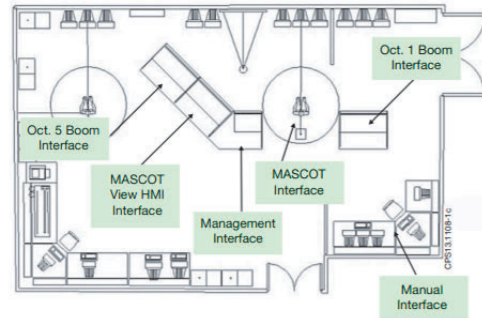
When a procedure is teleoperated, as described in Gentile et al. (2023), the operator has to guide all movements of the robot. If the human and the robot are in different places, it will be very useful to include cameras for the visual feedback as well as sensors for the force feedback. In this type of control, it will be the operator who always closes the control loop, without their action the robot will not do anything. Fig. 2.3 shows an operator at JET controlling the robotic system in the facility to replace components within the tokamak.

Whereas when applying supervisory control, the robot can carry out the necessary actions automatically, while the person checks the right progress of the task validating the execution of the steps. However, the operator can still take manual control whenever they consider. Fig. 2.4 shows how a control room for a procedure using supervisory control and a high automation level can look.

As an example, in the maintenance of one of the components in the beam line in IFMIF-DONES, a failure is detected while opening the drain valve, which is a level three action according to the NASREM diagram, the operator will intervene at the second level, controlling the primitives of the movement. Ideally, the operator will only need to take control at levels one, two, or three. Because if they have to intervene at higher levels, those that correspond to the whole definition of the procedure, it will mean that the planning or modelling of the procedure was not right. In case of identifying these types of failures, it is necessary to take them into account in the evaluation of the procedure execution and implement the necessary improvements.



(a) Operator at JET controlling manually the robotic system to perform maintenance procedures.



(b) Layout of the RH control room at JET.

Figure 2.3: Views of the RH control room at JET. (Collins et al., 2013)



Figure 2.4: Control room for a maintenance procedure using supervisory control and a high automation level. The screens show the information operators need to supervise the ongoing activities.

Also, it is very important to take into account what was discussed in the first section of this chapter. When automating a procedure, the role of the operator shall be taken into consideration to prevent their skills degradation that can lead to them not being able to take control when needed; their complacency, which can lead to unnoticed eventual failures and their situation awareness, which can result in them not following the progress of the operation. Referring to the situations where the operator has to take control, it can be due to two types of events:

- **Non automated task.** If the procedure includes a task that requires manual control, the operator will be in charge of carrying it out. Whenever this task is completed, the person will give control back to the system if considered, they can always maintain the control.
- **Failure detection in the sensors, actuators or the model.** The operator can take

the control of the system to solve any upcoming failures. Whenever the failure is solved, the system can keep going with the execution of the procedure.

2.3 Radiation considerations

This thesis focuses on the RH procedures in environments under radiation, so before going in detail about the behaviour of the electronic components in this kind of environments, it is important to analyse the different types of radiation, their effect in matter and the existing protection strategies.

There are different types of radiation, depending on the mass, charge and energy of the particles producing it, see Table 2.2. Regarding the protection strategies, in Fig. 2.5 the stopping capabilities of different materials for α , β and γ radiation are illustrated (Wang et al., 2017). The penetration of the different particles in matter depends on its energy and other environmental conditions, so this is a generalization.

Radiation	Characteristics	Effects in matter	Protection strategies
Neutrons	<ul style="list-style-type: none"> $m_n = m_{p+}$ Charge: 0 	<ul style="list-style-type: none"> High penetration Ionization 	<ul style="list-style-type: none"> Components with H (water) Capture results in emission of a γ ray
γ and X rays	<ul style="list-style-type: none"> Photons Mass: 0 Charge: 0 	<ul style="list-style-type: none"> Highly penetrating Lightly ionizing 	Thick sheet of material with a large Z (lead)
β , electrons	<ul style="list-style-type: none"> $m_\beta = m_{e-}$ β charge: ± 1 e^- charge: -1 	<ul style="list-style-type: none"> Medium penetration Lightly ionization 	Aluminium sheet is usually enough
Protons	<ul style="list-style-type: none"> Nucleus of a H atom $m_{p+} = 1800 * m_{e-}$ Charge: +1 	<ul style="list-style-type: none"> Low penetration More ionization than β 	Aluminium or plastic package around components
α particles	<ul style="list-style-type: none"> Nuclei of He atoms Mass: 4 Charge: +2 	<ul style="list-style-type: none"> Very low penetration Highly ionizing 	Paper sheet is usually enough

Table 2.2: Characteristics of the different radiation types. (Holmes-Siedle, 2007; Houssay, 2000)

In general, the heavier the particles of the radiation are, the more energetic collisions they can produce, which results in higher ionization. Nevertheless, as shown in Table 2.3, mass also affects penetration in the irradiated material, as these magnitudes are indirectly proportional, expects for neutrons that their lack of charge makes them very difficult to stop. In the literature examples of the effects of the different types of radiation in materials, in particular in electronic components can be found. In Kandlakunta et al. (2022) is analysed the effect of the gamma radiation on silicon solar cells; first theoretically, then by simulation means, and finally comparing those results to the ones obtained experimentally. Another example is P. Li et al. (2022), where the authors evaluate the damage caused due to gamma radiation and

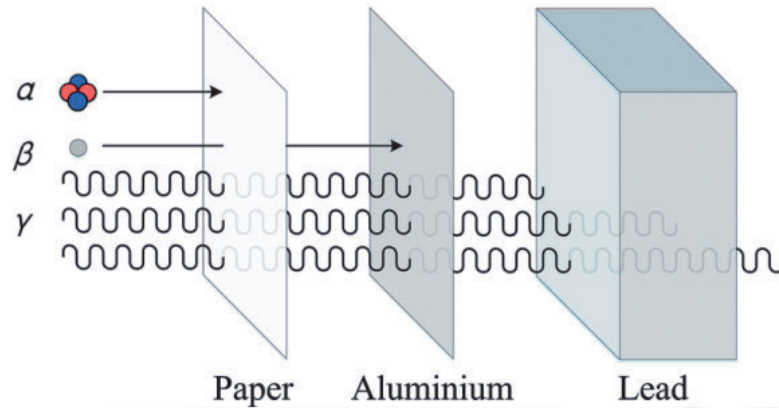


Figure 2.5: Penetration ability of α , β and γ radiation through different materials. Neutrons would be capable of trespassing all those obstacles, and would only be stopped by materials containing H, as water. (Wang et al., 2017)

neutrons, mixed and separately on SiGe Heterojunction Bipolar Transistors.

Penetration ←

Radiation type	n	γ , X rays	β , e^-	p^+	α
Mass of the particles (u)	1	0	$5 \cdot 10^{-4}$	1	4
Charge of the particles	0	0	$\pm 1, -1$	+1	+2

Ionization →

Table 2.3: Penetration and ionization capabilities of the different types of radiations.

2.4 Design considerations and guidelines

In this section, the ideas to bear in mind when designing the tools to be used in a RH procedure will be commented. The first thing to consider is that the tool might already exist in the market, although it has to be adapted for RH. In general, it is always advisable to use commercially available tools even when they have to be slightly modified, rather than designing them from scratch. One of the main reasons for this is that commercial solutions have already been tested and usually are certified.

The requirements and constraints for the tooling design come from different aspects of the RH procedure. Some of them come from the task itself, for example, for a bolting task it is necessary to have a tool that fits with the bolt and is capable of tightening and loosening with the necessary torque, etc. In addition to that, other requirements come from the environmental conditions in which the procedure will take place, for example spatial constraints or radiation

levels, as presented in Saito et al. (2016), where a radiation hardened robotic equipment is developed to withstand the working conditions in the facility.

When adapting existing tools to RH or designing new ones, it is important to make them RH friendly, so they can be easily operated by the RHE. Also, in this section the existing design guidelines advising on what to use and what to avoid when developing the tools and components for a robotic application will be commented.

There exist several collections of guidelines giving advice on how to design RH friendly tooling and components. In Owen and Skilton (n.d.) are listed the considerations for this purpose applied to the RH system in JET, below is presented a generalisation of these topics:

- **Redundancy to guarantee recoverability.** In the sense that the robotic equipment shall have redundant elements to make sure that it will always be recoverable, and always avoid the possibility of any RHE left stranded in the facility. This applies also to the elements of the facility that are foreseen to be transported by RH, it is a good idea to add extra grasping features so they can be attached from the floor and recovered in case of emergency situation.
- **Simplicity and standardisation.** To minimise the risk of failure it is important to develop designs as simple as possible, as a result the components will be easier to use. Also, enhancing standardisation enables easier and quicker remote maintenance procedures, as less tools are needed and, for example, putting the grasping features in the same location for all the components, facilitates the operator the grasping procedure. Linked to the standardisation is the use of high reliability components.
- **Modularity and maintainability.** This is important because the maintenance period of a big science facility is highly costly, so it shall be as short as possible. The idea is that the diagnostics of the RHE are as accessible as possible and that they are modular, so when a component of the system fails it can be changed quickly and easily and the rest of the system can keep working. An example of this can be designing a bolting tool, where the socket wrench can be separated from the rest of the tool, so in case of malfunctioning, it can be replaced and the rest of the tool will still work.
- **Flexibility and reconfigurability.** Thanks to this, the RHE can adapt to new tasks or new technologies without very little change. This is very important in order to guarantee the usability of the system throughout the life-cycle of the facility.
- **Environmental conditions.** This has been briefly commented at the beginning of this section, the environmental conditions will determine the type of technology that can be used. For example, in Owen and Skilton (n.d.) is mentioned that due to the radiation levels expected, they avoid to use conventional encoders because these are more sensitive to radiation than resolvers. Another approach for this situation can be using radiation hardened components.
- **Human in the loop.** As was explained in the section 2.2, it is always a good practice to give the option of manual control even in the autonomous systems, so the operator can be aware of the status of the procedure and intervene if necessary.

- **Integration.** It is fundamental to keep in mind when designing, that the tool will have to be integrated with the rest of the components involved in the procedure and the RHE. This means that, for example, it will have to include compatible interfaces with the other elements in the facility. Also, they have to be able to communicate with the rest of the devices that take part in the same procedures and give feedback to the operator supervising the task, as well as store the operation data to facilitate diagnostics.
- **Laws and regulations.** It is very important to follow the corresponding laws and regulations of the country where the facility is placed.

Particularising to the good practices when designing a tool or a component, there are several RH Handbooks and codes of practice, as "Basic guidelines for the design of remotely maintained components in DONES" (Miccichè, Gioacchino, 2018) or "ITER Remote Handling Code of Practice" (Rajendran & Palmer, 2010), where instructions to make the RH friendly designs of components are given. There are two basic ideas that come up in all the design guidelines:

- Always design bearing in mind to enable a clear view of the procedure while it is taking place. This will make the operation much easier to control and supervise.
- Take into account the spatial needs of the RHE, it is important to guarantee the accessibility and reachability to the components.

Besides that, there are specific guidelines depending on the type of component that it is being designed, some of these are listed in Table 2.4.

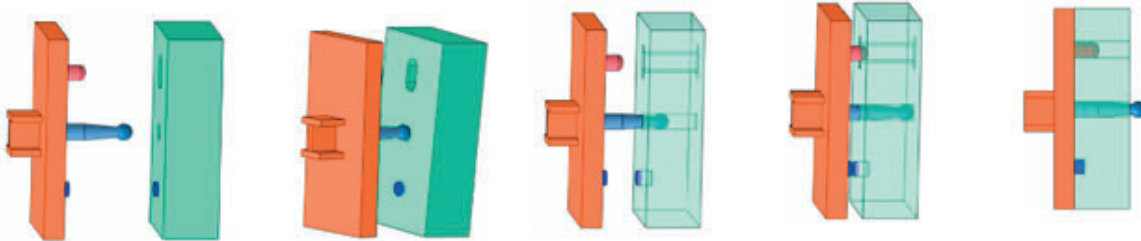


Figure 2.6: Design guidelines for elements that need to be positioned fitting one into the other using pins. (Tripodo, 2024)

It is also remarkable that the best way of designing components suitable for RH is to take into consideration the remote maintenance since the design phase of the facility, and carry out simulations and other checks to test the feasibility of the procedures designed, this idea is mentioned in Miccichè, Gioacchino (2022). Thanks to this, the specifications coming out from RH analysis will be included in the general engineering specifications of the facility since the earliest stages.

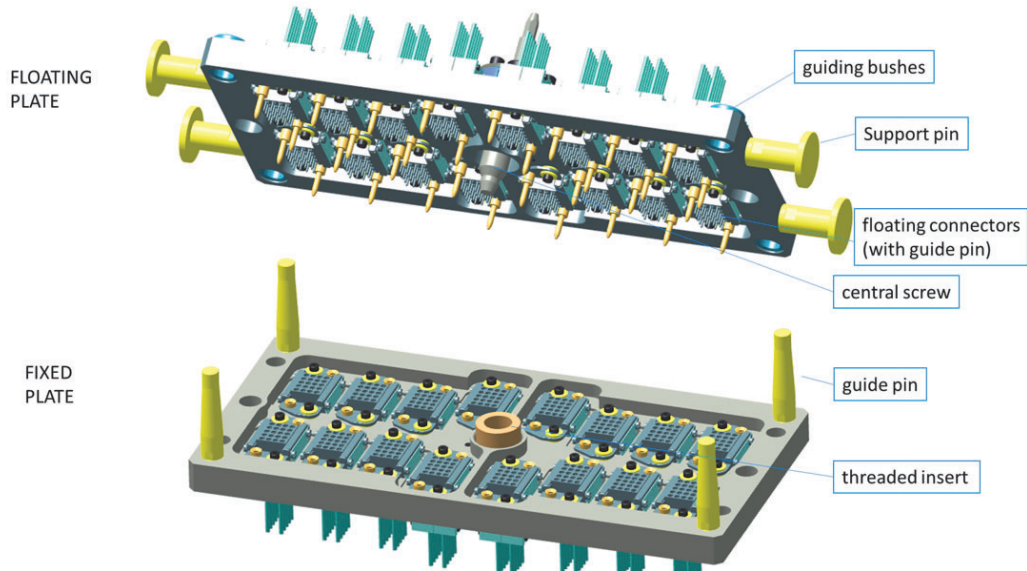


Figure 2.7: Example of designing advice for electrical connectors for RH. (Tripodo, 2024).

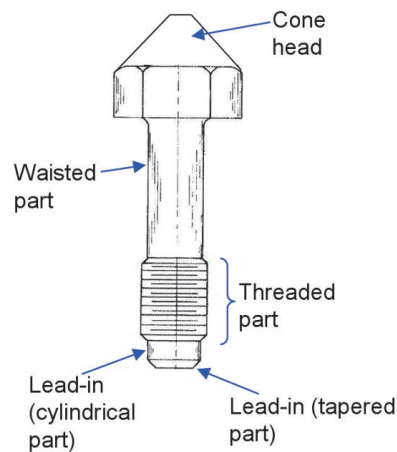


Figure 2.8: View of a captive bolt. This type of fasteners is highly recommended to be used in components that will be maintained by RH. (Tripodo, 2024)

Element	Design guidelines
Elements to be positioned	<ul style="list-style-type: none"> • Include alignment guides like pins or flanges. But avoid redundancy. • Use contact points and surfaces to limit the DoF when positioned. • These aspects are shown in Fig. 2.6.
Elements to be grabbed by a gripper	<ul style="list-style-type: none"> • The gripping interfaces shall be knurled, and parallel rather than cylindrical. • Include limits and guides for the gripper.
Elements to be lifted	<ul style="list-style-type: none"> • Include guides. • Guarantee the stability during and after lifting. • Place lifting points the closest to the centre of gravity
Electrical connectors	<ul style="list-style-type: none"> • If possible, the connection shall be vertical. And it is convenient to add guiding features. • Consider using a multi connector rather than several individual connectors. • It is advised to use a connecting mechanism, like a lever, if needed. • Make sure the cables do not interfere during the RII procedure. • An example is displayed in Fig. 2.7.
Pipes	<ul style="list-style-type: none"> • If possible, the connection shall be vertical. And it is convenient to add guiding features (spigots). • Consider grouping the pipes, if possible, to minimise the number of connecting operations. • It is recommended to use devices like quick disconnections systems(QDS) when possible (commercial, highly reliable and standard). • The seal shall be fixed to the flange. • There shall be mechanical means to avoid over-compression when connecting the pipes.
Fasteners	<ul style="list-style-type: none"> • The bolts can be fastened in horizontal or vertical but leaning positions shall be avoided. • It is recommended to add pins or other guiding features to position the component before tightening the bolts. • Always use captive bolts if possible, avoiding sizes smaller than M5.Fig. 2.8. • Prioritise standardisation, using the same model and size of fasteners wherever is possible and select commercial ones.

Table 2.4: Table showing design guidelines specific for different features. Besides them, for all is necessary to keep in mind providing a clear view of the procedure while it is taking place and respecting the spatial needs of the RHE to guarantee the reachability needed.

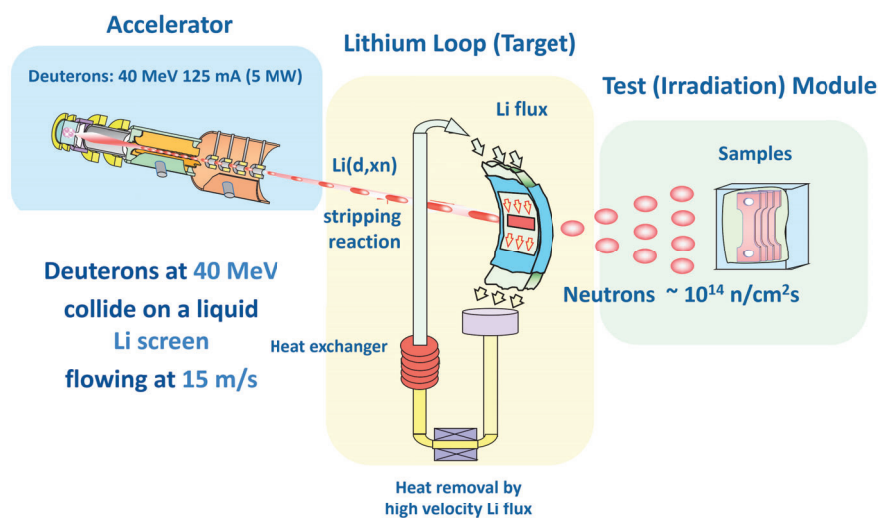
2.5 Examples of facilities implementing remote handling maintenance

Finally in this section will be presented some examples of large scientific facilities where there has been an ongoing collaboration throughout this thesis.

2.5.1 IFMIF DONES

As described in Bernardi et al. (2022), International Fusion Materials Irradiation Facility-DEMO-Oriented NEutron Source (IFMIF-DONES) is a high-intensity neutron irradiation facility for qualification of fusion reactor materials, which is being designed as part of the European roadmap to fusion-generated electricity. It is currently in the design phase, and will be based in Granada, Spain. The main purpose of this facility is to study the behaviour of material under irradiation in a neutron flux able to simulate the same effects they are expected to withstand in the first wall of the future fusion power plants.

The neutron flux is generated by interaction of a high current (125 mA) deuteron beam accelerated to 40 MeV and a liquid lithium target (Brañas et al., 2024). This is represented in Fig. 2.9.



A neutron flux of $\sim 10^{14} \text{ cm}^{-2}\text{s}^{-1}$ is generated with neutron spectrum up to 50 MeV energy

Figure 2.9: Representation of the mechanism used in IFMIF-DONES to obtain the neutron flux by accelerating deuterons and impacting them with a Li flux. (Ibarra, 2019)

The general view of the facility can be seen in Fig. 2.10, including the layout of its main systems. The RH procedures are foreseen for components in the accelerator system, test system and lithium system because of the environmental conditions of those areas.

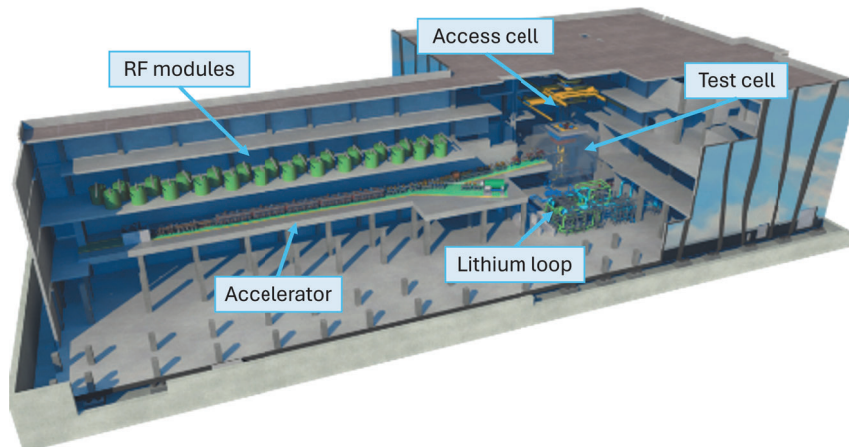


Figure 2.10: View of the expected IFMIF-DONES layout.

2.5.2 CERN

The European Organization for Nuclear Research (CERN) is based in Geneva, Switzerland. Its mission is to enable international collaboration in the field of high-energy particle physics research; to this end it designs, builds and operates particle accelerators and the associated experimental areas (Kershaw et al., 2013).

It provides a unique range of particle-accelerator facilities enabling research at the forefront of human knowledge. Its main mission is finding out what the Universe is made of and how it works. It includes several particle accelerators with different energies, Fig. 2.11. The biggest and more energetic is Large Hadron Collider (LHC), which consists in a 27 km circumference. The particle collisions, taking place in this accelerator, recreate, for a fraction of a second, the conditions that existed moments after the Big Bang, when the Universe was born. By studying the debris of these collisions, physicists try to settle mysteries such as what matter is made of and how particles get their mass, (Perkins, 2022).

Many important scientific advancements have been made at CERN. Highlights include the 1983 discovery of a pair of elementary particles called the W and Z bosons, which was later awarded the Nobel Prize for Physics. British computer scientist Tim Berners-Lee helped invent the World Wide Web at CERN in 1989 by developing a way for computers to talk to each other, called hypertext transfer protocol (HTTP). In 1995, CERN scientists were the first to create atoms of hydrogen's antimatter counterpart, antihydrogen. In 2000, they discovered a new state of matter: a hot, dense, particle soup called quark-gluon plasma. And the Higgs boson was observed for the first time in 2012 at CERN's Large Hadron Collider (LHC), scooping its discoverers a Nobel Prize, (Perkins, 2022).

This organization has been running since 1954 (Mobach and Felt, 2022). However, according to Horne (1988) it was not until the 1960s that remote handling applications started to be developed. Since then, the use of robots for the inspection and maintenance procedures has greatly increased (Di Castro et al., 2018).

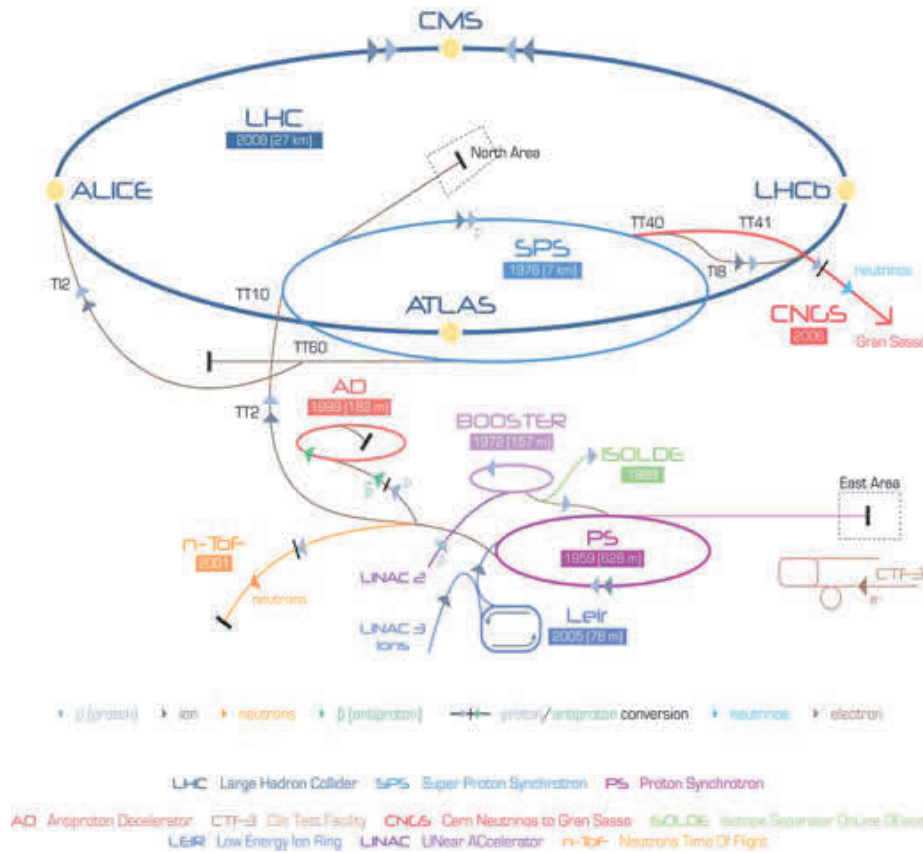


Figure 2.11: Representation of CERN accelerator complex. (Kershaw et al., 2013).

2.5.3 DEMO

DEMOstration power plant is foreseen to be the first industry and technology driven fusion power plant. The goal of this facility is to produce electricity, however not yet at the price and amount of commercial power plants. It is expected to generate up to 500 MW net electricity to the grid and operate with a closed fuel-cycle, which means that the spent tritium will be recovered (Ciattaglia et al., 2017).

This project is expected to be the last step before a commercial fusion power plant, according to Federici et al. (2016) its goals are the following:

- Solving all remaining physics and technical issues foreseen in the plant and demonstrating the necessary reactor relevant technologies.
- Achieving the production of several hundreds of MW of electricity.
- Being tritium self-sufficient
- Operating with adequate availability-reliability over a reasonable time span.

This project presents several challenges in its design, like the materials to use in the tokamak that will have to withstand very harsh conditions during operations. Another one of the key challenges is the maintenance of the facility, because of the high expected radiation levels

and difficult access. Remote handling will be essential for the development of this facility, and it presents many challenges as the deployment of the tools and the strict constraints of the procedures. In Fig. 2.12 can be seen the developed design of the tokamak including the ports for the introduction of the RHE during the maintenance periods (Crofts et al., 2016).

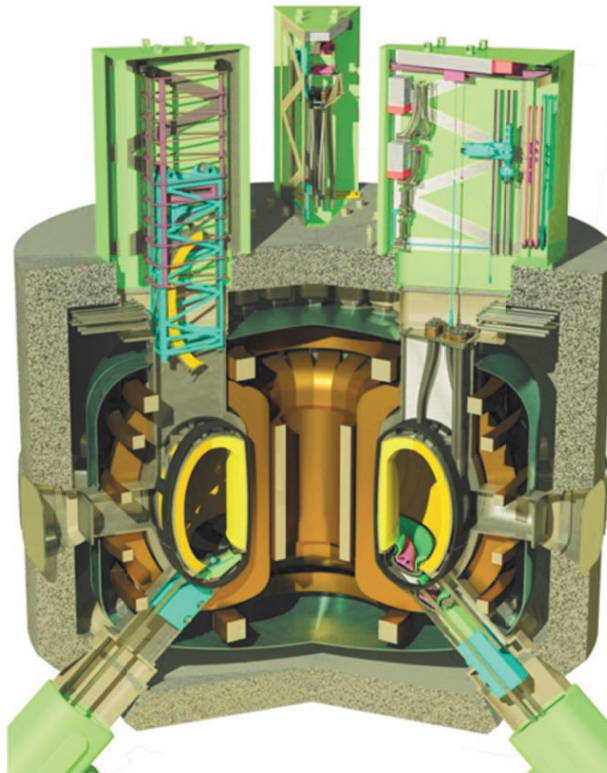


Figure 2.12: View of the foreseen design of the tokamak in DEMO including the RHE. (Crofts et al., 2016)

Chapter 3

Procedure modelling for remote handling tasks

When modelling a remote handling task there are three pillars to take into account:

- The requirements of the task. They will determine the equipment needed and the procedure to be performed.
- The equipment to be used. It consists of the robots, tooling, and other hardware available and suitable for the task.
- The procedure to be performed. It is a succession of steps designed to achieve the task. It also includes the corresponding control mode, actions validation and failure management, among other aspects.

Sometimes, requirements can imply the use of equipment that is not available and might be needed to design it.

3.1 RH considerations

According to Tesini (2009), remote handling enables operators to safely, reliably and repeatedly perform manipulative operations of items without being in personal contact with them.

This is specially interesting for applications that take place in hazardous environments or with difficult access. As commented in Sheridan (1992) and Siciliano and Khatib (2016), some of the main fields where this happens are listed below:

- Underwater robotics
- Space robotics
- Nuclear robotics
- Construction
- Telemedicine
- Agriculture
- Chemical industry and toxic waste management

The strategies for modelling RH procedures presented in this chapter are focused on robotics for environments under radiation, especially on the remote maintenance of accelerators. However, the approach can be applied to other fields where RH is used, such as the ones mentioned above.

It is also remarkable that, when modelling RH procedures, it is not enough to develop the sequence of actions to achieve the task. It is also necessary to select properly the robotic equipment and design, or adapt the tooling that will be used. More information about this was given in Subsection 2.4.

Another important aspect to take into account when developing new RH applications is the failure managing. This means developing also mitigation strategies and courses of action for the emergency scenarios. This will be explained in detail in Subsection 3.3.3.

Operator considerations

Besides the general remarks made for RH procedures, there are some important aspects about the operator. As will be explained in 3.2, it is very important to train the operators so that they become familiar with the task and the tooling used.

Also, there are studies about the impact of the operator conditions on their performance in a RH procedure, Piercy et al. (2024) presents one carried out at JET, which concluded that factors as the experience of the operator, or their sleepiness, or frustration impacts significantly their work.

To improve the performance of the operator there are different strategies. One that is dragging more interest recently is using haptic augmentation to increase the remote environment awareness of the person controlling the robotic equipment. This idea was applied to the RH of the Divertor Test Platform 2 (DTP2), generating virtual forces based on virtual models of the teleoperation environment and sensor data from the slave manipulator to help the guidance done by the operator (Viinikainen et al., 2014). Another strategy is described in Niu et al. (2019), where is developed a software for locating and detecting the position and orientation of components with respect to a stereo camera pair. This enables target depth mapping, stereo camera calibration and online target tracking, which are key aspects for teleoperation.



Figure 3.1: In ARIEL the operator can control the hall crane thanks to the visual feedback and the readings of the mechanical encoders in the bridge, trolley and hoists. (Minor et al., 2021)

Fig. 3.1 shows the operator controlling remotely the hall crane at ARIEL (Advanced Rare IsotopE Laboratory in Canada), to enable safe operation besides the cameras in the working environment the readings of mechanical encoders in the bridge, trolley and hoists are displayed in the operator interface, (Minor et al., 2021).

3.2 Remote handling life cycle

There are different types of methodology for developing RH tasks. These give support to all phases of the procedure. Even if the applications are very different, thanks to these it is possible to follow the guidelines to analyse the problem and implement the corresponding robotic procedure to achieve the goal. Some examples are detailed below:

- Hirshorn et al. (2017). This methodology developed by NASA gives guidelines to carry out each step of the project, from the concept phase to the implementation, including the key decision points and major reviews.
- Coloma et al. (2019). Gives design guidelines for the components of the facility. Starts by describing the operation for which the component will be designed and finishes with the analysis of the results of the functionality tests. It is remarkable that this diagram takes into account the information feedback to improve the design with each iteration.
- Di Castro (2019). It was developed for the robot CERNTAURO at CERN. It includes continuous improvement, as even in the operation phase it records information to analyse the performance and identify possible improvements.

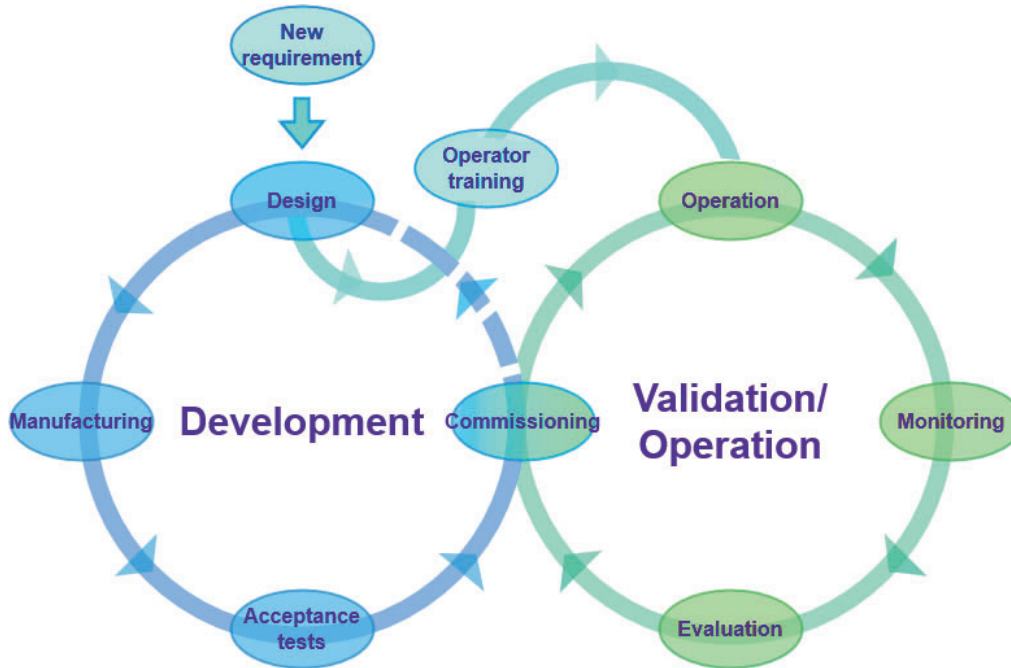


Figure 3.2: Proposed methodology for the development and operation of RH procedures. (Redondo et al., 2023)

In addition to these, in Redondo et al. (2023) another methodology is proposed (Fig. 3.2) that includes not only information feedback between stages and a continuous improvement model, but also the training of the operators. This is very important, because if they become familiar with the designed procedures and tooling during the development phase, they will be ready to operate them, and this will enable the operation phase to start earlier.

This methodology has two main phases: the development and the validation/operation. Remote handling strategies are seen as a continuous improvement process, even during operation if either new requirements or potential improvements are identified, another iteration of the loop is done going back to the development stage.

At first, when creating a new RH procedure, the second phase will be validation, because the goal will be gathering information about the components and procedures to identify potential improvements. This continues until the validation stage is considered successful, which means that the evaluation results are valid. Even in the operation phase, the behaviour of the components and procedures will still be monitored and evaluated to go back to the development stage if needed.

An iteration of the loop, starting with the identification of new requirements, will go as follows:

- **Design.** Once the new requirements have been identified, the design of the components and procedures can start. The tools usually used are listed below:
 - Design guidelines for the components. Documents that give recommendations and ground rules for the designer, for example Tripodo (2024) in IFMIF-DONES.

- Computer assisted design. There are several options, such as Autodesk Inventor. Can be used to do 3D modelling, including efforts and deformation analysis.
- Robotic simulation software. This software is very useful once the preliminary design is done. It allows the user to test the tools and procedures developed. Some examples are RoboDK or CoppeliaSim. Other examples are the simulations carried out for the maintenance procedures in IFMIF-DONES that led to their optimisation and improvement (Rouret et al., 2023), or the use of digital mock-ups to verify the RH systems design as it was done at ITER (Sibois et al., 2014).
- **Training of the operators.** Once the design is completed the operators can start to be trained on how to use the newly developed tooling and procedures. This is relevant because acting this way when the prototypes get to the validation/operation phase, the people will already be familiar with them saving a lot of time. This is a key aspect because stopping large scientific facilities is very expensive. There are different ways to train the operators:
 - Using digital means. This includes simulations and digital twins, which are digital simulations of the whole facility. In Attaran and Celik (2023) are shown examples of the use of digital twins.
 - Using physical means. Similarly to the digital options the physical means can be mock ups of a single component or a system or replicas of the whole facility. In Huang et al. (2024) is presented a scaled vacuum vessel to test the RHE for the maintenance of a Tokamak.
- **Manufacturing.** This takes place at the same time as the training of the personnel. Can be done by traditional manufacturing or by 3D printing, the best option will be selected taking into account the design stage and the characteristics of the components to be manufactured. For instance, for a proof of concept of the preliminary design, the 3D printing can be a good option, because it can save time and money and give a first validation of the components and procedures.
- **Acceptance tests.** Following existing standards, acceptance tests are designed and carried out to validate manufactured components. The designing team sets the acceptance criteria as part of the requirements for the components. There are different types:
 - Factory Acceptance Tests (FAT). These aim to check that the manufacturing requirements are met.
 - Site Acceptance Tests (SAT). Are done by the designers to check the requirements.
 - Functionality tests. Are done after installing the components in the system to test their correct connection and functioning.
- **Commissioning.** After the design phase the validation/operation one starts. The main difference between validation and operation is that during validation is common to use mock ups to analyse the behaviour of the developed tooling and procedures. The commissioning consists in starting the operation of the new components or procedures.

- **Operation.** The personnel already trained carry out the procedures using the components.
- **Monitoring.** During this phase performance information is gathered, is very important to do a careful selection of the data to collect.
- **Evaluation.** Finally the information is analysed to identify possible improvements. Also personnel satisfaction questionnaires are taken into consideration. The improvements identified will be implemented in the next iteration of the loop. It is also remarkable that if the evaluation is successful during a validation stage the next iteration could go directly to operation. Even in that scenario the monitoring and evaluating will carry on, as this is a continuous improvement methodology.

3.3 Modelling RH procedures

Besides the automation considerations mentioned in Section 2.1, there are other remarks that need to be analysed. The stages of the procedure, their validation and failure scenarios.

The stages of the procedure refer to the general structure of a step in a procedure. This is a representation of the possible outcomes of the procedure depending on the decisions of the operator and the results obtained during execution. This thesis focuses on modelling the stages of the RH procedures following the supervisory control architecture, where if no error comes up and the operator validates the advance after every stage, the system will follow the automatic flow.

In order to facilitate the validation of the steps, the system shall give the operator meaningful information about the execution of the step. In addition to that, it is crucial when modelling a RH procedure to analyse the possible failures that might come up during execution to develop mitigating strategies and courses of action when they cannot be avoided. In this section, all of this will be presented in detail.

Another approach for implementing the supervisory control in RH procedures can be found in Zieba et al. (2013). In this work tools for the definition of generic RH procedures under a supervisory control architecture are proposed. Authors present a three layers model approach, that goes as follows:

- **First layer:** Interfaces. Defines the available operations via physical interfaces which are attached to the scene elements, enables a function centred model of the environment.
- **Second layer:** Behaviours. Correspond to the logical link between two or more objects, representing the high-level functionalities.
- **Third layer:** Interaction modes. In this case corresponds to the supervisory control.

3.3.1 General diagram of a RH procedure

RH procedures consist in a series of steps, corresponding to the actions that need to be carried out to achieve the task. Following the supervisory control architecture there will be an automatic flow, where the system will advance to the following step after the operator validates the current one. Also, they can take manual control of the task if necessary and

complete the faulting step or make the system repeat it.

In Fig.3.3 is represented the diagram of a RH procedure using supervisory control. The assumptions made for this model are that the system is self-aware and that the steps consist in low level instructions. The self-awareness of the system corresponds to its ability to detect any upcoming error.

The steps contain low level instructions corresponding to the procedure control algorithms. However, these instructions do not affect the control architecture. If the operator decides that a step needs to be repeated, the system shall go to the last safe position known, which is the end of the previous step. This means that in case step N has to be repeated, the system shall go back to the finishing position of the N-1 step, as this is the last known safe position.

Even though there is an automatic flow, it does not mean that all the steps have to be automated. If the system reaches one that is not, the operator will take manual control to execute and then go back to automatic control.

This diagram refers to the automatic/manual flow of the procedure. The necessary safety actions, such as the emergency stop, shall be included in the corresponding safety diagram. What makes this diagram suitable for supervisory control is the fact that the operator can take control whenever it is needed, and can make decisions regarding the advancement or regression in the procedure based on the feedback received from the system. According to this approach, when step N finishes, the operator can decide if the execution of that step was successful and the procedure can go on, or if there was any malfunctioning and the step has to be repeated, either automatically or in manual control.

As will be commented in Subsection 3.3.2, the operator has to be aware of the performance of the system to decide whether to continue or not. For this end, it is necessary that there are validation tests at the end of each step to give them meaningful information about the status of the task. An example of these tests can be a visual inspection.

To illustrate the use of the diagram presented in this subsection, it is going to be applied to a very common RH activity: tightening a bolt. The steps could be modelled in different ways, one option is as displayed in Fig. 3.4.

These steps will correspond to the different "Steps N" blocks in the diagram presented in Fig. 3.3. They could all be automated or, for example, the coupling between the tool and the bolt could have to be done manually. So, after the centre of the bolt is successfully localized, using probably a camera installed in the tool and a vision algorithm, the operator will take manual control to move the tool centre point (TCP) of the robot to the given position. After the coupling is achieved, the operator can give control back to the system, so it can automatically tighten the bolt.

Referring to the validation of the performed steps, using the example of the localization of the centre of the bolt. The feedback to the operator, so they validate this step, can be the image of the bolt with the detected centre marked on it, so they can easily validate or reject it. If the resulting point is not compliant with the set tolerances, they can set the point manually or request the repeat of the step. For repeating the step automatically, the system will have to go back to the last known safe position, which is the one resulting of the approaching step and start the localization step from the beginning.

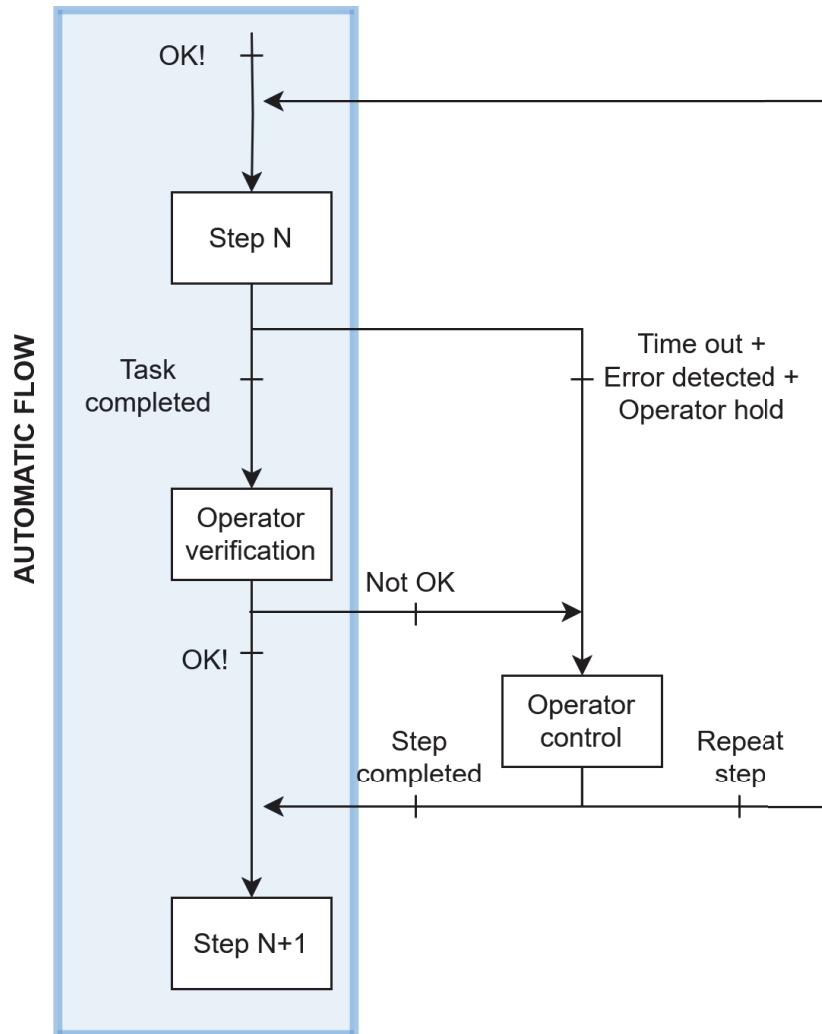


Figure 3.3: Diagram of a generic RH procedure using supervisory control.

3.3.2 Step validation

This type of check is done within a procedure to verify its performance before moving onto the following step. In the design phase of the procedure, the validation criteria is defined, and it enables a straightforward way of categorising the advancement of the procedure. If the result of the validation test is successful, which means that it meets the validation criteria, the operator can be confident of the success of the task. However, if the result obtained is not within the expected range, the operator will be warned that something did not go as expected.

Depending on the type of control used and its specific definition, it can be directly the system that activates the failure mode in case of refusal of the validation test results, or the system can show the results to the operator, so that they decide whether to continue or not. The latter was the case presented in the diagram of the previous section.

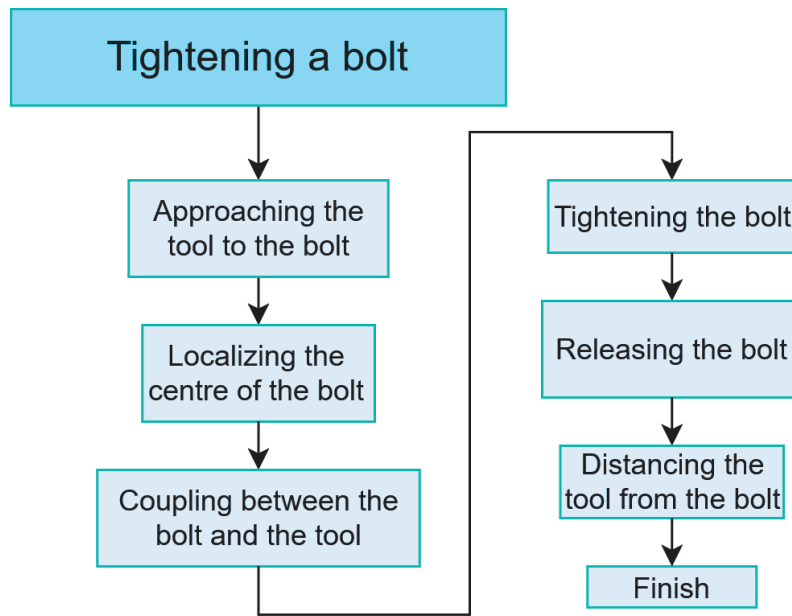


Figure 3.4: Example of the stages in the procedure developed to tighten a bolt by RH.

To ensure the appropriate functioning of this strategy, it is very important to establish relevant validation tests and significantly determine validation criteria. For example, if the step consists in positioning a component in its support, the validation test could include visual feedback of the positioned element and the reading of the alignment sensors. As a consequence, the information obtained will be significant to determine whether the positioning was successful or not. In the case of the alignment sensor readings, the validation criteria will have to match the necessary precision in positioning, for example, ± 5 mm if the maximum positional deviation is 5 mm.

The importance of correctly defining the validation criteria has previously been commented on to enable validation or rejection of the step being carried out. For some tests, it is easy to establish a numerical validation criterion. For instance, when checking the installation of a pipe, the leakage rate in the flange can be measured and compared to the validation criteria that would be the threshold rate.

However, there are some other types of procedures in which it is very difficult to quantify their success, such as the tightening of a bolt or the plugging of an electrical connection. In those cases, the test will give a categorical result rather than a numerical one.

For the tightening of a bolt, a way of checking the tightening torque can be repeating the tightening procedure with the same parameters, if the bolt is more tightened, the second time means that the desired torque was not achieved at the beginning. In the case of plugging an electrical connector, a way of checking that the connection is properly made is checking the functioning of the electrical elements connected, the result will inform about the reception of the electrical signal. So if it is not received, the installation will be rejected, and the plugging procedure will have to be corrected.

3.3.3 Failure scenarios

According to Del Frate (2013) a failure is "the inability of a system or component to perform its required functions within specified performance requirements".

There are some strategies to predict potential failure scenarios and develop mitigation strategies and courses of action in case these failures cannot be avoided. One of the most common ones is failure mode effect analysis (FMEA), which consists in analysing potential failures in every component involved in a procedure throughout all the steps. This analysis takes into account the probability of detection, the likelihood of occurring, the consequences and their severity, and proposes solutions and mitigation strategies. An example can be found in Shaw and Butler (2023), where FMEA is used to perform an initial safety analysis of the tritium fuel cycle in DEMO.

Depending on the severity of the consequences, there might be different courses of action. For example, if the failure considered is the rejection of an electrical connector plugging, a possible solution might be to unplug it and repeat the plugging, as the severity of the failure is not high. Another potential situation could be the breakdown of the robotic arm being used for the procedure, the solution can be using a spare one if available. However, if the failure is the fall of a critical component that is being transported, the consequences can affect several systems, and the solution might not only be the rescue of the lost component, but also the evaluation and repair of potential faults in the surrounding systems.

In cases like the one described above, where the consequences of the failure cannot be predicted and have to be evaluated at that moment or the solution cannot be automated, the FMEA can establish the need for an emergency scenario. There can be different types of emergency situations, for example, the rescue operation of a lost load or the recovery of a non-responding RH equipment. In these situations, the operator will take control of the system to evaluate the damages and, if possible, guide the robotic equipment to solve them. Once the emergency is managed and the procedure can continue, the operator can exit the emergency scenario and go back to the automatic flow of the supervisory control.

Even if emergency scenarios are managed on manual control, thanks to the analysis of potential failures using the FMEA, or the corresponding chosen method, the necessary strategies and tooling to deal with these situations can be developed. This means that in the design phase elements to minimise the risk of failure or its consequences can be added to the components, because of the identification of possible emergency situations. For example, for a component that will be grabbed and transported by a crane, to make it easier for the possible recovery procedure, it can be very useful to add grasping elements to it, so a teleoperated hook can grasp it. Or, if the emergency situation considered is the breakdown of robotic equipment, due to environmental radiation, the planning of the task can consider having back-up robotic components to eventually replace the malfunctioning ones.

So, potential failures that might occur throughout a procedure have to be analysed when planning the procedure. Some failures can be mitigated with design strategies, such as protective shielding or redundant grasping points. But when failures cannot be avoided and their consequences can be severe, emergency scenarios can be used. However, even in this case, in the planning phase some aids can be developed for the operator to manage the situation. When a failure comes up there are two possibilities, it can be recovered using the available RHE, or it needs external intervention, which is a fatal error. For the first case, it can be

classified as orange failure, the system is stopped in a safe position and the operator takes manual control to manage the situation using the available RHE. The objective of analysing the failures in advance is to be able to plan all the necessary equipment, including the tools for rescue and recovery, and minimize the probability of needing external interventions. When a fatal error comes up, red error, it is needed external intervention for the rescue. This classification corresponds to the security grafacet.

3.4 Application examples

In this section two application examples of the aspects explained above will be presented. The RH procedures used for these examples correspond to the replacement of the scraper in the HEBT of IMIF-DONES, Fig. 3.5 and the plugging of the vacuum pump electrical connector oin a collimator in the LHC at CERN, Fig. 3.6. The reason for choosing them is that they are very common components in particle accelerators.

The structure will be similar for both examples, first an overview of the characteristics of the component will be explained, then the main requirements for their maintenance will be presented and, finally, the RH procedure including the validation tests.

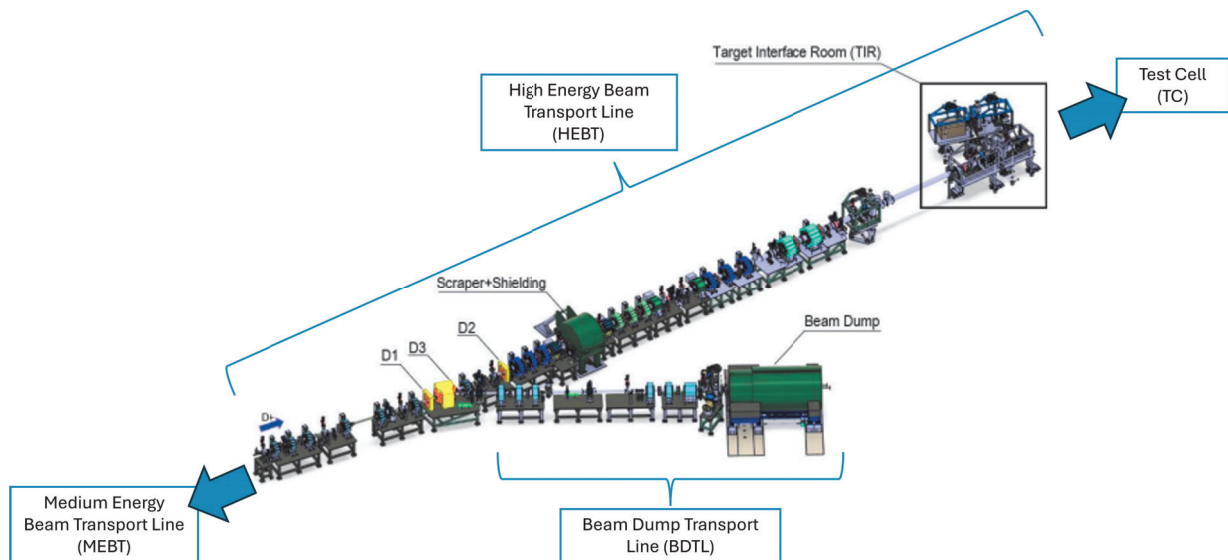


Figure 3.5: High Energy Beam Transport Line (HEBT) and Beam Dump Transport Line (BDTL) of IMIF-DONES. It corresponds to the last part of the accelerator just before the Test Cell (TC), where the particles will impact the target. (Sánchez-Herranz et al., 2023)

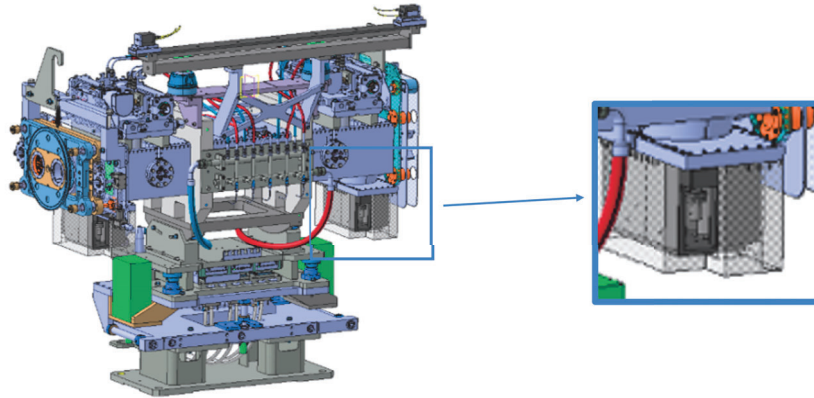


Figure 3.6: View of the collimator model for which the plugging and unplugging of the vacuum pump electrical connector will be performed. It can be seen the location and arrangement of the connector. (Redondo Gallego et al., 2024)

3.4.1 HEBT Scraper

Characteristics of the component

This element that consists of four moving blades that can be adjusted to shape the beam properly stopping peripheral particles. In particular, in IFMIF-DONES, it is one of the key components in the High Energy Beam Transport (HEBT) line, see Fig. 3.7. It is responsible for cleaning the beam and detecting beam losses (Lopez-Revelles et al., 2024).

It consists of four blades moved by stepped motors and a water cooling circuit to remove the heating power of the stopped particles (Arranz et al., 2020). Due to its high activation, it is placed inside a shielding, yet both motors and water connections are placed outside the shielding to allow access without opening it.

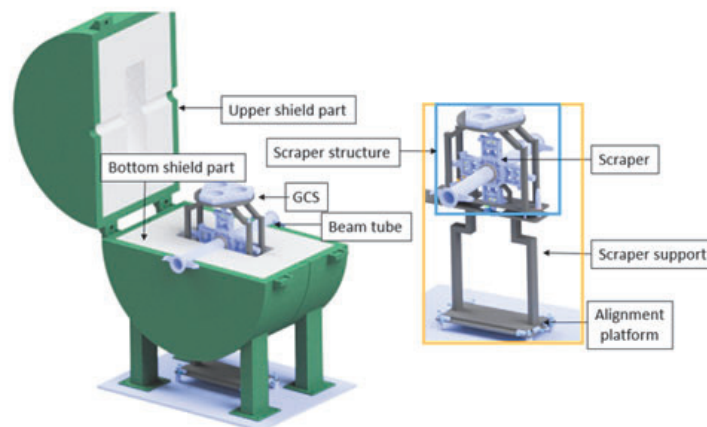


Figure 3.7: View of the HEBT Scraper in IFMIF-DONES. It is responsible for cleaning the beam and detecting beam losses. (Lopez-Revelles et al., 2024)

Requirements and conditions of the maintenance procedure

One of the most determining conditions for the maintenance procedure is the radioactive environment. As stated in Qiu et al. (2024), the HEBT Scraper is in a very activated area, so it is better to avoid opening the shielding if possible. Seeing the radiation maps presented in Fig. 3.8 (Lopez-Revelles et al., 2024), one day after the accelerator has been shut down, the radiation dose with the HEBT scraper shield closed is around $500 \mu\text{Sv/h}$ in the surroundings of the component. According to Arranz et al. (2020), in IFMIF-DONES a room with those radiation levels will be classified as a limited permanence controlled area ($10\mu\text{Sv/h}$ - 1mSv/h). This means that hands-on limited interventions would only be allowed if the activated components are inside their closed shielding. As a consequence, the replacement of the HEBT Scraper will have to be done by RH.

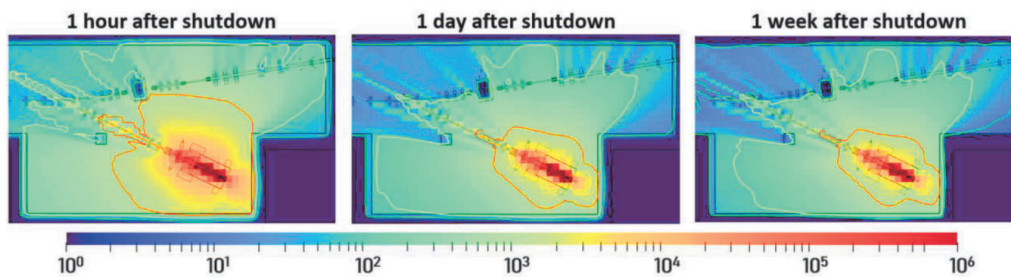


Figure 3.8: Radiation maps showing the evolution of the radiation levels in the accelerator area in IFMIF-DONES ($\mu\text{Sv/h}$). (Lopez-Revelles et al., 2024)

The foreseen maintenance is preventive and consists in replacing the component once a year. If the intervention is done due to an unexpected failure the environmental radiation would be higher than expected because the cooling down period would not have been respected. In ITER Org. (2004) can be seen that in the preliminary design phase of ITER the considered radiation levels for an scheduled intervention are 10 times lower than for an unexpected intervention.

The available remote handling equipment (RHE) for the HEBT Scraper replacement can be seen in Fig. 3.9. It includes an overhead crane with a telescopic mast, a robotic arm, a bolting tool and a gripper, the goal of each component is the following:

- The overhead crane with the telescopic mast has the necessary interface to attach and transport the scraper. In addition, it can attach the robotic arm.
- The robotic arm has six degrees of freedom (DoF). It can attach the tools and provide them with the necessary electrical connections remotely. And thanks to the DoF of the robotic arm, the tooling will be able to reach the necessary positions to carry out the tasks.
- The bolting tool will be used to tighten and loosen the bolts fixing the scraper to its support and to fix and unfix it from the beam pipe.
- The gripper will only be necessary for emergency situations, such as picking up something that has fallen to the floor.

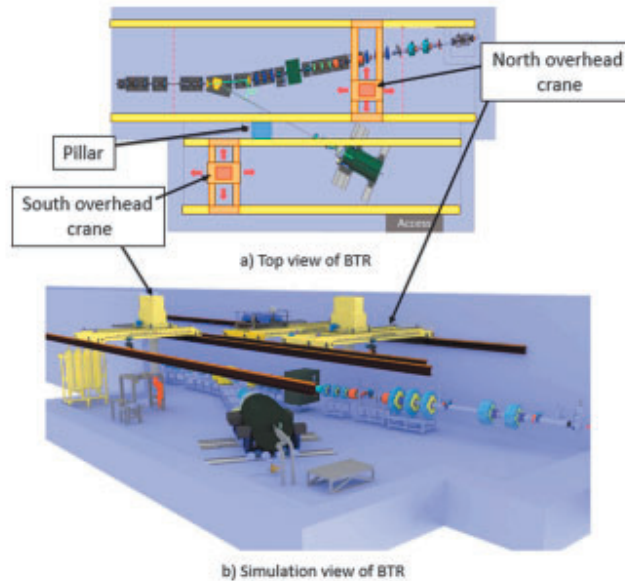


Figure 3.9: Remote Handling Equipment (RHE) available for the maintenance procedure of the HEFT Scraper and Beam Dump in IFMIF-DONES. (Coloma et al., 2021)

In a nutshell, the RH task will consist in replacing the HEFT Scraper inside the shielding with another one that will be introduced in the room inside a closed container box. That box will also be used to transport the old one safely.

Maintenance procedure

Nowadays the RH tasks carried out in large scientific facilities as JET or CERN use mainly manual control. However, efforts are being made to increase the automation level of the procedures, so the proposed control architecture for the application examples given here is supervisory. In particular, the diagram presented in 3.3.1 will be applied to this RH procedure. In Rouret et al. (2023) is presented a simulation of the RH procedure defined for the replacement of this component. It is a distinctive aspect that the new component to be installed comes in a closed container box transported also by teleoperation. The stages of the replacement can be seen in Fig. 3.10.

In Fig. 3.11 is presented the high-level procedure. The main stages listed above are divided into specific steps. Each of the steps in this diagram corresponds to a task that needs several actions for its completion. An important remark to make is that all the steps include validation tests, so the operator can decide whether to continue to the next step, or repeat it, automatically or manually. For example in the step "Unfix old scraper", the validation test can be a visual inspection to check that all the necessary bolts were loosened, and it will be possible to transport the component. If in that test the operator finds that all the bolts were correctly unfix except one, they can manually control the system to unfix that bolt, rather than repeating the whole automatic sequence.

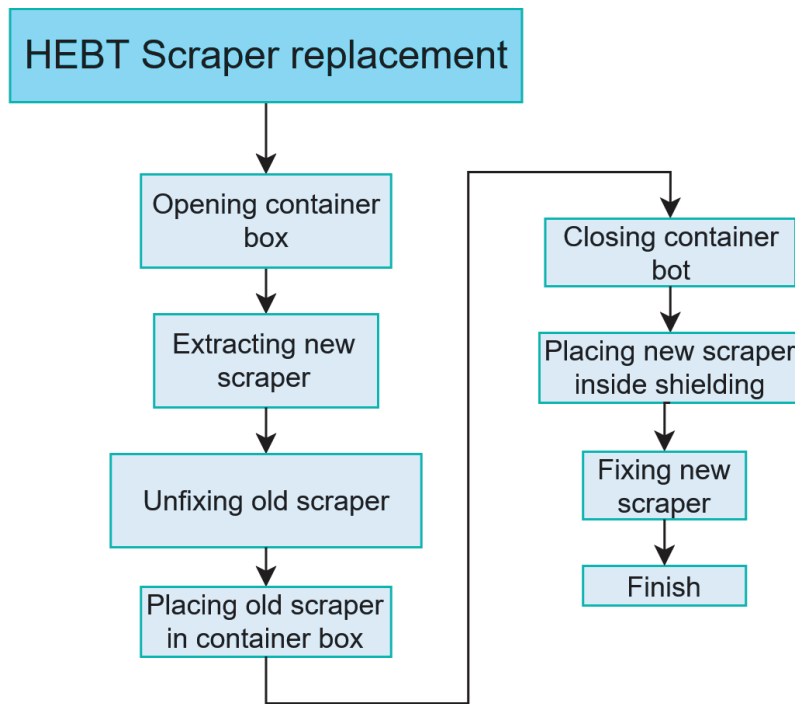


Figure 3.10: Stages of the replacement procedure of the HEBT Scraper in IFMIF-DONES.

Also, in every step, as the system is self-aware, whenever it detects a failure it can request the operator to take manual control and solve it. This can happen, for example, if when the old scraper has to be put in the container box, it appears not to be in the expected position and the system experiences a time out when trying to find it. In this case, the operator can enter the new position manually in the system and go back to the automatic flow. Another example of error that could come up, is, if when transporting the new scraper to its position in the beam line, something falls and the operator has to rescue it under manual control using a gripper or hooks to grab the element if needed.

Finally, when the whole procedure has been carried out, there is a step specially dedicated to the post maintenance acceptance tests. For the diagram in Fig. 3.11, these tests will check the functionality of the installed component. This means testing the readings of the thermocouples, the movement of the blades, and the functioning of the cooling system. In case the result of any of those tests is not satisfactory, the operator can decide to repeat the test or go back to the most convenient step to fix the problem.

As mentioned before in the case of the intermediate validation tests, they have to be a meaningful check, defined depending on the actions carried out in that particular step. For example, in the step "Extract new scraper", a visual test is suitable to check that the container box is empty after extracting the component, and that it has been correctly placed in the temporary support. Otherwise, for the step "Fix new scraper", the visual inspection can be useful again, but checking the tightening torque of the bolts will be also needed to make sure that the component will remain in its place during operation.

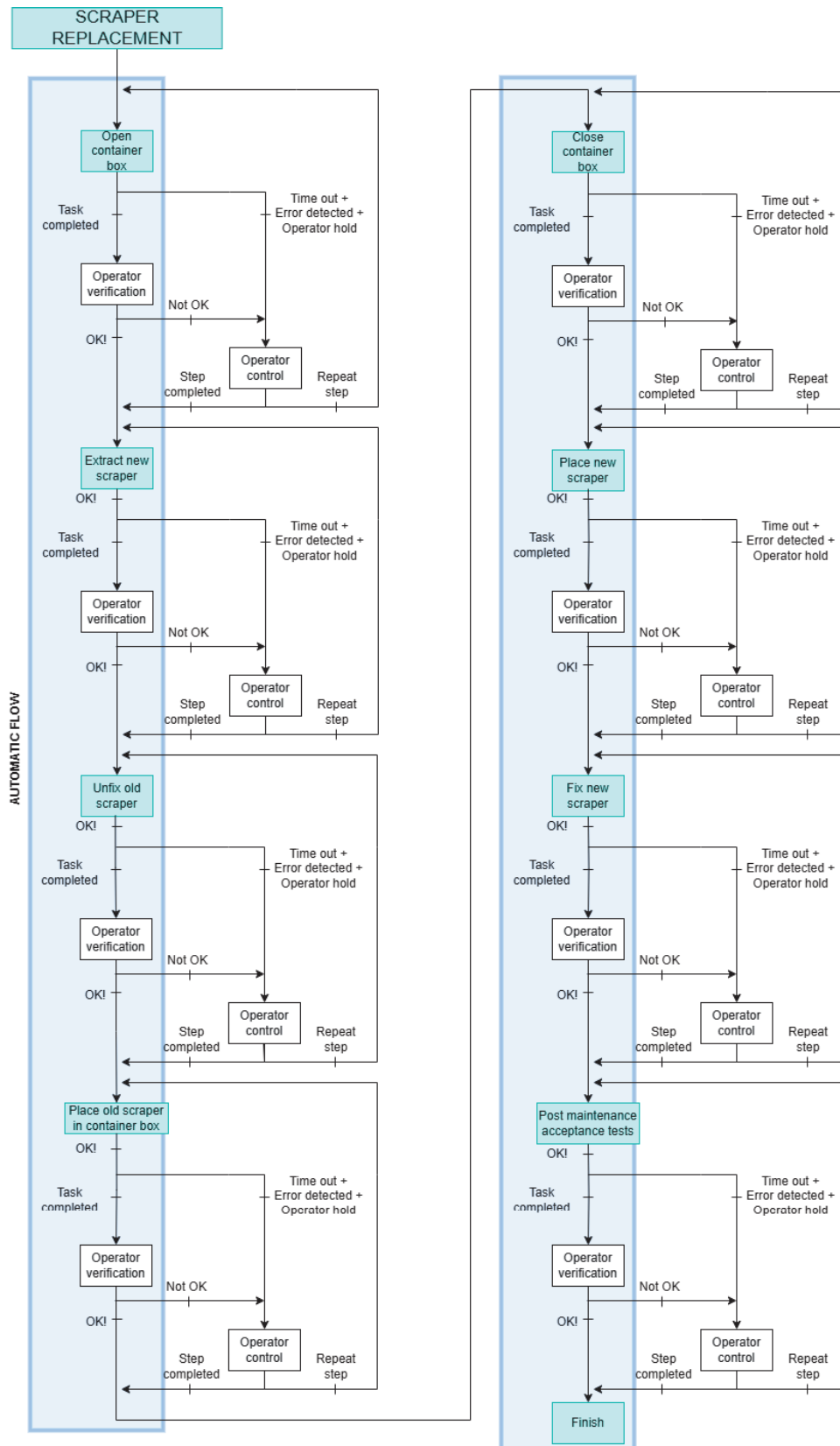


Figure 3.11: Maintenance procedure for the HEBT Scraper replacement using supervisory control.

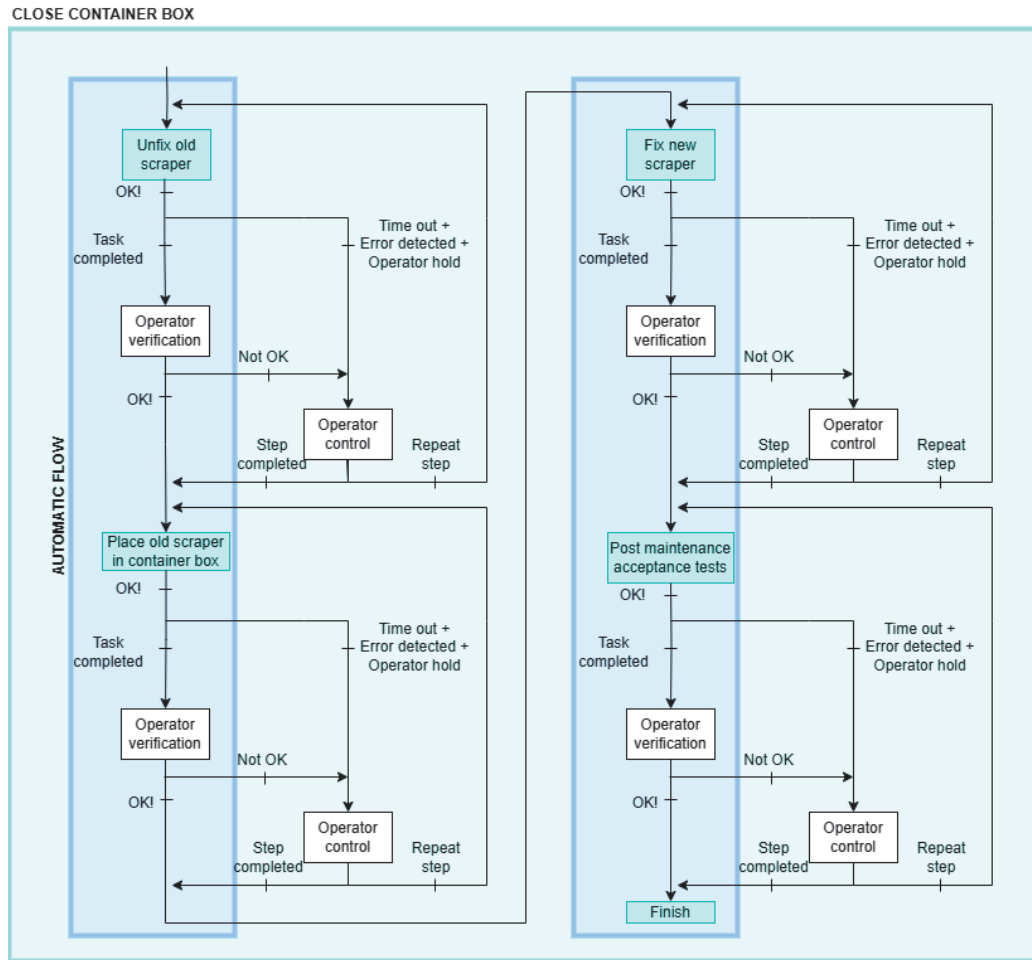


Figure 3.12: Diagram expanding the high level step "Close container box" in the RH maintenance procedure of the HEBT Scraper replacement.

The steps represented in Fig. 3.11 correspond to high level activities. Referring to the NASREM classification presented in Subsection 2.2.2, this diagram can be considered as level 5, as any of the steps require several tasks to be accomplished.

In Fig. 3.12 is represented the inside of the step "Close container box", it contains all the necessary actions to achieve that step. The structure is similar to the higher-level diagram, as it still follows the supervisory control architecture. Looking at this diagram, it is possible to notice the lower level of the actions appearing on it. Instead of closing the container box, the instructions correspond to the activities that need to be done to achieve the bigger step. In the NASREM classification, this diagram can be considered as level 4 as it contains the actions needed to accomplish the "Close container box lid" task.

The steps appearing in the diagram in Fig. 3.12 can still be divided into simpler actions, creating a new diagram that would be included in the level three of the NASREM classification. This is what can be seen in Fig. 3.13, where the step "Grab container box lid" has been expanded. The steps in this diagram correspond to the movements that the RHE needs to do to close the lid of the container box.

Even though the actions in this diagram correspond to a lower automation level, the diagram maintains the same supervisory control structure. It requires the validation of the steps to advance and enables the operator to take control upon their criteria. Going deeper in these steps would mean entering the movement of the motors in the RHE, the steps deeper would become instructions to the actuators rather than functions. This is the reason why it is considered that using this type of representation is suitable for the levels of NASREM.

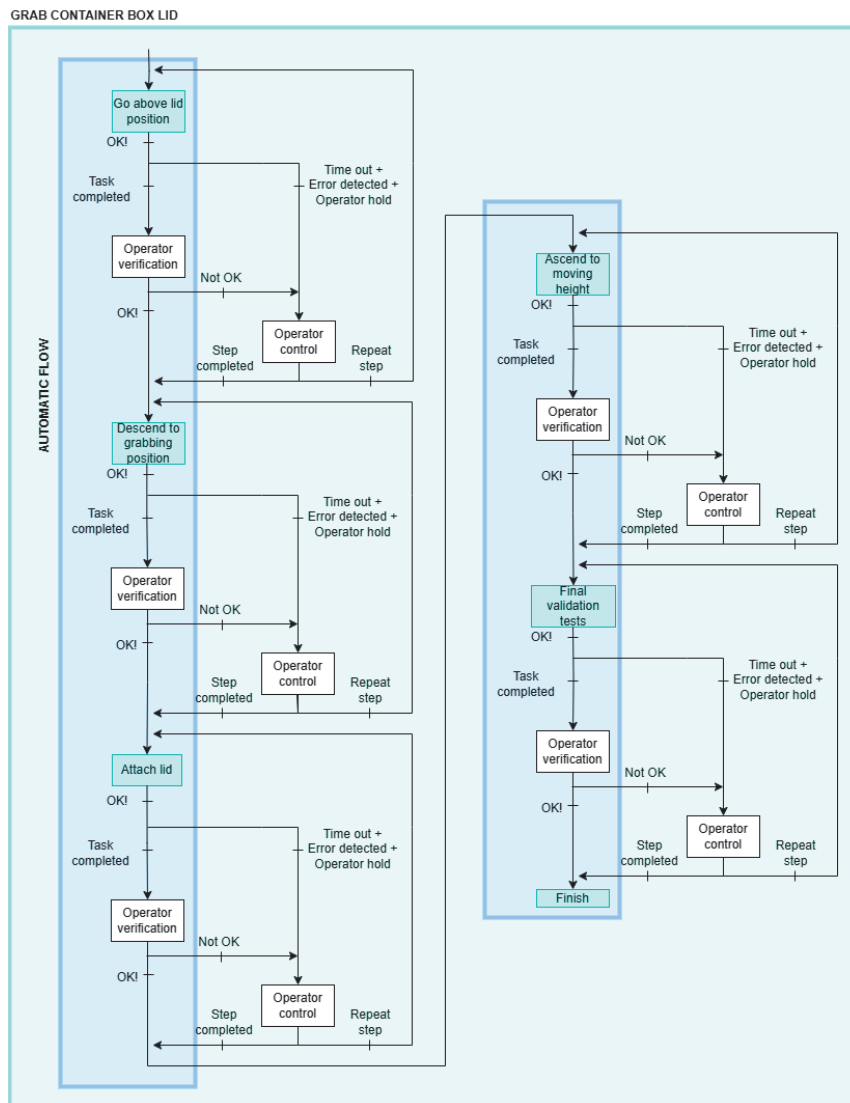


Figure 3.13: Development of the step "Grab container box lid" appearing in Fig. 3.12.

3.4.2 Vacuum pump electrical connector in collimator at LHC

Characteristics of the component

This is a particular case of the plugging and unplugging of the electrical connector, which is a very common RH task. The electrical connector that will be used for this example, is located in the collimators present at LHC, the biggest particle accelerator at CERN. This connector is responsible for powering the vacuum pump in collimator, Fig. 3.6 shows the corresponding layout.

The parts of the connector are shown in Fig. 3.14, the female side is fixed to the vacuum pump so it cannot move, and the male part is expected to be laying somewhere on the ground. For the insertion, it is necessary that both parts of the connector are aligned along their longitudinal axis, however their orientation does not affect the connection.



(a) Female part of the electrical connector.



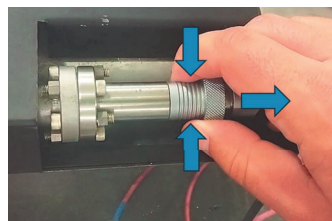
(b) Male part of the electrical connector.

Figure 3.14: Views of the female and male parts of the electrical connector. (Redondo Gallego et al., 2024)

As this connector is designed for radiation environments, it has a safety system to avoid undesired disconnection. It will remain plugged unless it is pressed in the direction perpendicular to its axis and the male part is pulled out of the female at the same time, see Fig. 3.15.



(a) Connector plugged.



(b) Forces to be applied to unplug the connector due to its safety system.



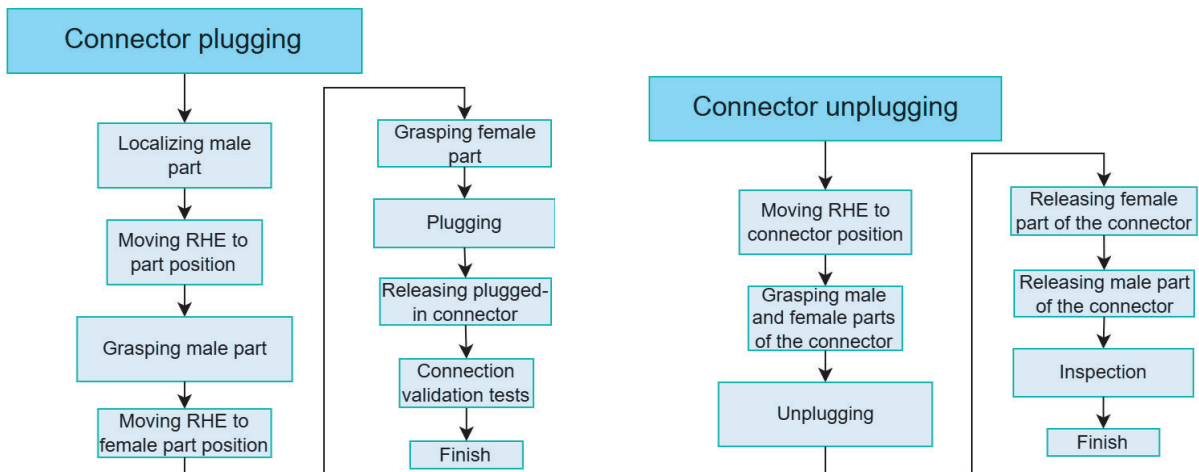
(c) Electrical connector unplugged hands-on.

Figure 3.15: Electrical connector hands-on unplugging procedure.

Procedure

This operation was initially done manually by a person going into the tunnel. However, during this thesis, work has been done to develop the corresponding RH application. This subsection will focus on the procedure developed and Section 5.5 will explain the tool designed and the laboratory tests carried out.

This procedure can be considered to be of level 3, according to the NASREM classification. It is included in the maintenance procedure of collimators at LHC. For this high level procedure to advance towards RH supervisory control, it is necessary to implement supervisory control solutions in the different stages of the maintenance. And this is what this example illustrates, the implementation of RH applications to low level procedures in order to advance in the automation of higher level ones. The stages of the plugging and unplugging procedures have been represented in Fig. 3.16.



(a) Stages of the RH procedure developed for the plugging of the vacuum pump electrical connector at CERN.

(b) Stages of the RH procedure developed for the unplugging of the vacuum pump electrical connector at CERN.

Figure 3.16: Stages of the plugging and unplugging procedures for the vacuum pump electrical connector at CERN.

As the initial position of the male side of the connector is unknown, the first stage of the plugging procedure will have to use a vision system to localize it. Initially, this can be done manually thanks to cameras, but efforts have been done to automate it. The results obtained using the algorithm developed to localize the male part of the connector can be seen in Redondo Gallego et al. (2024).

The corresponding supervisory control implementation diagram is shown in Fig. 3.17. In the stage corresponding to plugging, is important to remark that an error that could be detected by the system could be a clash between both parts of the connector. At this point the operator could take manual control and perform the plugging manually, or get the robotic system to the last known safe position, the final position of the "Grasping female part of the connector" stage correcting the alignment, so the system automatically can repeat the faulting step.

For the unplugging, the RHE equipment has to grasp both sides of the plugged-in connector and extract the moving one. Once the unplugging is achieved the female part of the connector can be released and afterwards, the male part too. Finally, it is important to carry out an inspection, that can be a visual check to test the status of the components. The procedure using the supervisory control architecture can be seen in Fig. 3.18.

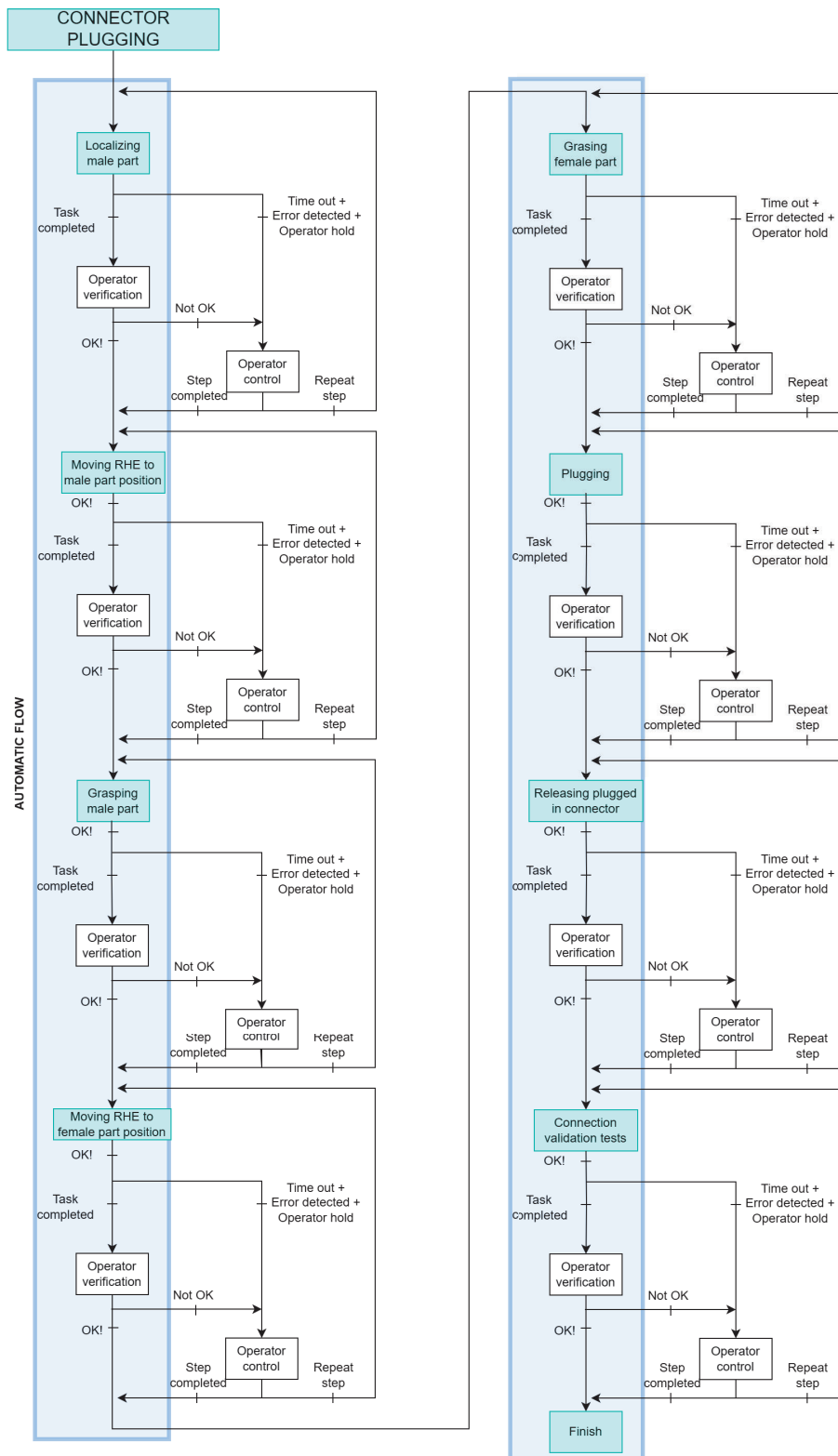


Figure 3.17: Plugging of the electrical connector powering the vacuum pump in collimators used at LHC, using supervisory control.

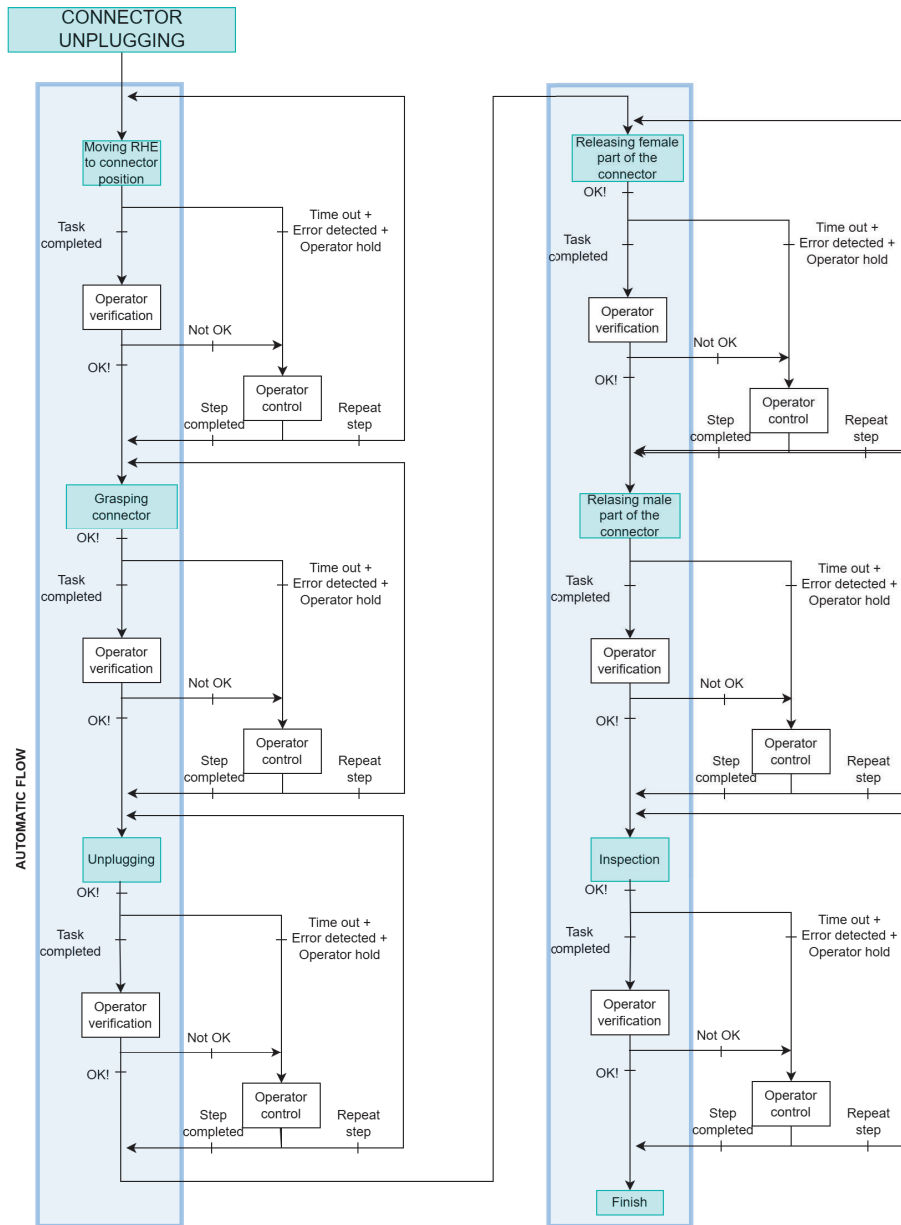


Figure 3.18: Unplugging of the electrical connector powering the vacuum pump in collimators used at LHC. This procedure diagram uses the supervisory control architecture.

Chapter 4

Robots and equipment for environments under radiation

Radiation can affect the functioning of the robotic equipment and, depending on the dose rate and time exposure, even permanently damage it. When the robots and tooling are foreseen to work in environments under radiation, this must be taken into account for the selection of the components and overall design of the equipment. Sensors, tooling and other components sensible to radiation shall be avoided in these situations.

4.1 Radiation effects to electronic materials

The irradiation of semiconductors, such as electronic materials, results in an energy transfer from the radiation particle to the irradiated component. These effects can be divided in two groups: single event effects (SEE), that are due to the energy deposited by one single particle, and cumulative effects (CE), that depend on the amount of absorbed dose (Faccio, 1999).

Single event effects are caused by protons and heavy ions impacting the electronic device. They can be transient, static or permanent. The difference is that transient effects, as single event upset (SEU), last for a clock cycle, static can be recovered by resetting the system, but permanent are hard errors, as latch up, that often cannot be solved. The incoming particle needs to be more energetic to cause permanent SEE than transient ones.

According to Holmes-Siedle (2007), cumulative effects can also be divided in two that can take place simultaneously:

- **Atomic displacement.** This causes the displacement damage (DD). When an incoming particle with more energy than the threshold (given by the properties of the irradiated material) impacts the material, it can displace an atom from its place in the lattice to a different position, leaving a hole in its original position (Frenkel pair).
- **Ionization.** This consists in the excitement of the electrons in the valence band promoting them to the conduction band. This effect is caused by the radiation dose, rather than by the energy of the incoming particles. The cumulated radiation dose absorbed by the component is called the total ionizing dose (TID), the higher this dose is, the higher the radiation damages due to ionization will be. The result will depend both on the exposure time and the dose rate.

As stated in Foster (2003), ionization accounts for most of the energy lost by radiation passing through semiconductors, and a smaller fraction of that energy causes the atomic displacement. In the case of photons, as they do not have any mass, and therefore momentum, they cannot produce displacement directly. However, they generate electrons by the Compton effect, and these particles produce the damage in the components.

To produce atomic displacement, it is necessary that the incoming particles transfer a certain amount of energy to the atoms in the lattice during the impact. This energy has to be at least the displacement energy, which will depend on the material of the component (depends on the energy of its atomic links and the type of lattice among other characteristics). In Kandlakunta et al. (2022), is stated that the displacement energy for Silicon is 21 eV.

The necessary kinematic energies for the different radiations to produce the atomic displacement are obtained theoretically and can be seen in Table 4.1. It can be noted that the heavier the particles of the incoming radiation are, the less speed is needed for the atomic displacement. It is also remarkable that if the displaced atom has enough energy, it will continue to displace others transferring them energy too.

Particle	Needed kinetic energy for the atomic displacement when impacting in Silicon
e^-	222 keV
p^+, n	158 eV
α	48 eV

Table 4.1: Displacement energies for Silicon depending on the particle of the incoming radiation. The energy threshold for the atomic displacement of this material is 21 eV. (Kandlakunta et al., 2022)

The atomic displacement causes the degradation of the materials affecting the electrical and optical properties of the devices (J. R. Srour et al., 2003). In J. Srour and Palko (2013), the effects of the displacement damage in different types of semiconductor devices are carefully studied. Whereas the ionization affects the conduction properties of the material, in Holmes-Siedle (2007) is mentioned that because of the electrons being excited from the valence band to the conduction one even insulators can conduct electricity at a higher level than normal for a certain time.

In Houssay (2000), the radiation effects in different types of electronic devices and materials are analysed. This work remarks the high sensitivity to radiation of the MOS technology devices, mainly due to ionization damage that contributes to the creation of electron-hole pairs in the insulator. This results in a build-up of charges in that region.

As a result, EPROM memories, that are based on MOS technology, are very sensible to radiation. The effects of radiation in this type of memories become remarkable after a TID of 10-200 Gy, they consist in the modification of the cells logic conditions and the stored information. Usually, this is the most sensitive element in the electronic devices, affecting the radiation resistance of the whole system.

Another electronic component that uses MOS technology is the charge coupled device (CCD), used as, light sensor in cameras. This device suffers not only from the cumulated dose, which effect is usually noticeable for doses higher than 100 Gy, but also from the dose rate, appearing a snow effect deteriorating the image quality. The dose rate limit for the usability of the camera due to this effect is often around 1 kGy/h, according to Houssay (2000). It is also important to remark that high cumulated doses in cameras result in a darkening effect of the lens.

There are some electronic components that are radiation hardened because they have been designed and tested against radiation. On one hand, developing components to withstand radiation is called radiation hardening by design (RHBD), this field studies the most suitable elements and layouts to be used to increase the radiation resistance of the electronic components. On the other the components in the market labelled as rad-hard are certified to guarantee a certain radiation dose before failing. The absorbed dose failure threshold for this type of devices is usually higher, and also this type of components result more robust and reliable than conventional ones when used under radiation. It will be analysed in the following section.

4.2 Robotic equipment for environments under radiation

In this section will be analysed the radiation resistance of robotic equipment, including the rad-hard components that have been designed and tested against harsh radiation conditions, and conventional ones (COTs) that have not been certified as radiation resistant.

4.2.1 Radiation hardened components

The errors in electronic devices due to radiation effects can be divided into two groups, hard and soft. Hard errors refer to the permanent errors that cannot be recovered, whereas soft include the temporary ones that can be solved via software or through hardware correcting systems. Also the errors can be divided in two groups depending on the event causing them, total ionizing dose (TID) and single event effect (SEE). TID errors come from the cumulative exposure to radiation, whereas SEE are caused by specific particles impinging on Si devices, which is a stochastic effect.

To protect the electronic devices they can be shielded to become radiation tolerant, but also they can be made radiation hard by design. In Calligaro and Gatti (2022), radiation hardening by design (RHBD) is defined as the set of techniques used to mitigate the effects of radiation on silicon devices. The goal of this design methodology is to mitigate hard errors and minimize soft ones. It includes reducing the probability of an accident due to radiation, minimizing the consequences of the eventual accident and error detection and correction (EDAC). To achieve this, it describes three different RHBD levels, each of them in charge of minimizing the probability of a specific type of error. These levels are architectural, circuit and physical layout, the latter is the only one capable of protecting the system from TID errors.

Examples of the use of this methodology can be found in Schrape et al. (2024) and Van Bockel et al. (2023). In the first one, Magics Technology, a company specialized in rad-hard systems presents the design of a highly precise time to digital converter where the electronics used are selected to make it insensitive to TID and heavy ions effects. In the second one, is described the design of a triple modular redundancy flip-flop with self correction radiation hardened by design to mitigate single event effects (SEE).

A particularly relevant countermeasure for soft errors is redundancy (Banteywalu et al., 2021; Otsuka & Ito, 2025). A common approach is using N Modular Redundancy (NMR), which consists in developing systems including N copies of a module so the data acquisition and calculations are done N times in parallel, and the results obtained can be voted. If N is an even number and voting does not get to a clear result, the operation will have to be repeated. Whereas if N is an odd number, the voting will choose the correct result. This type of systems is capable of tolerating faults in up to $\frac{N-1}{2}$ modules. An example of using Triple Modular Redundancy (TMR) can be found in Su et al. (2021) where this strategy is used to design a framework to apply to FPGAs processors. And referring to Double Modular Redundancy (DMR), in Vaisakhi and Surendran (2023), is applied to the development of a fault tolerant filter for image de-noising.

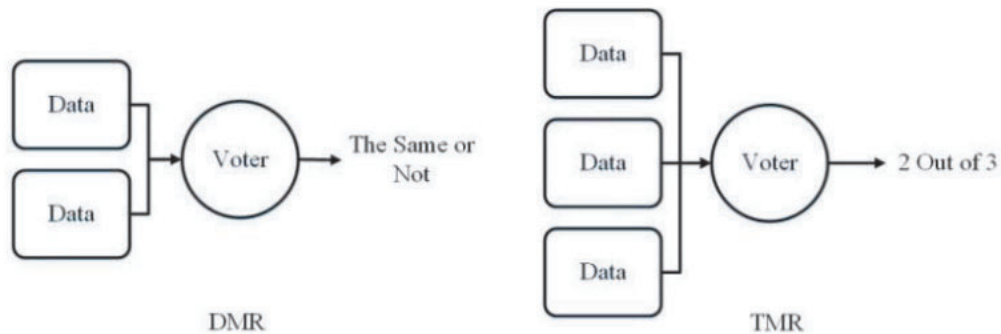
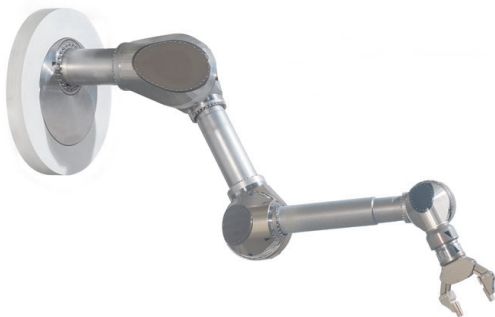


Figure 4.1: Diagram comparing the voting system of Double Modular Redundancy (DMR) and Triple Modular Redundancy (TMR). In DMR if an error is detected the operation will be executed again, whereas in TMR despite the error detection the result will be obtained anyway. (Su et al., 2021)

There are commercially available options of radiation hardened electronic components. Some companies, such as Magics Technologies or Altera, offer a wide selection of electronic systems designed and certified to withstand radiation. Not only small electronic devices, like time to digital converters, but also entire robotic arms such as the Telbot developed by Walischmiller (Whälischmiller, n.d.), or Dexter by Veolia (Veolia, n.d.), Fig. 4.2. MASCOT is an example of a robotic system developed specifically for the remote maintenance at JET, it can be seen in Fig. 4.3. In subsection 4.2.3, examples of radiation hardened cameras will be presented.



(a) Telbot rad-hard robotic arm developed by Walischmiller. (Whälischmiller, n.d.)



(b) Dexter rad-hard robotic system developed by Veolia. (Veolia, n.d.)

Figure 4.2: Views of rad-hard commercial robotic systems.

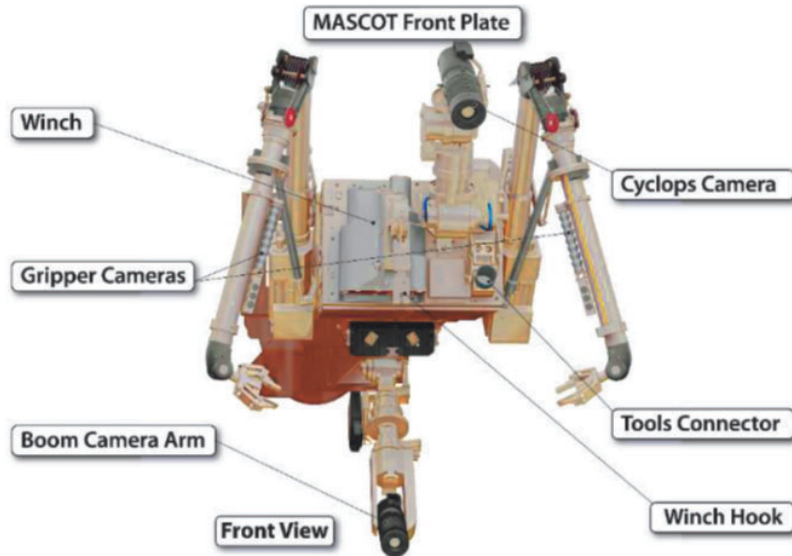


Figure 4.3: View of the MASCOT robot used for the maintenance at JET.

4.2.2 Components of the shelf (COTs)

In Section 4.1 has been analysed the effect of different types of radiation to some electronic components. Moving a step forward, this subsection will focus on the radiation resistance of commercial robotic systems. To study the effect of radiation in systems containing elements made of different materials and electronics the behaviour under radiation of every component can be analysed.

By analysing the radiation resistance of the different parts of the system, it can be estimated the radiation resistance of the whole system, as it will fail whenever the weakest part does. This method also helps in the design of the system, as thanks to this analysis the components can be selected according to the radiation resistance needs.

In French et al. (2016), is analysed the radiation resistance of a robotic finger according to the materials and type of electronic components present in it, and the distance there will be between them and the radiation source during the foreseen operation. Similar studies have been carried out in Shi et al. (2024) for the RHE of the ITER upper port, the authors analyse the radiation conditions that the robotic equipment will have to withstand and plan protection strategies for those components they predict will not be able to resist them.

Following the methodology presented in the works mentioned above, in Ferre et al. (2024) has been estimated the radiation resistance of the bolting tool proposed for the installation of the quick disconnection system (QDS) in the maintenance procedures of the beam dump (BD) of IFMIF-DONES. This tool will be presented in detail in Subsection 5.6. In Fig. 4.4. can be seen this bolting tool and all its components and materials. In Table 4.2 is summarized the estimated radiation resistance of the different parts of the tool, (Houssay, 2000; R. E. Sharp, 2009; Vandergriff, 1990). For the metallic parts, the damage threshold means the cumulated dose above, which the metal becomes less ductile and the yield strength increases, whereas for the electronics refers to the TID where their functioning is no longer reliable.

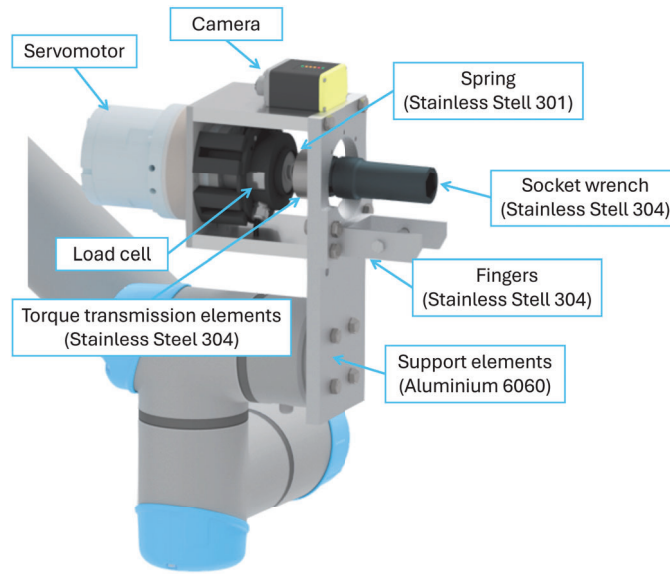


Figure 4.4: Components and materials of the bolting tool proposed for the installation of the quick disconnection system in the maintenance procedures of IFMIF-DONES. This design will be explained in detail in Subsection 5.6.

Component	TID damage threshold
Metallic components	
Torque transmission elements (Stainless Steel 304)	10^{11} Gy
Socket wrench (Stainless Steel 304)	10^{11} Gy
Fingers (Stainless Steel 304)	10^{11} Gy
Springs (Stainless Steel 301)	10^{11} Gy
Support elements (Aluminium 6060)	$5 \cdot 10^{11}$ Gy
Electric and electronic components	
Cables	10^6 Gy
Load cell	10^5 Gy
Camera	400 Gy
Servomotor	10^4 Gy

Table 4.2: TID damage failures for the components of the bolting tool for the QDSs in IFMIF-DONES. The parts can be seen in Fig. 4.4. (Houssay, 2000; R. E. Sharp, 2009; Vandergriff, 1990)

To estimate the radiation resistance of the servomotor its parts have been considered separately, the lubrication and the sealing have been identified as the most vulnerable to radiation. However the radiation degradation may be accelerated if the motor works in a harsh environment in terms of thermal and mechanical stress. For the most commonly used sealing materials and lubricators, the damage threshold corresponds to a TID of around 10 kGy.

It is important to remark that in the case of the camera, it is needed to take into account not only the TID but also the radiation dose, as above 155 Gy/h (R. Sharp et al., 1995) it starts to appear a snow effect in the image. This effect is temporary and only present when the camera is under radiation dose rates above the threshold. As was mentioned previously, the literature sets 1 kGy/h as the upper threshold for the usability of the camera because of this snow effect.

The bolting tool design analysed in Ferre et al. (2024) was developed to be integrated in the RHE of the accelerator system in IFMIF-DONES, the radiation levels expected in that area one day after shutting down the beam, are more or less 10^{-4} Gy/h around the closed shielding of the beam dump (Lopez-Revelles et al., 2024). The RH task for this tool is expected to last maximum 1 h, so the tool can be expected to last for several maintenance cycles, also it can be considered to shield the most critical parts to make it last longer.

4.2.3 Considerations for equipment selection for radiation environments

To illustrate this subsection will be used the example of cameras. They are widely used in RH applications not only for the visual feedback to the operator in teleoperated operations, but also for the positioning of the robot in automated steps of the task. In the market can be found a wide range of cameras, including the rad-hard models.

As was explained in the previous Subsection 4.2.1, the rad-hard models are designed and certified to be used in radiation environments. However, as has been demonstrated before, in subsection 4.2.2, conventional components can also withstand certain radiation conditions. Of course these devices are less reliable for their use in harsh radiation conditions, but a careful study and the corresponding tests can lead to an accurate estimation of the radiation they can withstand.

Sometimes it can be interesting to choose one of this conventional devices, if they can resist at least one maintenance cycle and then periodically replace it. This is due mainly to economical reasons, but also performance aspects may be taken into account. The rad-hard components are developed to resist radiation conditions, but this design usually limits their performance capabilities and increases its cost significantly.

In Toth (2017) is listed a wide selection of cameras (rad-hard and not), including important radiation related characteristics, like their maximum TID and dose rate, and performance related ones, such as their resolution. There are different levels of radiation resistance among them, for example:

- DACON VT 360 PT HD (Fig. 4.5a, (DACON Inspection Technology, n.d.))
 - Can withstand a TID of 420 Gy and a dose rate up to 70 Gy/h.
 - Has a resolution of 2,38 MP.
 - Weights 3 kg.
- Mirion RC720 CPC03A (Fig. 4.5b, (Mirion Technologies, 2024))
 - Can withstand a TID of 1 MGy and a dose rate up to 100 Gy/h.
 - Has a resolution up to 750 tvl.
 - Weights 3,4 kg.



(a) View of the camera DACON VT 360 PT HD. It can resist a TID up to 420 Gy and a dose rate up to 70 Gy/h. (DACON Inspection Technology, n.d.)



(b) View of the rad-hard camera Mirion RC720 CPC03A. It is capable of withstanding up to 1 MGy of total absorbed dose and a dose rate up to 100 Gy/h. (Mirion Technologies, 2024)

Figure 4.5: Examples of cameras and their radiation resistance.

It is important to remark that the most radiation resistant camera is heavier and has less resolution, without paying attention to the cost of any of them, which is expected to be higher for the second one, (DACON Inspection Technology, n.d.; Mirion Technologies, 2024).

Summing up, the equipment selection will depend on the specific requirements for each situation, nevertheless sometimes it is interesting to choose components with less radiation resistance if this allows better overall performance, still guaranteeing enough duration of the system.

4.3 Example of robot selection for radiation environments

This section will continue developing the idea presented in the previous subsection 4.2.3, in this case optimizing the radiation resistance of the components will not only focus on one device but in the whole robotic system.

In Smith et al. (2020), is presented a review of the main challenges that robots need to face to be deployed on a nuclear environment. Two different scenarios will be taken into account, low-medium radiation environments and high radiation environments.

As can be deduced, the difference between these two cases is the expected radiation level in the area. The threshold selected for this division has been 100 mSv/h, as this is the limit set for high radiation areas at different facilities such as CERN (Forkel-Wirth et al., 2013) or IFMIF-DONES (Tripodo, 2024). For radiation levels above this magnitude, the areas are prohibited for human access, so the operations shall be fully remote. Therefore, rooms with radiation levels below 100 mSv/h are considered low-medium radiation environments, whereas high radiation scenarios will present radiation levels above this threshold.

European regulation establishes dose limits for workers and general public (European Society of Radiology (ESR), 2015). As can be seen in Table 4.3, the limitation for general public is set at 1 mSv/year, whereas for workers is 20 mSv/year. This amount can be exceeded exceptionally getting to 50 mSv/y, but has to average 20 mSv/year over 5 years. Referring to the effects of radiation on the human body, they are summed up in Table 4.4 (Forkel-Wirth et al., 2013).

	Maximum allowed effective dose on the whole body
General public	1 mSv/year
Workers	100 mSv for 5 years Cannot exceed 50 mSv/year

Table 4.3: Annual exposure limits beyond medicine and natural radioactivity according to European regulations. (European Society of Radiology (ESR), 2015)

Dose (whole-body irradiation)	Effects
<0.25 Gy	No clinically recognizable damage
0.25 Gy	Decrease in white blood cells
0.5 Gy	Increasing destruction of leukocyte-forming organs (causing decreased resistance to infections)
1 Gy	Marked changes in the blood (decrease in the numbers of leukocytes and neutrophils)
2 Gy	Nausea and other symptoms
5 Gy	Damage to the gastrointestinal tract causing bleeding and ~50% death
10 Gy	Destruction of the neurological system and ~100% death within 24 h

Table 4.4: Summary of the effects on the human body of increasing radiation doses. (Forkel-Wirth et al., 2013)

4.3.1 High radiation environments

Now it will be presented an application where using radiation hardened robots is totally necessary, because of the harsh environmental conditions. There are some radiation hardened robotic arms available in the market, as the Telbot developed by Walischmiller (Whälischmiller, n.d.) or Dexter, developed by Veolia (Veolia, n.d.). In Tugal et al. (2024), is presented a comparison of the performance of both systems when teleoperated.

The particularity of this type of robots is that the parts exposed to radiation are only mechanical, the electronic components are separated from the end-effector in order to avoid the radiation damage. In addition to this, the mechanical elements used are also radiation hardened, see Fig. 4.6.

Hot cells are an example of this high radiation environments. In Lali and Setayeshi (2011),

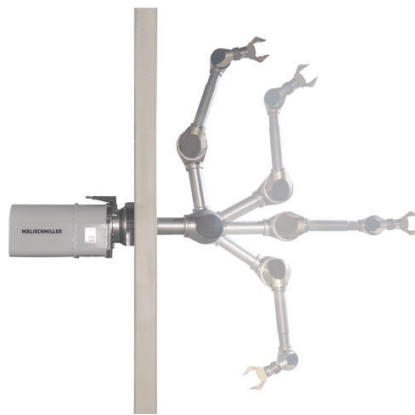


Figure 4.6: View of the Telbot robotic arm developed by Walischmiller. It is possible to notice that it is installed on a wall that protects all electronic components. Thanks to this the components withstanding radiation conditions are only mechanical. (Whälischmiller, n.d.)

the authors propose the use of the Telbot robotic system using the master-slave manipulator architecture for the RH in a hot cell. However, sometimes the requirements for this kind of tasks are very demanding and authors end up designing their own robots, Prikhodko et al. (2019) presents an example of this situation. The authors design and develop a robot, which can resist up to 10^7 Gy, to be controlled by master-slave architecture, with the idea of presenting a cheaper option for the radiation hardened robots. Another example can be found in Skilton et al. (2018), where the authors present the design of the sixth version of MASCOT, the telemanipulator used at JET for the RH, also using the master-slave architecture, see Fig. 4.7.

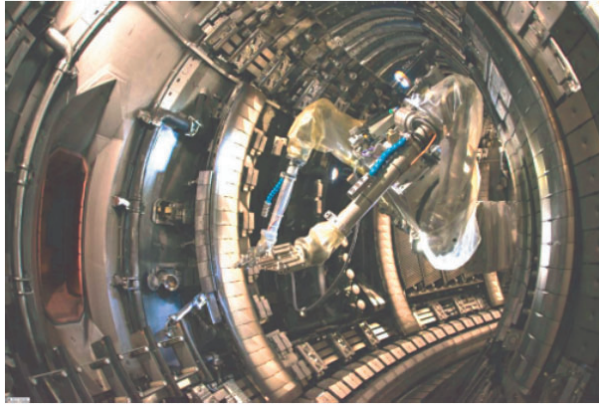


Figure 4.7: View of the Mascot robot inside the tokamak of JET performing replacement activities. (Piercy et al., 2024)

4.3.2 Low-medium radiation environments

This refers to the working areas where the expected radiation levels are below 100 mSv/h. In these areas human access is allowed, but for a limited stay. The proposal here is to use a commercial off the shelf robotic arm, which can withstand at least one maintenance. First, the examples found in the literature will be studied, and afterwards, using the example of the robot selection for the accelerator maintenance in IFMIF-DONES, the feasibility of this strategy will be analysed.

In Zhang et al. (2020), the radiation resistance of a KUKA iiwa 7 LBR800 robotic arm (KUKA, 2022) has been studied by putting it at 1,6 m from a 20 TBq source of cobalt-60 (^{60}Co). During the experiments the robotic arm had to follow a fixed trajectory while being monitored, to identify possible mistakes in the task due to radiation. Finally, the failure of the robot happened at the optical encoder of the end effector after it had absorbed 164,55 Gy, this failure was noticed by the control system of the robot which stopped the functioning of the system. The robotic arm was exposed to radiation for about 16,8 h. The authors proposal is to measure the absorbed dose in the joints of the robotic arm, which are the most vulnerable parts due to the electronics inside, and give the system preventive maintenance, replacing the necessary components when it reaches the 75% of its dose-to-failure lifetime.

Keeping this experiment in mind, now the selection of the robotic arm for the maintenance procedures in the accelerator vault (AV) in IFMIF-DONES will be analysed. According to Lopez-Revelles et al. (2024), everywhere in this room one day after shutting down the beam the predicted radiation levels are below 0,1 Gy/h, which is well below the threshold set for the low-medium radiation environment. The expected maintenance procedures in this room are the replacement of the scraper, the beam dump (BD) and the radiation isolation module (RIR), as detailed in Arranz et al. (2020). In Redondo Gallego and Ferre (2024), is presented a very conservative estimation of the expected time the robotic arm will have to stay in the room until the three maintenance procedures are completed, and the radiation dose it will absorb during that time, which is stated to be 8 Gy in total.

Bearing in mind the result of the experimental tests done in Zhang et al. (2020), and the analysis of the radiation resistance of the electronic components presented in Subsection

4.2.2, it will be considered that a commercial robotic arm without shielding or any additional protection can withstand an absorbed dose of 150 Gy before failing. So, if it is estimated to absorb 8 Gy per complete maintenance procedure (scraper, BD and RIR replacement), it can be stated that it will be able to complete 14 entire maintenance cycles before absorbing the 75% of the considered failing dose.

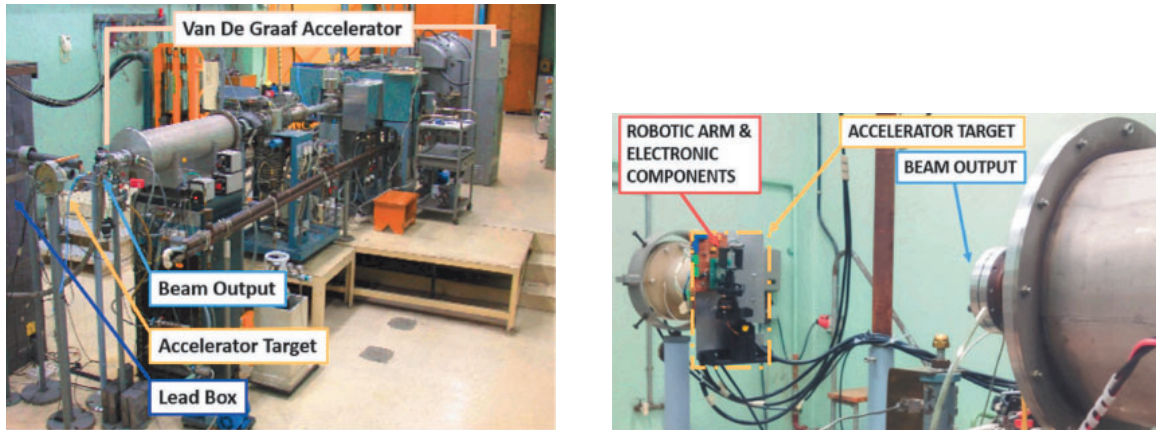
This is the result of a conservative estimation, but shows that a commercial robotic arm can be used in a harsh radiation environment such as the accelerator vault of IFMIF-DONES. This can be a safe strategy if during the use of the component its absorbed value is monitored and it undergoes maintenance when a set absorbed dose is reached. Also, the radiation tolerance of the robotic arm can be increased by shielding the most vulnerable parts, which has been identified as the joints.

4.4 Radiation resistance tests

The previous sections have focused on the theoretical estimation of the radiation resistance of RH equipment, and the need for designing radiation hardened components and certifying them as that. This final section will focus on irradiation tests. Carrying out this type of experiments is very important to characterize the performance of the components under radiation, identifying the failures that might come up during operation, and also to contrast the estimations done theoretically. For example, in Goiffon et al. (2017) are presented the results obtained when exposing RHBD CMOS image sensor (CIS) demonstrator developed for ITER remote handling to X-rays and γ radiation up to 10 MGy. Or in Zhang et al. (2020), the authors propose a methodology to carry out radiation resistance certification tests on commercial robotic arms.

In particular, this section will present two radiation resistance tests carried out using the linear Van De Graaff accelerator at the Centre for Energy, Environmental and Technological Research (CIEMAT by its Spanish acronym), it is shown in Fig. 4.8a. This accelerator can get to currents up to 150 μ A and energies up to 2 MeV. Further details about this accelerator can be found in CIEMAT (n.d.). These experiments have been published in Coloma et al. (2023).

The aim of these experiments was to analyse the behaviour of electronic components over time when exposed to ionizing radiation under different conditions (protected, unprotected and rad-hard version). The electronics tested were microcontrollers, servomotors, digital temperature sensors and a 3 DoF custom made robotic arm. As can be seen in Fig. 4.8b, the components were placed in the target of the accelerator in order to get direct impact of the electron beam, and achieve an homogeneous irradiation. In the first experiment were tested microcontrollers, servomotors and digital temperature sensors under different conditions each. Whereas in the second experiment, a custom made 3 DoF robotic arm was irradiated controlled by two different microcontrollers, a regular one and a radiation hardened one. In the following subsection each experiment will be explained in detail.



(a) General view of the linear Van De Graaff accelerator at CIEMAT.

(b) Detailed view of the target of the linear Van De Graaff accelerator at CIEMAT.

Figure 4.8: Views of the linear Van De Graaff accelerator at CIEMAT used for the radiation tests. (Coloma et al., 2023)

4.4.1 Microcontrollers, servo motors and temperature sensors test

As can be seen in Fig. 4.9 in this experiment were tested three different scenarios at the same time:

- Non protected Arduino Uno (ATmega328P) controlling:
 - Shielded servomotor with a 2 mm thick lead cover.
 - Unshielded servomotor.
 - Two unshielded temperature sensors LM35.
- Arduino Uno (ATmega328P) protected under a 2 mm thick lead cover controlling:
 - Shielded servomotor with a 2 mm thick lead cover.
 - Unshielded servomotor.
 - Shielded temperature sensor LM35 with a 2 mm thick lead cover.
 - Unshielded temperature sensor LM35.
- ATmegaS64M1, radiation hardened commercial board controlling:
 - Unshielded servo.
 - Unshielded temperature sensor.
 - Embedded internal temperature sensor (unshielded).

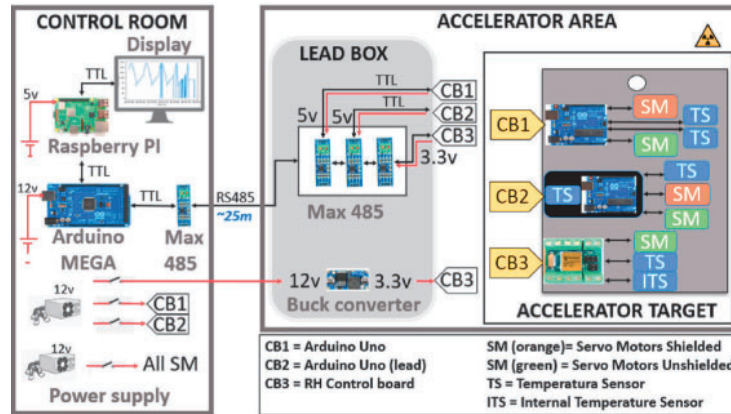


Figure 4.9: Experimental setup for the first experiment. The controllers irradiated are two Arduinos (CB1 without protection and CB2 with a lead shielding) and an ATmegaS64M1 (CB3). Also, several servomotors (SM) and digital temperature sensors (TS) connected to the control boards were irradiated. The orange color of some of the servomotors in the scheme means that those were shielded, whereas the green ones were unprotected. Finally, ITS corresponds to the internal temperature sensor embedded in the ATmegaS64M1 controller. (Coloma et al., 2023)

During the experiment, each microcontroller generated PWM signals (with a period of 50 Hz at 120 kHz clock) for the servomotors while their positions were monitored, as well as the readings of the temperature sensors. The radiation conditions of the experiment were 0,18 Gy/s during the first 29 minutes, and 1,5 Gy/s during the last 9 minutes. It is considered that a microcontroller failed when it stopped working due to a severe error.

In Fig. 4.10 is represented the absorbed dose and duration of each microcontroller before failing. The first board to fail was the unshielded Arduino Uno (CB1), which was irradiated for 26 minutes and 34 seconds and withstood 286,92 Gy. Then the rad-hard ATmegaS64M1 board (CB3), which lasted for 28 minutes and 6 seconds and absorbed a total dose of 303,48 Gy. Finally, the shielded Arduino Uno (CB2) resisted the whole experiment absorbing 1123 Gy throughout 38 minutes without failing. It can be concluded then, that the radiation mitigation strategy that obtained the best result was shielding the microcontroller with a 2 mm lead cover, thanks to this protection the control board in this experiment did not experiment any fatal error causing its shutting down.

Focusing now in the performance of the servomotors, in Fig. 4.11 is represented the evolution of their position throughout the experiment compared with a reference in green. Each graph corresponds to each controller, and the blue line corresponds to the unshielded servos, whereas the red one to the shielded ones.

To evaluate their performance, it has been analysed the evolution of the absolute trajectory error (ATE), which measures the difference between the ground-truth position and the estimated position. It has been calculated as $ATE = \sqrt{\frac{1}{n} \sum_{i=1}^n T_i^2}$, where T_i stands for the Euclidean distance along the horizontal plane between the obtained position and the expected one at frame i , and n corresponds to the number of frames. The evolution of the ATE for each servo is shown in Fig. 4.12, it can be seen that the minimum ATE throughout the experiment, corresponds to the shielded servo controlled by the shielded Arduino Uno. For the

servos controlled by the unshielded Arduino Uno, the ATE increases rapidly as the absorbed dose gets higher, however there is not much difference between the shielded and unshielded one. Regarding the servo controlled by the rad-hard board, ATE does not get as high as with the unshielded Arduino Uno, which is an advantage because it means that it stays reliable in spite of the radiation effects. Finally, comparing the shielded and unshielded servos controlled by the shielded Arduino Uno, the results are better with the shielded one, but seeing this figure can be stated that the most significant radiation mitigation strategy is shielding the control board, rather than shielding the servomotor.

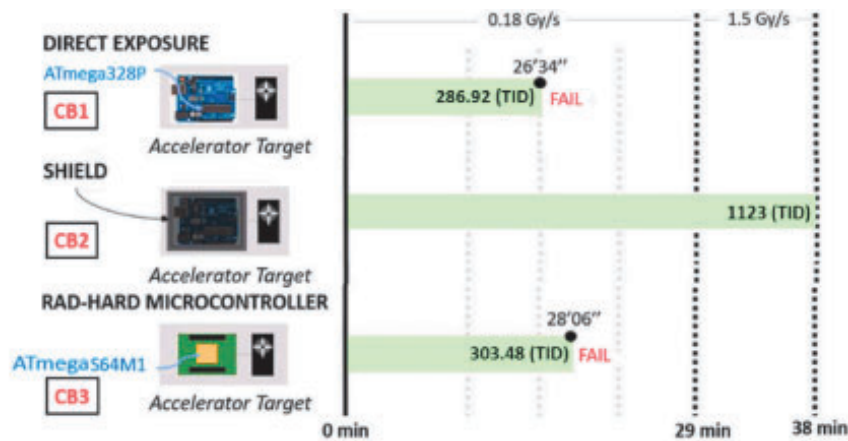


Figure 4.10: TID absorbed by the microcontrollers before failing during the first experiment. (Coloma et al., 2023)

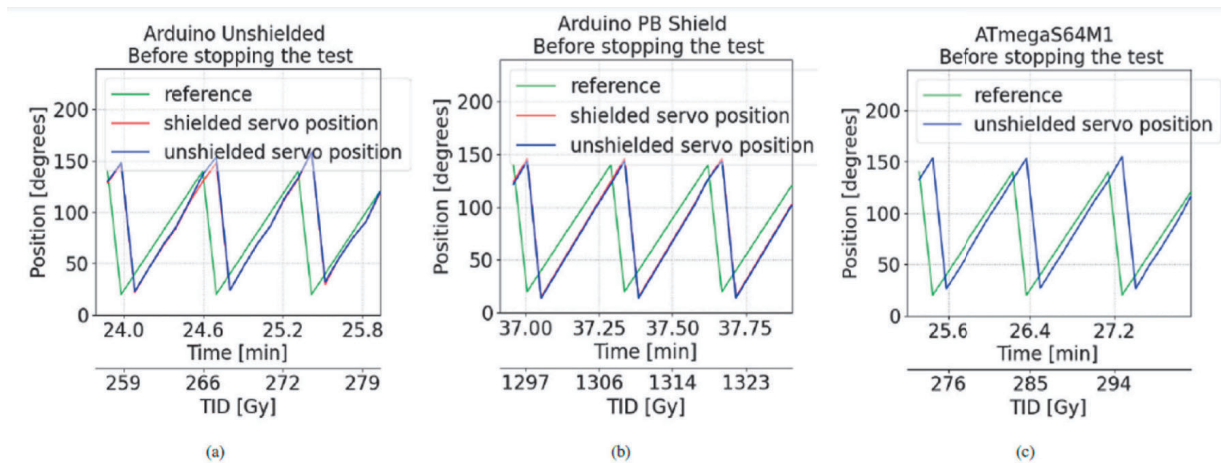


Figure 4.11: Evolution of the position of the servomotors during the first experiment for the different controllers, (a) Unshielded Arduino Uno, (b) Shielded Arduino Uno and (c) ATmega564M1 rad-hard. (Coloma et al., 2023)

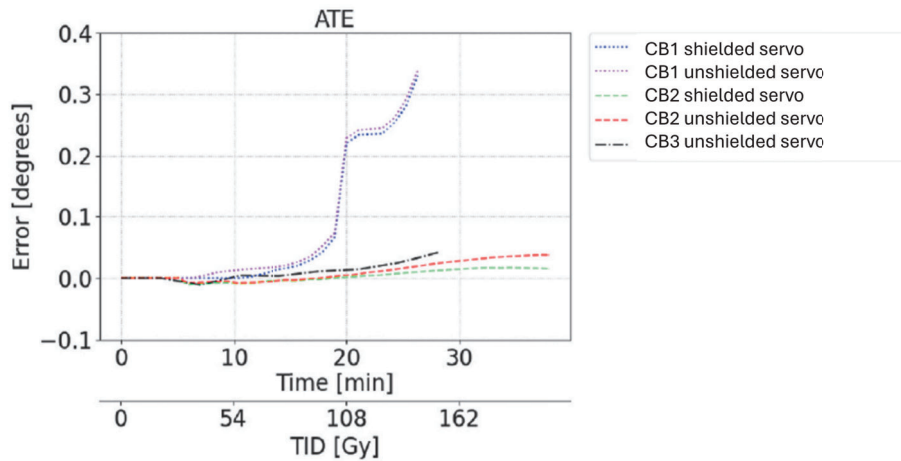


Figure 4.12: Evolution of the absolute trajectory error (ATE) throughout the first experiment for the different servomotors. (Coloma et al., 2023)

Finally, regarding the readings of the temperature sensors, their evolution can be seen in Fig. 4.13. The unshielded Arduino Uno (CB1) read two unshielded temperature sensors which presented similar evolution. They both increased significantly 13 minutes before the failure of the board evidencing the electronic degradation. Moving to the shielded Arduino Uno (CB2), it controlled one shielded temperature sensor and another one unshielded. In this case, the performance of both sensors was different. The shielded sensor did not increase as the absorbed dose increased, whereas the unshielded one raised rapidly to its saturation levels as a consequence of the degradation of its internal structure, causing its digital to analogue converter circuit to be always at its higher, and the permanent damage of the sensor. For the rad-hard microcontroller ATmegaS64M1 (CB3), the internal temperature sensor and the unshielded one connected to this board do not present sudden changes. The reason for this is that this control board reduces the accumulative errors in the readings of the sensors. Upon this analysis, it can be stated that in this case shielding the sensors and using rad-hard microcontrollers make a difference in the quality of the readings obtained. And it is also noticeable that during the experiment there was a temperature increment in the target of the accelerator.

4.4.2 3 DoF robotic arm test

In this case, the experiment consisted in exposing to ionizing radiation a 3 DoF custom made robotic arm controlled, first by a conventional microcontroller (ATmega64M1), and then by the rad-hard version of this control board (ATmegaS64M1). The results obtained with each microcontroller were compared and will be analysed in this subsection. The experimental setup is represented in Fig. 4.14, and the irradiated robotic arm can be seen in Fig. 4.15.

Joints one and two of the robotic arm were controlled in position mode, they described a semicircular trajectory throughout the whole experiment, going from 0° to 90° and back to 0° . Whereas, joint three is controlled in velocity, moving at a constant speed of $180^\circ/\text{s}$.

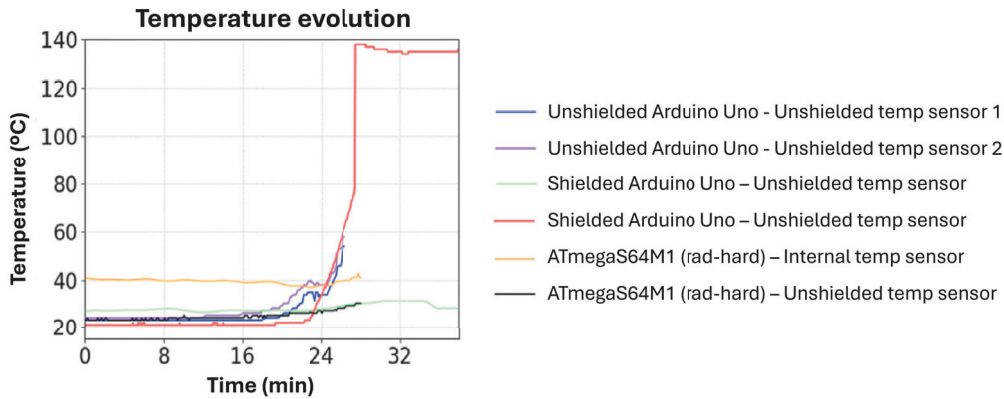


Figure 4.13: Evolution of the readings of the temperature sensors during the first experiment. (Coloma et al., 2023)

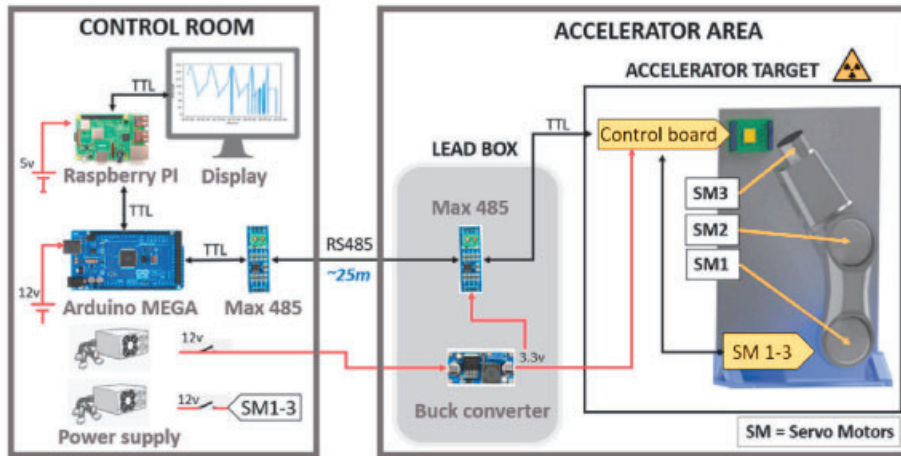


Figure 4.14: Experimental setup for the second experiment. A 3 DoF robotic arm was irradiated with a regular microcontroller and a rad-hard one. SM corresponds to the servomotors of the robotic which were not protected against radiation. (Coloma et al., 2023)

The irradiation conditions in this experiment were 0,18 Gy/s constantly. And, as in the first experiment, it is considered that a microcontroller fails when it stops working due to a severe error. As can be seen in Table 4.5, the conventional control board absorbed a total dose of 218,88 Gy before failing, and the rad-hard version 311,22 Gy.

Now the performance of the servomotors for each case will be analysed, the comparison between the expected results and the obtained ones for each joint and each microcontroller can be seen in Fig. 4.16. It can be seen that for the rad-hard microcontroller (ATmegaS64M1), the results obtained for all the joints remain closer to the reference, than for the conventional controller. To see how this error affects the trajectory of the robotic arm, in Fig. 4.17 have been represented the comparison between the reference of the trajectory and the last lap before the failure of each microcontroller.

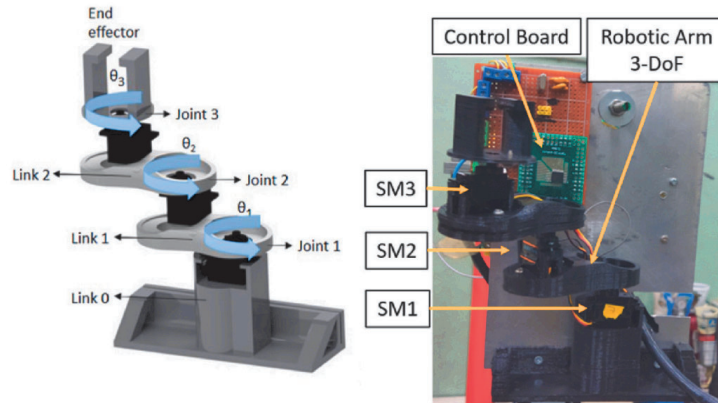


Figure 4.15: View of the robotic arm used for the second experiment and diagram showing its characteristics. (Coloma et al., 2023)

Microcontroller	Radiation dose (Gy/s)	Duration	TID (Gy)
ATmega64M1	0,18	20 mins 16 secs	218,88
ATmegaS64M1 (rad-hard)	0,18	28 mins 49 secs	311,22

Table 4.5: Radiation absorbed until failure by the microcontrollers used in the second experiment. (Coloma et al., 2023)

Following with this comparison, to quantify the error it has been used the absolute trajectory error as in the first experiment. In Fig. 4.18, can be seen its evolution for each joint and microcontroller. It can be noticed that in both cases the evolution of the error in the joints one and two was similar, nevertheless significantly lower for the rad-hard control board. However, for the third joint the error increases more, the reason for this is that, because of the trajectory of the robotic arm, this servomotor is closer to the beam. Looking at the overall performance of the robotic arm, it is easy to conclude that the error was smaller for the rad-hard microcontroller. This can be explained as this board is designed to reduce cumulative errors, as was already mentioned for the analysis of the digital temperature sensors in the first experiment.

In conclusion, although the rad-hard board did not last significantly longer in this experiment, it showed to be more resistant to errors caused by radiation, reducing significantly the errors in the trajectory of the robotic arm. This makes it more reliable until the end which is always important when operating robotic systems remotely in hazardous environments.

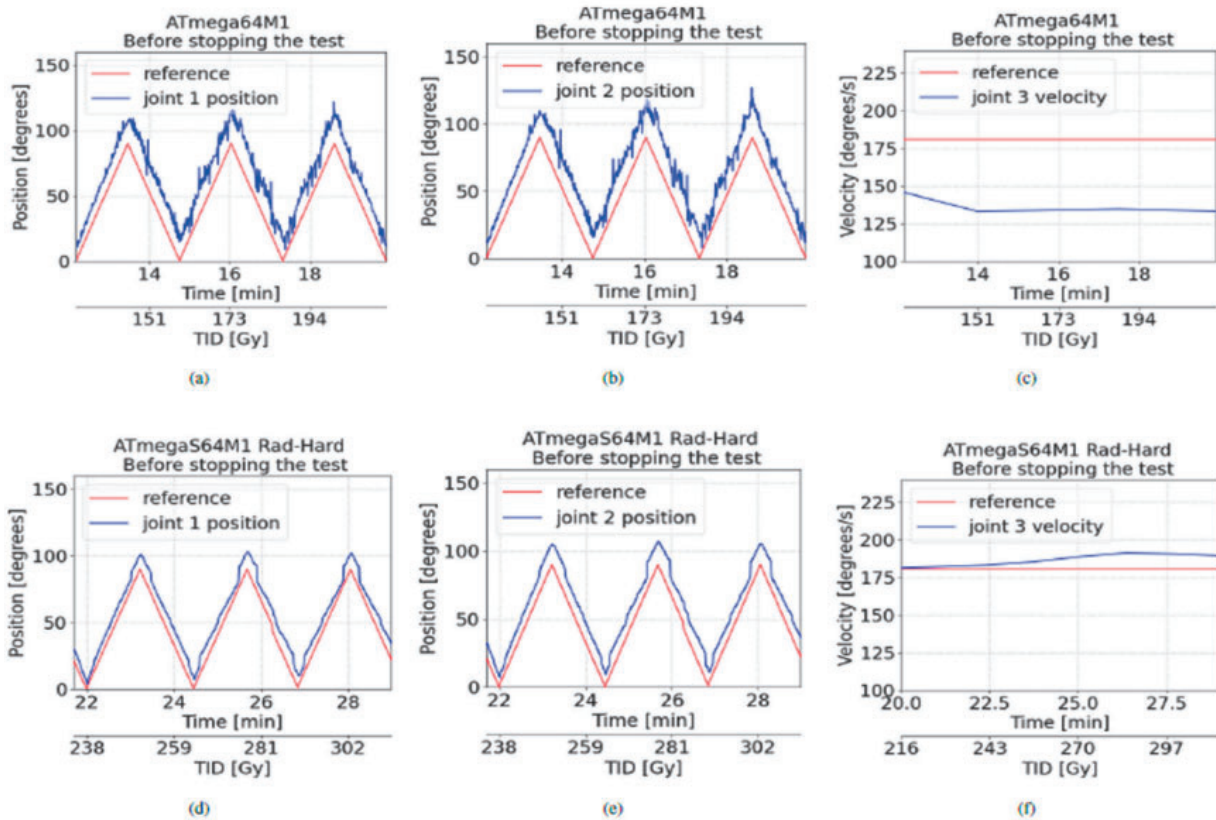


Figure 4.16: (a,b,c) Evolution of the position of the first and second joints and the speed of the third one during the experiment when the robotic arm is controlled by the non rad-hard controller (ATmega64M1).(d,e,f) Evolution of the position of the first and second joints and the speed of the third one during the experiment when the robotic arm is controlled by the rad-hard controller (ATmegaS64M1). (Coloma et al., 2023)

4.4.3 Lessons learnt from the radiation tests performed

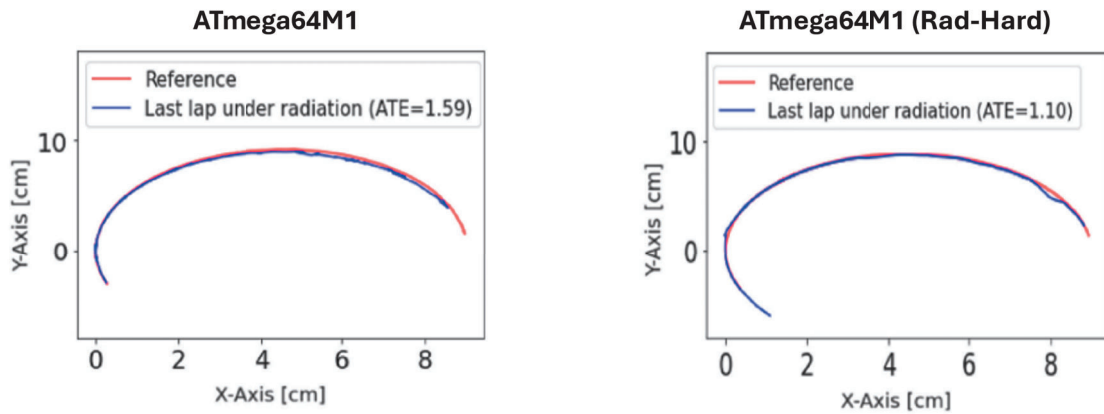
In both experiments the radiation-hardened microcontrollers lasted longer than the unshielded conventional ones. Nevertheless, shielding a conventional microcontroller presented a more significant improvement in terms of duration, than using the rad-hard version of the control board. Focusing on other aspects than the duration, the rad-hard microcontrollers showed less errors throughout their functioning under radiation than conventional boards, for example, in the readings of the temperature sensors or in the ATE of the robotic arm joints.

For the servomotors, the experiments carried out showed that it did not really make a significant difference to shield them or not. The greater difference came from the conditions of the microcontroller. However, the third joint of the robotic arm in the second experiment showed greater errors, because of its closer position to the beam, so it can be concluded that the distance to the radiation source is actually a significant factor for the servomotor performance under radiation, as was predicted.

Regarding the temperature sensors, their degradation due to the radiation became very clear in the first experiment. Shielding a temperature sensor with a 2 mm thick lead cover

demonstrated to be as effective for the error mitigation as using a rad-hard control board capable of reducing the cumulative errors.

Summing up, the radiation mitigation strategies tested in these experiments were proved effective improving different aspects of the devices performance under radiation. Shielded microcontrollers withstood a higher TID, whereas the rad-hard ones reduced the cumulative error caused by radiation. It can be concluded that, depending on the task, one or the other can fit best, and they can even be combined.



- (a) For the ATmega64M1, the non rad-hard microcontroller, the radiation absorbed throughout the whole experiment until the last lap was around 190 Gy.
- (b) For the ATmegaS64M1, the non rad-hard microcontroller, the radiation absorbed throughout the whole experiment until the last lap was around 290 Gy.

Figure 4.17: Comparison of the trajectories described in the reference and in the last lap of the second experiment for each microcontroller (non rad-hard in the right and rad-hard in the left). (Coloma et al., 2023)

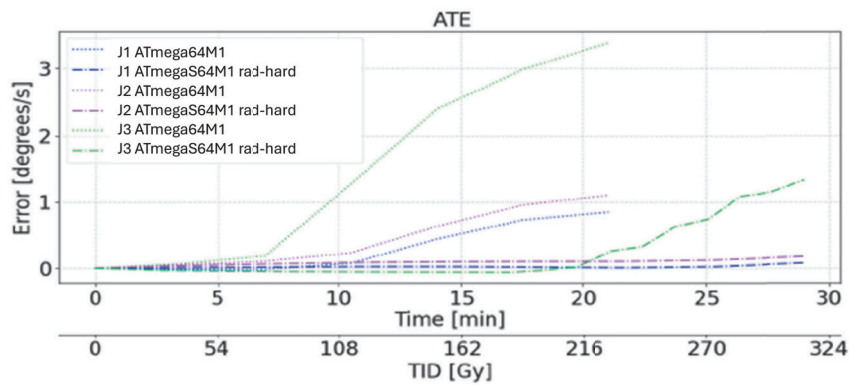


Figure 4.18: Evolution of the absolute trajectory error (ATE) throughout the second experiment for the different microcontrollers and joints of the robotic arm. (Coloma et al., 2023)

Chapter 5

Design of tooling for remote handling

The tools used in the RH procedures shall be designed taking into account the requirements and constraints of the tasks carried out with robots, as well as those specific of the environment where they will take part. This means providing interfaces that enable the robotic equipment to operate them reliably and stick to the particular needs of the procedure. As a result, it is not possible to develop a generic tool for all the RH tasks, only methodologies and design guidelines for the design of the particular tooling necessary for each application.

In this chapter are shown some examples that could be considered the base of other designs for similar procedures. However, modifications to the design would have to be made to use them for other activities.

5.1 Proposed design methodology

In this chapter will be explained in detail the proposed design methodology for the RH tooling:

- Starting by gathering all the requirements and constraints possible for the tool and the procedure.
- Studying the state of the art and then carrying out a market survey to check if the needed tool already exists, or if an existing one can be adapted for the new application.
- If it is necessary to design the component or modify an existing one, do it following the design guidelines that will be explained later in this chapter.
- Once the preliminary design is completed, it is recommended to carry out a simulation to test the functioning and integration of the tool in the RH system.
- When the simulation results are considered successful, a mock-up can be manufactured, or 3D printed, to test the system in the laboratory. Paying attention to test the key aspects of the functioning of the tool. This stage of the design methodology is crucial as mock-ups enable the testing of cables, connections and other elements that might behave different in real life than in the simulations. In the following sections examples of this laboratory tests will be presented.
- Finally, when the newly designed tool is accepted during the testing, it can be manufactured and used in operation. Even during this phase, data about its performance will be gathered to identify potential improvements to the design.

5.2 Classification of the main RH tasks

Earlier in this thesis have been proposed ideas on how to face the challenge of designing tooling for RH, in this section will be analysed which are the main maintenance RH tasks needing specific tooling. This is a key aspect of the design as each type of task has its particular requirements, different from other tasks.

To analyse the different types of tasks that are usually carried out by RH in maintenance procedures, JET, CERN and IFMIF-DONES have been consulted. The resulting proposed classification has been summarized in Fig. 5.1. Seven groups have been created according to the goal of the activity and the tool used, they will be explained in detail in this section.

The goal of this classification is to remark the similarities among the tools used for analogue procedures. Thanks to this when facing the design of a new tool with very demanding requirements this classification can be used as a guide for the common aspects for similar tools, making it easier for the designers to adapt commercial models to new tasks.

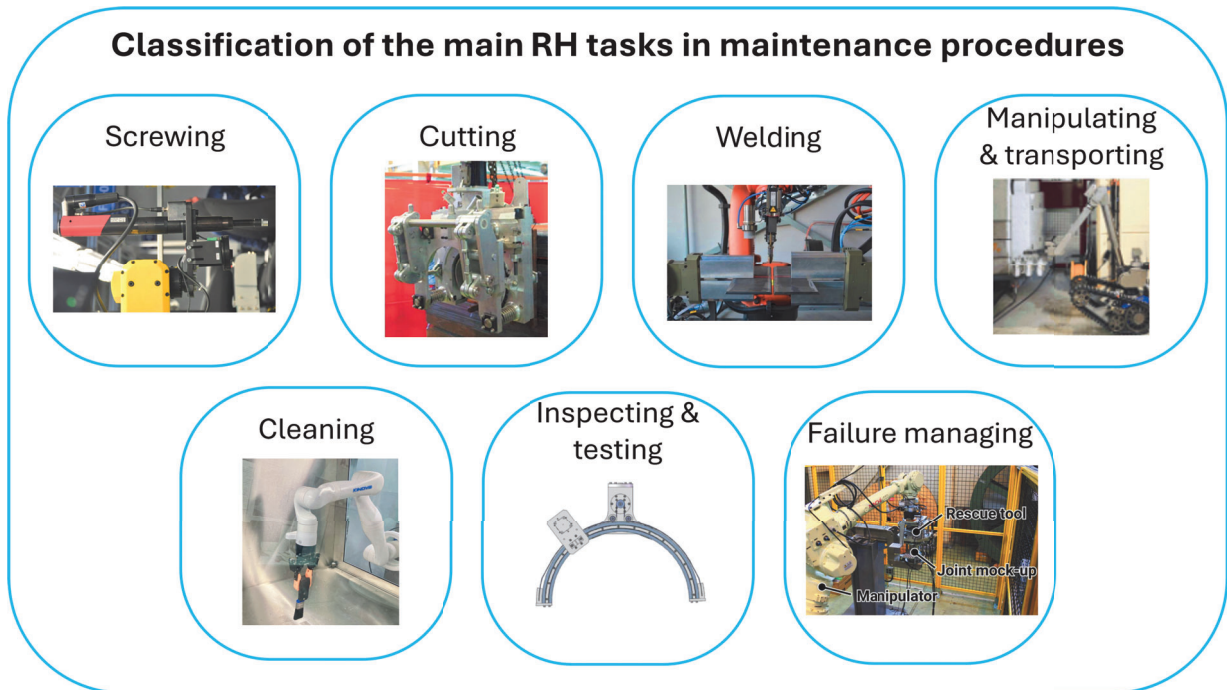


Figure 5.1: Proposal for classifying main procedures for which RH is used. (Ferrari et al., 2022; He et al., 2020; Kovarikova et al., 2022; Maruyama et al., 2019; Sága et al., 2020; Tabia et al., 2022; Thomson et al., 2017)

Screwing

This category includes screwing and unscrewing bolts, screws, fasteners... Usually the same tool is used for both procedures, but not always. An example of a tool developed specifically to loosen bolts is shown in Fig. 5.2.

The main characteristics of the (un)screwing tools are that they need an interface with the bolts, usually a socket wrench; an actuator capable of achieving the necessary torque; a positioning system to enable the coupling between the bolt and the tool; and, usually, it is needed a reaction torque limiter system to protect the robot against excessive reactions. There is a wide range of commercial robotic bolting tools, customized ones have to be developed only when the constraints of the particular do not match with the specifications of the commercial ones. Section 5.3 presents designs of customized bolting tools developed for the maintenance procedures in the accelerator system of IFMIF-DONES.



Figure 5.2: Robotic bolt loosening tool. This is an example of a tool designed only to perform unscrewing operations. (Lai et al., 2023)

Cutting

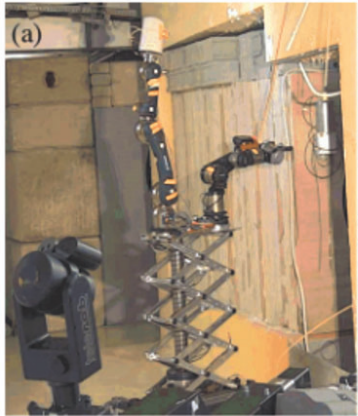
This group includes several activities, as cutting pipes or cables, drilling and grinding. The reason for this is that, even there are some differences among the considered tools, they all have in common the separation of materials that can provoke swarf, dust or other type of waste that will have to be contained or collected.

These tools will mainly include a cutting/drilling/grinding system, a waste collection system and a positioning system. Examples of tools used for the RH tasks included in this group can be seen in Fig. 5.3.

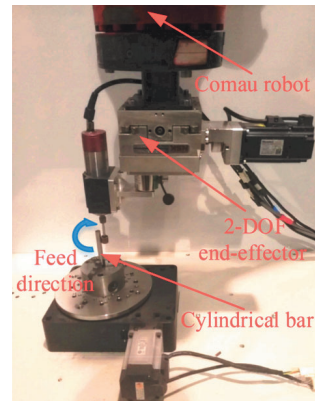
Focusing on the pipe cutting, there are several techniques as thermal, mechanical or erosional, depending on the one used the design of the tool will vary widely. For example, orbital lathes need to get in contact with the pipe, but, when using laser cutting, this is not needed. Section 5.3 will give more details about this task.

Welding

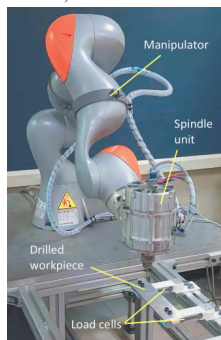
This category only includes one type of activity, nevertheless there are many different techniques that can be used for welding pipes. Section 5.3 will explain this into more detail. Also, the strategy used for deploying the pipe will impact significantly on the design of the tool, as welding can be done in-bore (from the inside of the pipe) or ex-bore (from the outside of the pipe), see Fig. 5.4. Ex-bore welding becomes specially interesting in situations where the space available is very narrow.



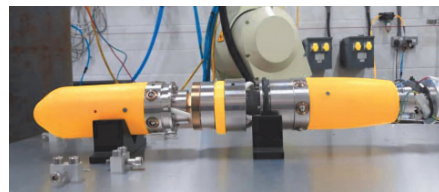
(a) Robotic system to cut cables at CERN. (Ferrari et al., 2022)



(b) Robotic grinding tool. (D. Li et al., 2022)



(c) Robotic drilling tool. (Cole et al., 2024)



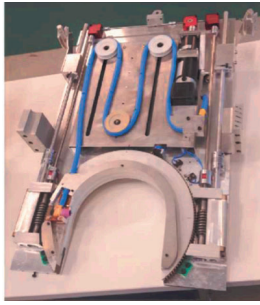
(d) In-bore laser cutting tool developed at UKAEA for the maintenance at DEMO. (Kirk et al., 2018)

Figure 5.3: Examples of robotic cutting tools.

Manipulating and transporting

This group refers to the manipulation and transportation of components belonging to the facility. Both tasks include the positioning of the elements being manipulated or transported. The fact that the components manipulated or transported belong to the facility is important, because if the activity consists in moving a sensor that was already in the room to a new spot, the task will be included in this group. However, if the sensor is introduced in the room for the maintenance, the goal of the task is to carry out an inspection, which will belong to the inspecting and testing category.

Manipulation includes all the activities related with plugging and unplugging connectors, or replacing small components, such as first wall tiles, which becomes of high importance in tokamaks. The grippers used for this purpose can be very different from one another, generalizing, they can be design to adapt to different geometries, under-actuated, or customized to fit a very specific component. Fusco et al. (2024), Noguchi et al. (2018), and Ogawa et al. (2024) show examples of different grippers developed for the replacement of first wall tiles in different facilities. However, even though the task is similar for each procedure, it was necessary to design an specific customized tool. One of these tools can be seen in Fig. 5.5.



(a) Orbital TIG welding tool developed for ITER maintenance. (Ren & Skilton, 2024)



(b) Laser in-bore welding tool developed by UKAEA for DEMO maintenance. (Kirk et al., 2018)

Figure 5.4: Examples of robotic welding tools.

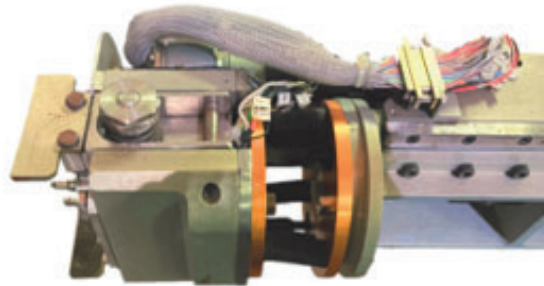


Figure 5.5: View of a customized gripper developed for the manipulation of the first wall tiles in the RFX-Mod2 fusion machine. (Fusco et al., 2024)

Regarding transportation, a very important part is related to heavy loads. It is very common in facilities where RH is implemented to have maintenance procedures, which include the replacement of components weighing several tons. In these cases, there are two options widely considered: using cranes with gripping mechanisms or transfer gaskets. In IFMIF-DONES can be found several examples of the first scenario (Miccichè et al., n.d.), in particular the crane in charge of removing the TC plugs has a payload of 140 tons, and the gripping mechanism consists of a load carrier with twist locks, see Fig. 5.6a. Another example is the gripping tool developed for the transportation of the target assembly, done by the same crane as the previous one, see Fig. 5.6b. On the other hand, other facilities like CFETR implement transfer gaskets for the transportation and positioning of the heavy components such as the blanket segments, see Fig. 5.7 (Cheng et al., 2022). In this case, the components are directly transported to radiation shielding gaskets and safely moved to the corresponding location in the facility. Fig. 5.8 shows the foreseen path for the blanket segments to be installed in ITER (Vale et al., 2017).

A remarkable part of the transportation activities is the moving of heavy loads. For this tasks, it is often necessary to use cranes or other robotic equipment with high payloads, and tools capable of withstanding heavy weights, while guaranteeing the necessary positional

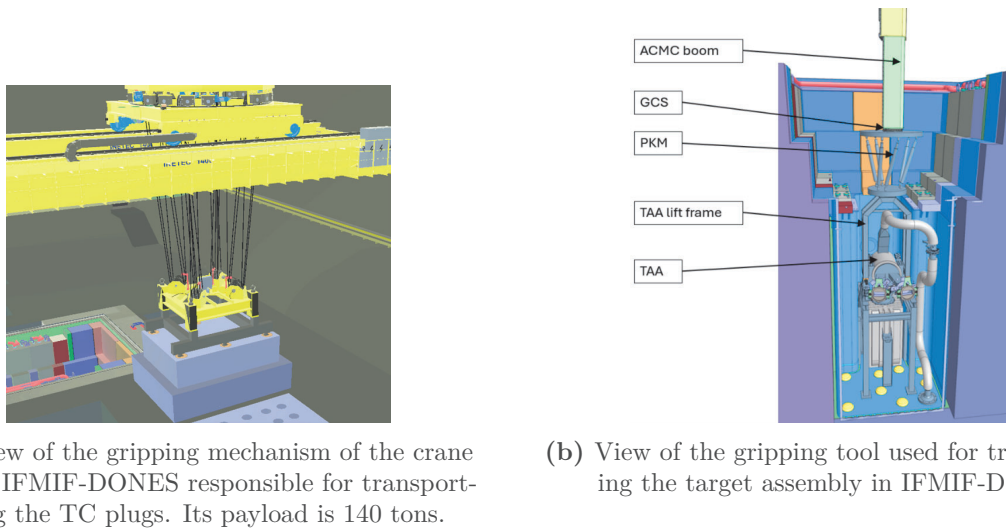


Figure 5.6: Gripping mechanisms for transportation of heavy loads in IFMIF-DONES. (Miccichè et al., n.d.)

accuracy.

The tools used for the activities in this group are mainly grippers. There is a wide range of commercial grippers, however, as it is not possible to develop a universal tool, it is usually needed to adapt existing ones or even design fully customized ones. According to Fusco et al. (2024), grippers in RH represent a delicate balance between customization, robustness and precision, while fulfilling weight limitation constraints and dynamic performance requirements. Shreyas Desai et al. (2020) presents a review of the design strategies for grippers depending on their foreseen application, remarking the grippers used for RH.

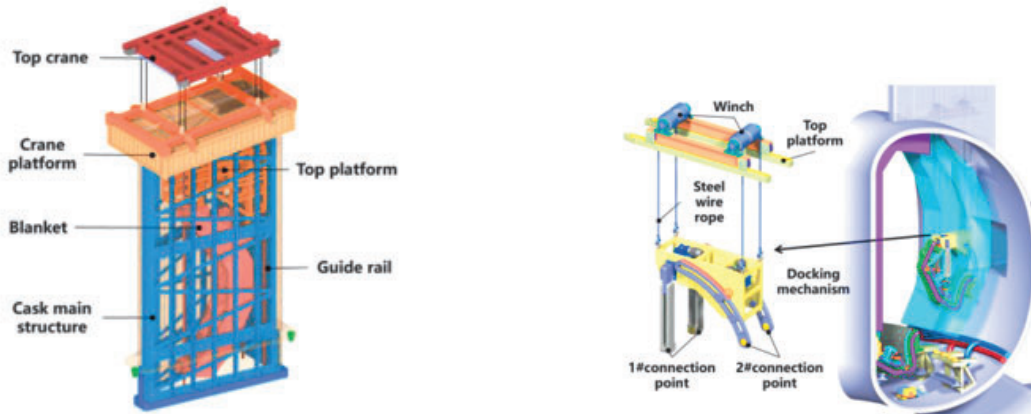
Section 5.4 and Section 5.5 present two examples of custom designed gripping tools. The first one for transportation and the second for manipulation.

Cleaning

Cleaning is a very important activity in maintenance procedures, as there are usually very strict regulations against leaving external substances in the facility. There are different types of tasks included in this group, for example, decontamination, waste collection or cleaning after a water leak.

The tools used for this category are very different, as the cleaning method used will impact the design of the tool. Sometimes to develop these systems, cleaning tools designed for humans, as brooms or vacuum cleaners, are adapted to robots, see Fig. 5.9a. However, other times the cleaning robotic system is directly designed for the use of robots, see Fig. 5.9b.

Cleaning, and, in particular decontamination, is a key activity carried out at hot cells. In this type of environments it is usually used the master-slave teleoperation architecture. An example of this is shown in Fig. 5.10, where the slave robotic system is using a vacuum cleaner to remove the contaminated dust from a component.



(a) View of the transportation mechanism developed for the blanket segments in CFETR.

(b) View of the positioning mechanism developed for the blanket segments in CFETR.

Figure 5.7: Gripping mechanisms for transportation of heavy loads in IFMIF-DONES. (Cheng et al., 2022)

Inspecting and testing

Inside this category are included all the activities aiming at surveying or testing the environment, for example carrying out radiation surveys or testing the installed pipes against leaks. Another important aspect of this activities is the calibration, as could be testing the functioning of the radiation sensors in the room. Additionally, it is remarkable that all the testing is necessary for the validation activities, as testing the welds performed in pipes is essential to validate their installation.

Most of the testing carried out during maintenance procedures is non-destructive, however, if any destructive trials were done, they would also be included here.

Referring to the inspection, it is very common to perform visual inspections, see Fig. 5.11, or using robotic systems to move around other types of sensors as oxygen, radiation or humidity to provide environmental awareness.

Sometimes it is necessary to measure remotely, for which can be used laser techniques, clouds of points or just a simple ruler. This task can be considered in this group, as it consists in carrying out a test to obtain a distance.

Failure managing

Thanks to the careful study of the failure scenarios that has to be done before operation, different tools are developed to be used in this situations. The goal of these tools is usually to recover lost components or rescue robotic systems.

Sometimes there is no need to use specific robotic systems, only to develop specific procedures for rescue and recovery activities, an example of this can be seen in Fig. 5.12, where trials for recovery scenarios are carried out at CERN (Ferrari et al., 2022). The robotic system used is the same as the normal conditions operation.

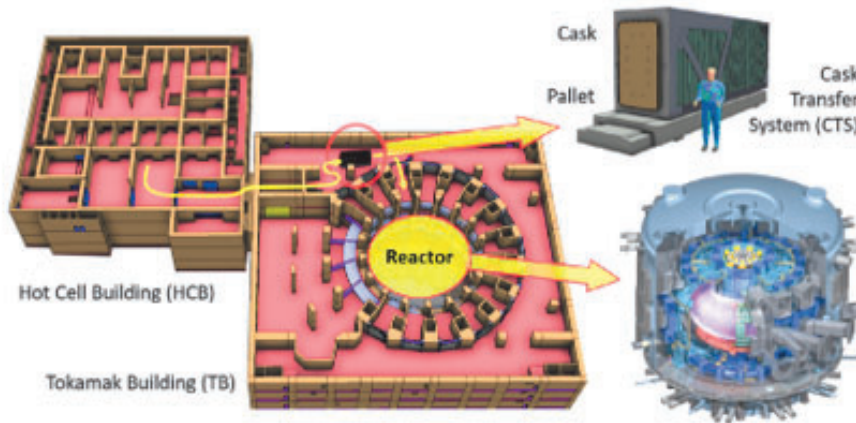
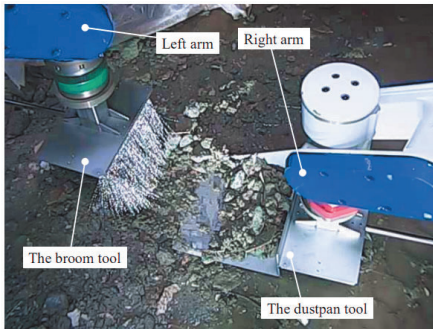
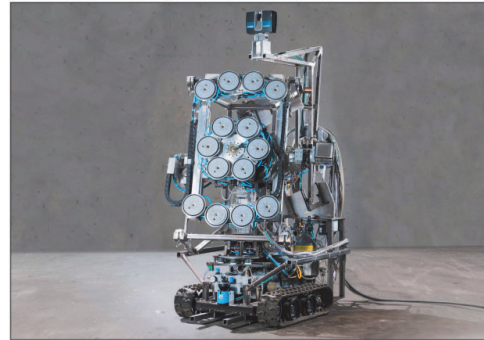


Figure 5.8: View of the planned trajectory for the blanket segments to be installed in ITER. (Vale et al., 2017)



(a) Robotic cleaning system consisting of a broom tool and a dustpan tool adapted to be used by a two arms robot. (WATANABE et al., 2015)



(b) MANOLA climbing robot developed at KIT for the decontamination of concrete walls. (Petereit et al., 2019)

Figure 5.9: Examples of robotic cleaning systems.

When developing tooling for these activities they are usually grippers, hooks or specific rescue tools (Maruyama et al., 2019). It is also important to add the corresponding grasping interfaces in the components, in order to enable their recovery.

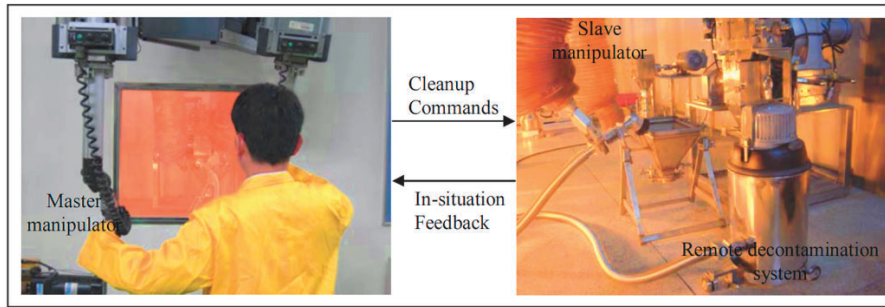


Figure 5.10: View of the teleoperated procedure to remove contaminated dust from a component in a hot-cell. (Kim et al., 2007)

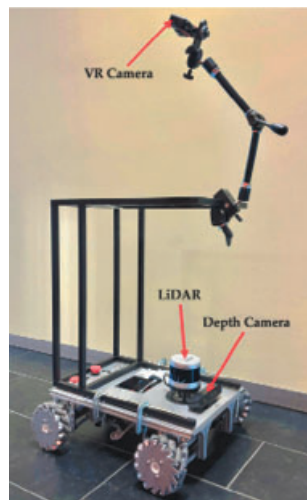


Figure 5.11: Robotic system developed at CERN to carry out visual inspections in the tunnel. (Bahreini et al., 2024)

5.3 Cutting and welding considerations

Cutting and welding play a key role in the maintenance procedures, as they enable the separation and rejoining of components, usually, they are specially used for pipes. There are several challenges in the performance of these operations, as to the common environmental constraints are added difficult access to the pipes, lack of visibility, and other constraints regarding the cutting and welding strategies to use.

Cutting and welding are actually very different procedures, each has its own specifications and constraints. However, often efforts are made to develop tools capable of performing both operations, as a way of optimizing the RHE.

One of the key aspects for the cutting and welding tools are the deployment to the working position. They can be deployed and perform the operation from the inside of the pipe, which are inbore tools, an example of an inbore cutting tool developed for the maintenance in DEMO can be found in Sorgente et al. (2024). Or the tools can be deployed and perform the operation from outside of the pipe, known as outbore. In Kovarikova et al. (2022) is presented a welding tool of this type.



Figure 5.12: Mock-up trials of recovery scenarios at CERN. The robotic system used is not specific for failure managing, but the procedures being tested have been developed specifically for these situations. (Ferrari et al., 2022)

Traditionally there are a wide range of cutting and welding techniques, so taking into account the requirements of the task it is necessary to choose the most suitable ones. In Ren and Skilton (2024) is presented a summary of the available technologies for pipe cutting, welding and non destructive testing.

Referring to cutting, the most commonly used techniques when performing the operation by RH can be divided in three groups:

- **Mechanical cutting techniques:** This group includes some very popular cutting techniques in RH, such as orbital lathe, grinding or milling. In Shigematsu et al. (2012) is presented an example of a RH milling tool developed for ITER maintenance, which includes a swarf collection system. This is a key aspect, because often requirements are very strict about leaving any external substances in the area, and swarf collection can present a challenge when developing a RH mechanical cutting tool.
- **Thermal cutting techniques:** The most popular one is laser because of its high cutting speed and no need for contact between the tool and the pipes. In Tremethick et al. (2020) is presented a tool developed for the RH at DEMO, with which authors successfully cut a pipe made of AISI 316L 5 mm thick.
- **Erosion cutting techniques:** The most common kinds of erosion cutting are water jet and electric discharge machining (EDM) (Zang et al., 2017).

Regarding welding techniques, the most commonly used by RH are laser and TIG. Fig. 5.1 shows a comparison between them. Laser welding results very attractive due to its welding speed and the little thermal stress it creates in the component, however, it is not feasible for thick pipes and the tolerance for the misalignment between the components is very narrow. An example of RH laser welding can be found in Hayashi et al. (2015), where authors develop a tool to weld cooling pipes 2,8 mm thick, made of SUS316L with a diameter of 59,8 mm. In that work, authors mention that one of the reasons why they decided to use laser welding instead of TIG, was the need to use inner and outer gas shielding for the latter. However, there are other cases where TIG welding is most suitable for the task, as in Thomson et al. (2017) where is presented a RH TIG welding tool for the maintenance procedures at ITER.

	Laser	TIG
Key parameters	Laser power 2.8 kW Laser spot diameter 1.2 mm Welding speed 1 m/min Gas flow rate 80 L/min Heat input 1.7 kJ/cm	Pulse frequency 1.7 Hz Peak width 35 % Current (peak/base) 121–130/43–45A Voltage (peak/base) 9.8/9.2 V 5.5 kJ/cm
Allowable gap and linear misalignment	0.2 mm 0.7mm	0.5 mm 1mm
Tool lifetime and maintenance	Small power drop from 2.82 kW to 2.77 kW after 50 times welding	Electrode damage after 10 times welding
Necessity of rescue for tool head	no	Electrode-sticking was avoided by employing DC power, touch start with arc voltage control
Shielding gas	N ₂ for inside	Ar and He for inside, N ₂ for outside
Production of welding fumes and spatter	large amount of fumes, post cleaning to be considered	Almost no, no post cleaning is needed
Cable handling and transmission	Relative cables/fibres to be separated from In-vessel Transporter cabling system	Tool cables to be developed in addition to the In-vessel Transporter cabling system

Table 5.1: Comparison between laser and TIG welding. (Ren & Skilton, 2024)

Referring to the RH maintenance procedures of the breeding blanket (BB) at DEMO, it is needed to cut and weld a collection of cooling pipes, called pipe forest in order to replace the segments of the BB. The characteristics of these pipes are the following:

- There are 20 pipes: 10 pipes DN 200 and 10 pipes DN 80.
- They are made of AISI 316L.
- They are 8 mm and 16 mm thick.

As can be seen in Fig. 5.13, there are two foreseen cutting and welding positions. In the vertical spot, the procedure is expected to be done by in-bore tools, and in the horizontal, by ex-bore ones. According to what is presented in Mozzillo et al. (2024), a diagram showing a proposal for the procedure can be seen in Fig. 5.14.

Focusing on the exbore cutting and welding tools, which will work in the horizontal cutting and welding positions, the main environmental requirements are that they shall withstand the radiation conditions, which are still to be defined, and that all the waste produced during the operation shall be collected. Also, the tools shall be deployed to the working position, but they shall attach themselves to the pipes. After a very careful study of the requirements, the conclusion is that, because of the characteristics of the pipes and the environment, the suggested cutting technique is mechanical, as an orbital lathe or a swage cutting tool, and it shall include a swarf collection system. Regarding the welding technique, the most suitable one is considered to be TIG, although it will be necessary to use gas shielding on both sides of the pipe, and that gas has to be compliant with the facility constraints.

Following the design guidelines presented in Subsection 2.4, the tools are preferred to be modular and if possible commercial or adapted from COTs, in this case this will present a challenge, as this application is unique in many aspects. However, adapting other designs present in the literature seems more feasible.

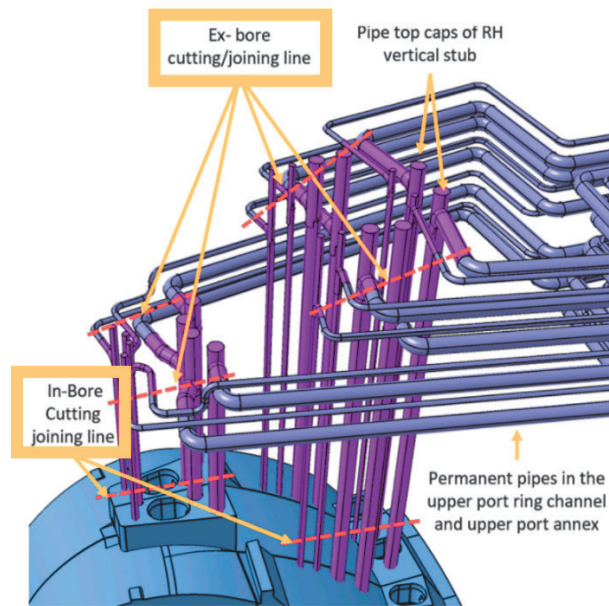


Figure 5.13: View of the pipe forest of the BB cooling pipes in DEMO. (Mozzillo et al., 2024)

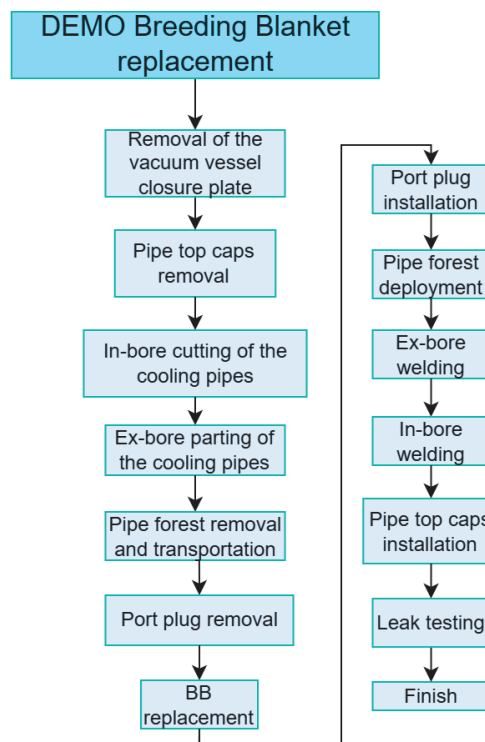


Figure 5.14: Diagram showing the stages of the proposed procedure for the breeding blanket replacement at DEMO. (Mozzillo et al., 2024)

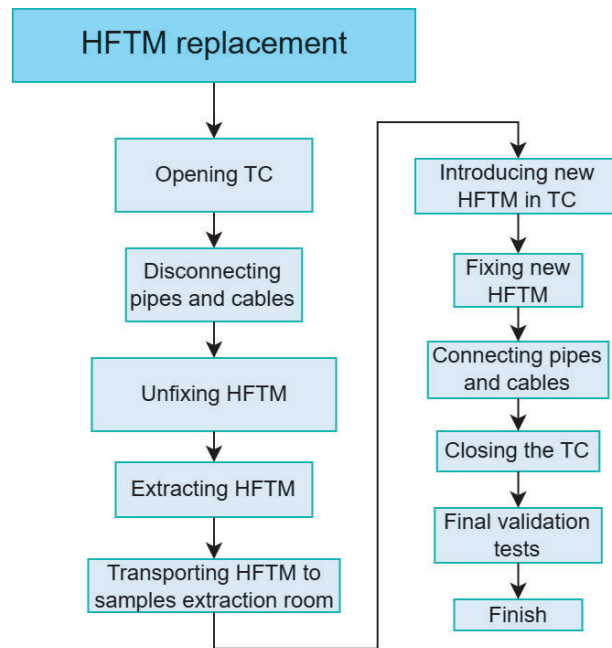


Figure 5.15: Stages of the procedure for the replacement of the HFTM in IFMIF-DONES.

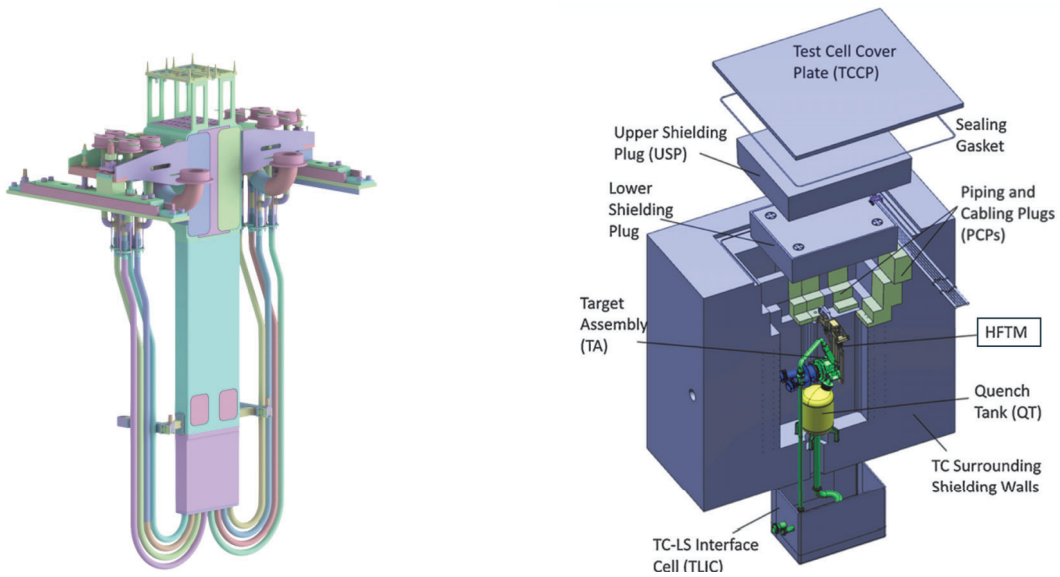
Finally, it is important to remark the importance of inspecting the pipes after the cutting and welding operations. After cutting is relevant to analyse the quality of the cut and ensure the feasibility of the posterior welding. And after the welding, it is a key aspect to test the quality of the welding to validate the procedure or correct it. When carrying out the cutting and welding by RH, usually the inspection has to be done also by RH, and the preferred inspecting methods are non-destructive, as x-ray or ultrasound. A deeper analysis about this can be found in Ren and Skilton (2024).

5.4 Example of a gripping tool for transportation

It is a very common RH operation to grasp objects with a gripper like tool and transport them. In this section will be presented a particular case of a gripping tool, designed for the maintenance procedure of the High Flux Test Module (HFTM) in IFMIF-DONES, see Fig. 5.16a.

The HFTM is the component that stores the samples being irradiated by the neutronic beam in the facility (Zsákai et al., 2024). It is located in the TC, see Fig. 5.16b, and due to the high radiation levels in the area, it has to be maintained by RH. The stages of the replacement procedure for the HFTM can be seen in Fig. 5.15.

The available RHE for the transportation is an overhead crane and a parallel kinematic manipulator. As none of this robotic components has an interface adequate to grab the HFTM, it is necessary to develop a specific tool that enables the operation. The main requirements of the grasping tool are the following:



(a) View of the High Flux Test Module (HFTM). The component where the irradiated samples are stored. (Arbeiter, 2023)

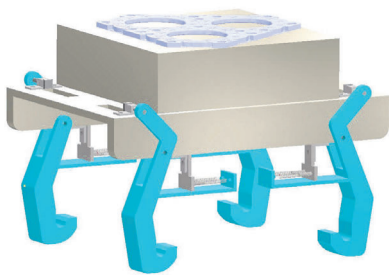
(b) View of the location of the High Flux Test Module (HFTM) in the Test Cell (TC) of IFMIF-DONES. (Qiu et al., 2019)

Figure 5.16: The High Flux Test Module (HFTM) is located inside the Test Cell (TC) in IFMIF-DONES. The gripping tool designed is in charge of grasping the HFTM in the TC and transported it to the room where the samples will be extracted, and the other way round with the new component.

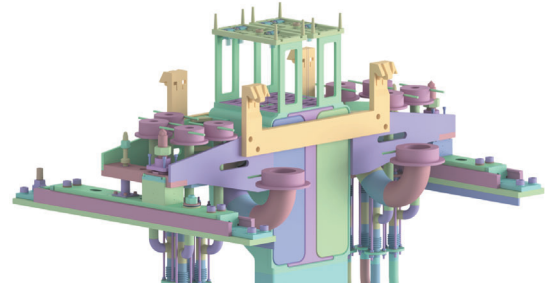
- The payload has to be enough to transport the HFTM (1t) with a safety margin.
- It shall withstand the radiation levels in the working area for at least one maintenance cycle.
- It has to be highly reliable, as it will transport one of the key components in the facility. For this reason, it is important that it includes redundancy in the grasping.
- It must include interfaces compatible with the RHE and the HFTM.
- It has to enable easy maintainability and decontamination. For this reason modularity is important.

The detailed design procedure followed for the development of this tool, and an explanation of the grasping and releasing procedures can be found in Annex A. In Fig. 5.17a is presented a view of the resulting gripping tool and, in Fig. 5.17b, the gripping interfaces added to the top of the HFTM.

The first version of the design of this tool is explained in Redondo Gallego et al. (2022), although that design has been optimised to make it more robust (adding redundancy in the springs and changing them to compression so the tool is more failure tolerant) and facilitate the manufacturing (simplifying the guiding paths). Also, the top platform has been updated to fit the changes in the HFTM design. The result can be seen in Fig. 5.17.

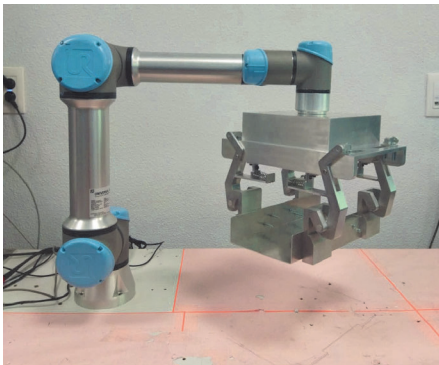


(a) View of the designed gripping tool. For the movement of the fingers compression springs are used. On top of the superior platform there are motors that insert security pins to block the fingers during transportation as a safety measure to avoid accidents.

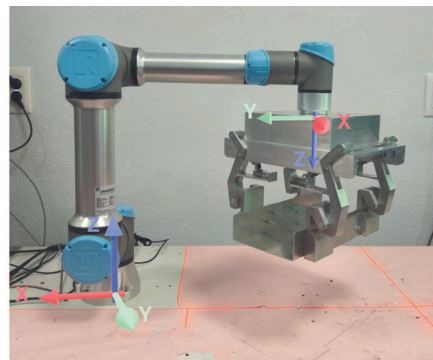


(b) View of the designed grasping interface that will be placed on top of the HFTM and will enable the attachment. The designed supports have leaning surfaces on top with guiding paths matching the fingers of the tool to provide a guided and controlled grasping.

Figure 5.17: Views of the designed grasping tool and grasping interface between the component and the tool. (Redondo & Ferre, 2024)



(a) View of the test bench layout.



(b) Coordinates systems used for the tests.

Figure 5.18: View of the test bench used for the tests of the gripping tool. The robotic arm used is an UR5e that attaches the mock-up of the tool. In the image the tool is carrying the mock-up of the HFTM, it corresponds to the transportation stage of the procedure.

5.4.1 Mock-up and tests

Following what was explained in 3.2, once the design phase was completed, a mock-up of the tool was manufactured to evaluate its functioning and identify potential improvements for the next design iteration. The development of the mock-up and the test bench is detailed in the Annex A.

Tests carried out

To validate the grasping mechanism of the designed tool there were three types of tests carried out, each with the goal of validating a different aspect of the functioning, see Table 5.2. All types of tests were performed several times with very similar results, and data was collected to evaluate the functioning afterwards.

Type of test	Description	Objective
Regular operation conditions test	Performing the grasping, transportation and releasing of the HFTM in regular operation conditions	Validating the functioning of the tool and the procedure when no failures come up
Rotation of the ensemble	While the transportation phase the robotic arm performs a rotation of the ensemble	Testing the reliability of the grasping, analysing the behaviour of the ensemble when rotated past the safety limits
Transportation speed	Moving the ensemble at different speeds	Testing the effects of the transportation speed on the ensemble

Table 5.2: Description of the different types of tests performed on the mock-up of the gripping tool designed.

Regular operation conditions test

This type of test consisted in grasping the HFTM mock-up with the tool, transporting it to another position in the test bench and performing the release, see Fig. 5.19. The forces in the tool centre point (TCP) of the robot were recorded and analysed to identify any potential critical situation. The resulting graph showing the evolution of the forces during the grasping, transportation and releasing can be seen in Fig. 5.20.

When evaluating the data collected, the conclusion was that the most critical situation for the robotic arm was the releasing of the HFTM mock-up. The reason for this is the contact between the top part of the supports and the metallic part below the springs, while the vertical descend of the tool to release the component, see Fig. 5.21. The force limit in the TCP is approximately 50 N, so even the highest force peak remains in the safety margin of the robotic equipment. Possible ways of action to minimise this peak:

- Improving the visibility for the operator during the descend. Or if the procedure takes place automatically, improve visibility, so the programmer knows clearly when the descend is enough.
- Adding contact sensors to the part of the tool that touches the top of the supports, so it will be totally clear when the descend is completed.

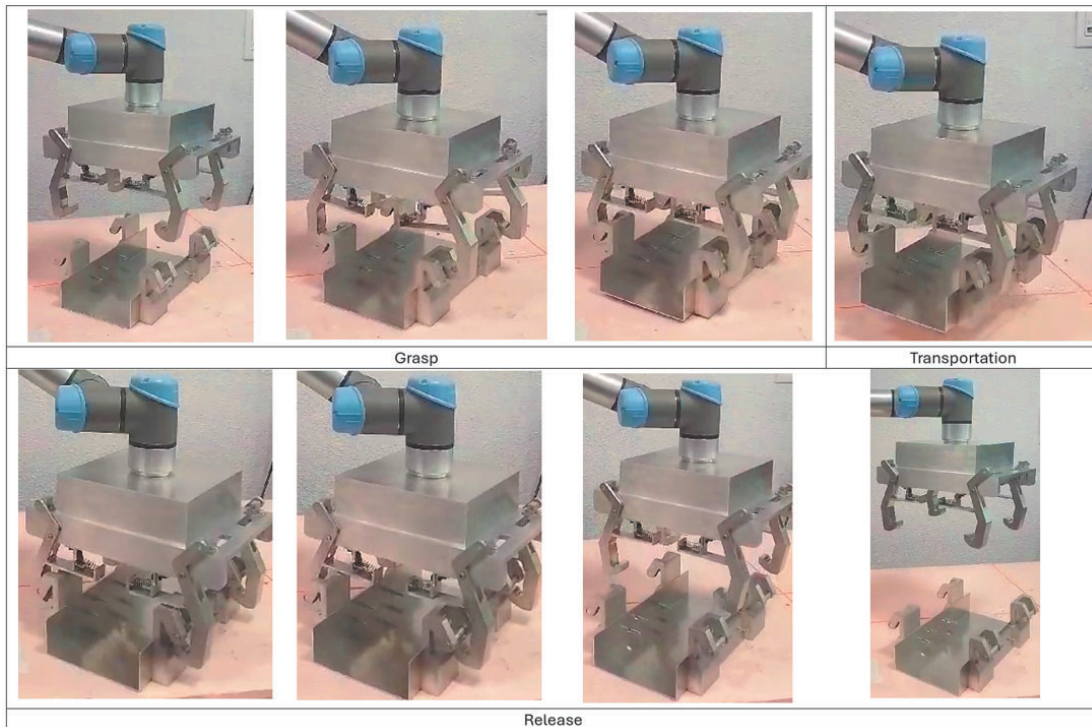


Figure 5.19: Photos of the regular operation conditions test. It is possible to see the different stages of the procedure to grasp the mock-up of the HFTM, transport and release it in the test bench.

Rotations of the ensemble test

In this type of test, rotations of the ensemble around the axis of the coordinate system in the TCP have been performed, some of them can be seen in Fig. 5.22. Due to the symmetry of the interface between the robotic arm and the gripping tool, the rotations around the Z axis do not destabilise the grasping. Following the methodology of the previous type of test, throughout the experiment data was recorded to analyse it afterwards.

The goal of this experiment was to check if there was a limit for the rotation angle, this means if it was possible to find an angle from which the risk of fall of the HFTM mock-up appeared. However, as can be seen in Fig. 5.22, no matter what the tilting was, the HFTM never fell from the robotic equipment. Obviously, in operation conditions these great rotation angles are not expected, and the whole structure of the HFTM will have to be considered to predict its behaviour. Nevertheless the goal of this test was to assure that the grasping would not be affected by the tilting of the RHE, and the results were considered satisfactory.

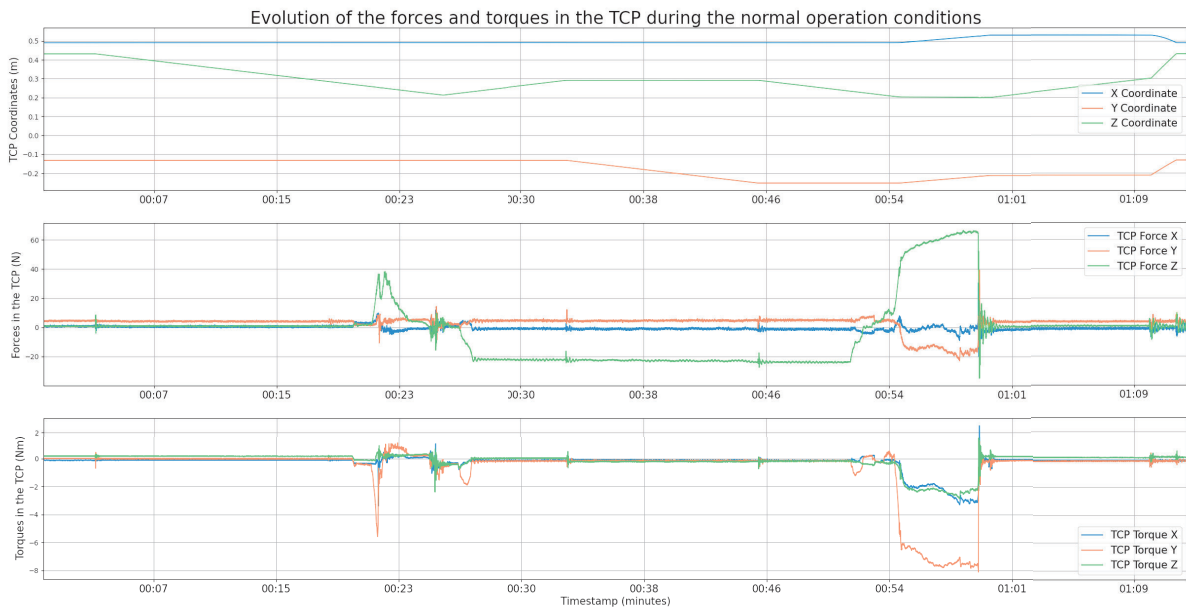


Figure 5.20: Graph showing the evolution of the forces during the regular operation conditions test. The different stages of the procedure are identified. This results are expressed according to the coordinates system of the TCP of the robot shown in A.7b

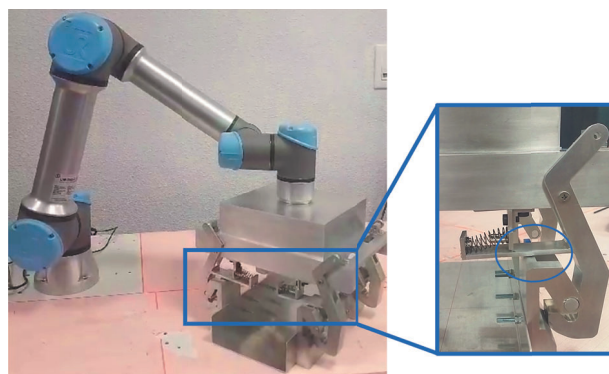
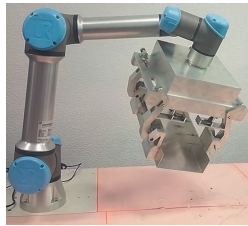
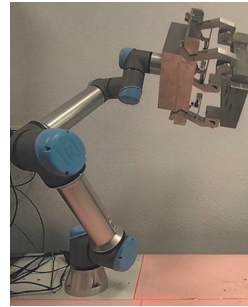


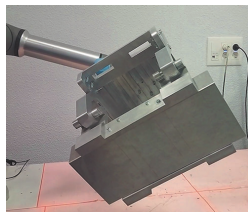
Figure 5.21: View of the contact between the bottom part of the platform and the top part of the supports during the release. This is the cause of the peak in the force felt in the TCP of the robot.



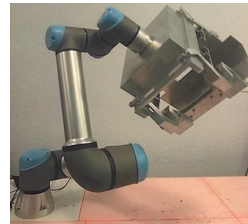
(a) Combination of rotations around the X and Y axis of the TCP coordinate system.



(b) Rotation around the X axis of the TCP coordinate system.



(c) Rotation around the Y axis of the TCP coordinate system.

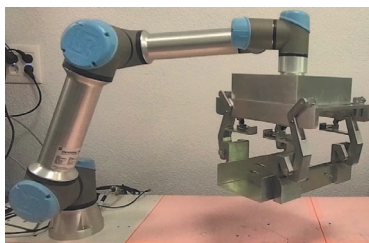


(d) Rotation around the Y axis of the TCP coordinate system, inverse sense.

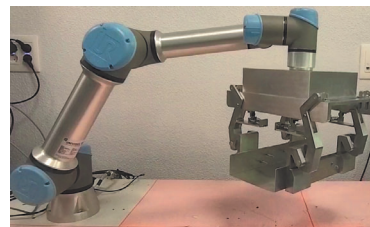
Figure 5.22: Views of different rotations performed during the rotation of the ensemble test. The rotation around the Z axis is not shown as the symmetry of the grasping makes it trivial.

Transportation speed tests

Finally, the transportation of the HFTM mock-up was tested at three different speeds: 12, 18 and 22 mm/s. The tests consisted in moving the ensemble in a linear trajectory increasing the transportation speed and collecting data for analysis, see Fig. 5.23. The goal of this type of test was to check that the grasping was reliable independently of the moving speed, so in the graphs below will be analysed how the speed affects the forces in the TCP of the robotic arm.



(a) Starting position for the transportation speed test.



(b) Final position for the transportation speed test.

Figure 5.23: Start and finish positions for the transportation speed test.

5.4.2 Lessons learnt

This example explains in detail the successful design of a gripping tool actuated by compression springs. The design procedure started by identifying the requirements for the tool and developing a preliminary design, following the recommendations of the existing guidelines and handbooks.

Then, the functioning of the tool was simulated to validate the requirements fulfilment, carrying out a Von Misses stress analysis, using Autodesk Inventor and a simulation of the procedure to make sure that it was feasible. Afterwards, the mock-ups were manufactured and laboratory tests were designed and performed. Thanks to this designing procedure, the potential improvements were identified and the design and procedure were validated, so the next design iteration can take place.

5.5 Example of a gripping tool for plugging and unplugging connectors

Another key operation in RH is the plugging and unplugging of connectors. In this section will be presented a gripping tool designed to perform the plugging and unplugging of an electrical connector. In particular, it was developed at CERN for the electrical connector of the vacuum pump located in the collimators in the Large Hadron Collider (LHC), see Fig 3.6. The procedure for plugging this electrical connector was presented as an example of the application of the proposed supervisory control diagram in Section 3.4.

Up to now this operation has been done hands-on by an operator that went into the tunnel and performed the plugging and unplugging of the connector. However, to avoid the unnecessary exposure of people to the environmental radiation, the objective is to adapt the procedure and tooling so it can be done by RH. To achieve this, besides designing the necessary tooling, the connector had to be modified to enable easy robotic manipulation. Images of the connector can be seen in Fig. 3.14.

The detailed design of this tool, and the corresponding plugging and unplugging procedures, can be found in Annex B. The resulting tool and interfaces added to the vacuum pump electrical connector can be seen in Fig. B.5. The design of this tool, along with the validation tests carried out, have been published in Redondo Gallego et al. (2024).

5.5.1 Mock-up and test bench

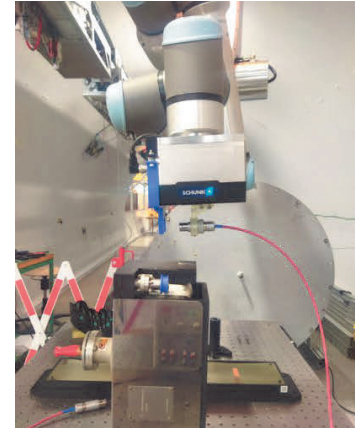
The designed components have been 3D printed, as explained in Annex B, the resulting mock-up can be seen in Fig. 5.24. The laboratory tests carried out consisted in performing the operation, according to the designed procedure using the 3D printed components mounted on a Schunk Gripper EGK50, attached by a UR10 robotic arm placed downwards, see Fig. 5.24c. During the tests the system was teleoperated, and for the visual feedback two cameras were used, one placed in front of the vacuum pump to allow a close look of the task, and the other, above the working station to give a general view of the situation.



(a) Connector plugged including the 3D printed designed collars.



(b) 3D printed designed fingers installed on Schunk EGK50 gripper.



(c) View of the test bench used for the gripping tool for plugging and unplugging connectors.

Figure 5.24: Views of the test bench including 3D printed elements. (Redondo Gallego et al., 2024)

5.5.2 Analysis of the tests results

The objective of all the tests carried out was to perform the plugging and unplugging of the electrical connector. However, it is possible to distinguish three different types of experiments:

- Carrying out the procedure when both parts of the connector are correctly aligned. This is the ideal scenario, when the robotic equipment brings both parts of the connector together, there is no clash between them and the plugging can be performed easily.
- Performing the plugging and unplugging when the misalignment between the connector elements prevents the connection from happening. This is a feasible scenario, the solution explored in this test has been the correction of the alignment until the plugging is enabled.
- Complete procedure, including retrieving the robotic equipment once the plugging has been achieved, and grasping it again for the unplugging.

These experiments have been designed taking into account different situations that can come up during operation. For example, the misaligned plugging is a situation that can happen and it was considered important to foresee and test a feasible course of action for it.

For the evaluation of the system performance, data of its status and evolution has been recorded. Below, will be shown graphs evaluating the behaviour of the force in the TCP and the current in the gripper, which enables the characterization of the moment in the procedure and the stress level for the robotic equipment used. The coordinates system used for the robotic system can be seen in Fig. 5.25, and in the following graphs the forces and torques are represented in absolute value.

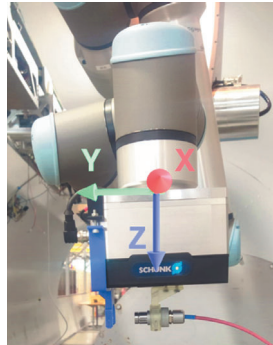


Figure 5.25: Coordinates system of the robotic system used for the validation tests.

Plugging and unplugging without alignment correction

The stages of this test are displayed in Fig. 5.26 and Fig. 5.27. It focuses on studying the forces and torques present in the robotic equipment, while plugging and unplugging the connector. In this case no alignment correction is needed, this means that the alignment between the axis of both parts of the connector is good enough to perform the connection. Although, there will appear reaction forces in the system due to this minimal misalignment.



(a) Approach of the male part of the connector to the female one.



(b) Beginning of the insertion of the male part in the female one.



(c) Connector plugged.

Figure 5.26: Images of the different stages of the connection during the test, taken by one of the cameras of the viewing system.

In Fig. 5.28, can be seen the evolution of the forces and torques in the TCP of the robotic arm, and the current in the gripper. Paying attention to the changes in these values, it is possible to identify the different stages of the test. Below they will be explained in detail:

- **Approach.** During this stage, one of the fingers of the gripper carries the male part of the connector and the other, the female one. The gripper is closing and getting the parts together, however the insertion has not started yet. The forces and torques in the TCP can be considered constant, as there are not any reaction forces.
- **Insertion.** It is possible to identify the start of this stage, because as the insertion starts, reaction forces start to appear, which cause also torques in the TCP. These forces are due to the existing misalignment between both parts of the connector, even



(a) Extraction of the male part of the connector.



(b) Connector unplugged.

Figure 5.27: Images of the different stages of the disconnection during the test, taken by one of the cameras of the viewing system.

though those misalignments are little enough to enable the plugging of the connector. The gripper is attaching one of the parts with each finger, so it firmly constraints their movement and maintains them at a fixed orientation, as the insertion goes on, the connector adapts its orientation to fit with the other part, causing reaction forces in the gripper and the robotic arm. The maximum force is in Z direction, which gets up to 20 N and the maximum torque is in Y direction which goes not above 3 Nm, these values are completely safe for the robotic arm.

- **Connected.** The start of this phase is recognised by the peak of the current in the gripper, caused by the impossibility of the tool to keep moving its fingers as the connection is achieved and the male part of the connector cannot keep advancing. The forces and torques in the TCP of the robot during this stage are higher than during the insertion, because the connection and the firm grasping of the gripper makes the robotic system to be in a forced position, increasing the reaction forces and torques. Even though these values are higher than before, the maximum force in the TCP is in the Y direction, and is no higher than 40 N, and the highest torque, in Z direction, is less than 3.5 Nm, still completely safe for the robotic arm.
- **Extraction.** Now there is a minimum in the current of the gripper, which is caused by the resistance offered by the connector to be unplugged. It is also remarkable that, as the disconnection starts, the forces and torques in the TCP decrease, because the position is less constrained. However, there are still reaction forces as there were during the insertion.
- **Disconnected.** When the extraction is completed, the system goes back to a state similar to the approach where there are not reaction forces.

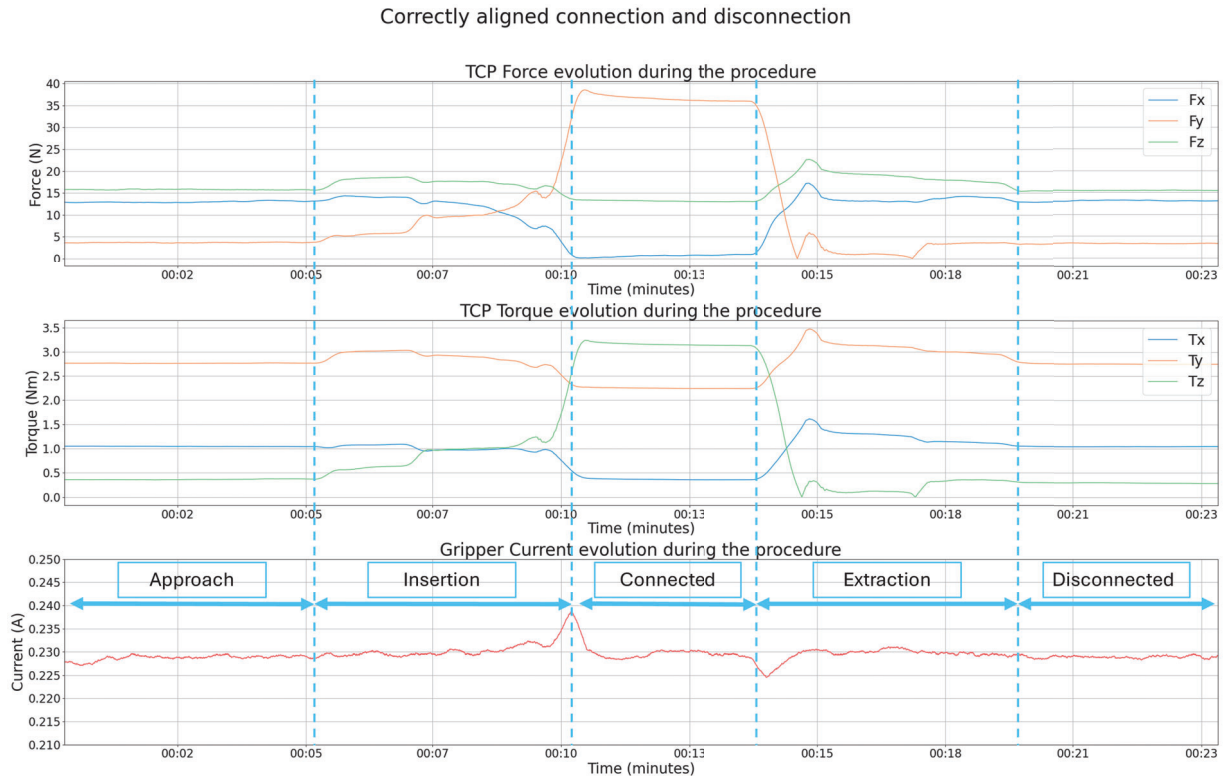


Figure 5.28: Graph showing the evolution of the forces and torques in the TCP of the robotic arm and the current in the gripper throughout the plugging and unplugging the electrical connector.

Plugging and unplugging including alignment correction

In this type of test, there is a first attempt to make the connection, however the misalignment between both parts is excessive and there is a clash between them. This clash does not cause any damage to the system, as the teleoperation allows the slow movement of the system. The solution is to separate the parts of the connector again and correct the misalignment, this can be done as many times as necessary. In Fig. 5.29, are displayed photos of the plugging in this test. The disconnection is similar to Fig. 5.27.

The evolution of the forces and torques in the TCP of the robotic arm throughout this test can be seen in Fig. 5.30. As it was done for the previous type of test, the different stages will be explained, remarking their effect on the robotic equipment.

- **Approach.** This phase is similar to the previous test, where both parts of the connector were correctly aligned. The gripper is attaching both parts and moving its fingers to bring them together for the connection. There are no friction forces causing reactions in the TCP of the robotic arm, only the weight of the tool and the connector.
- **Clash.** It is easy to spot this moment in the graph, because the forces in the TCP of the robot increase quickly, due to the impossibility to continue the movement. They decrease as the moving order given by the operator stops, but they do not disappear, as the parts of the connector are still touching each other.

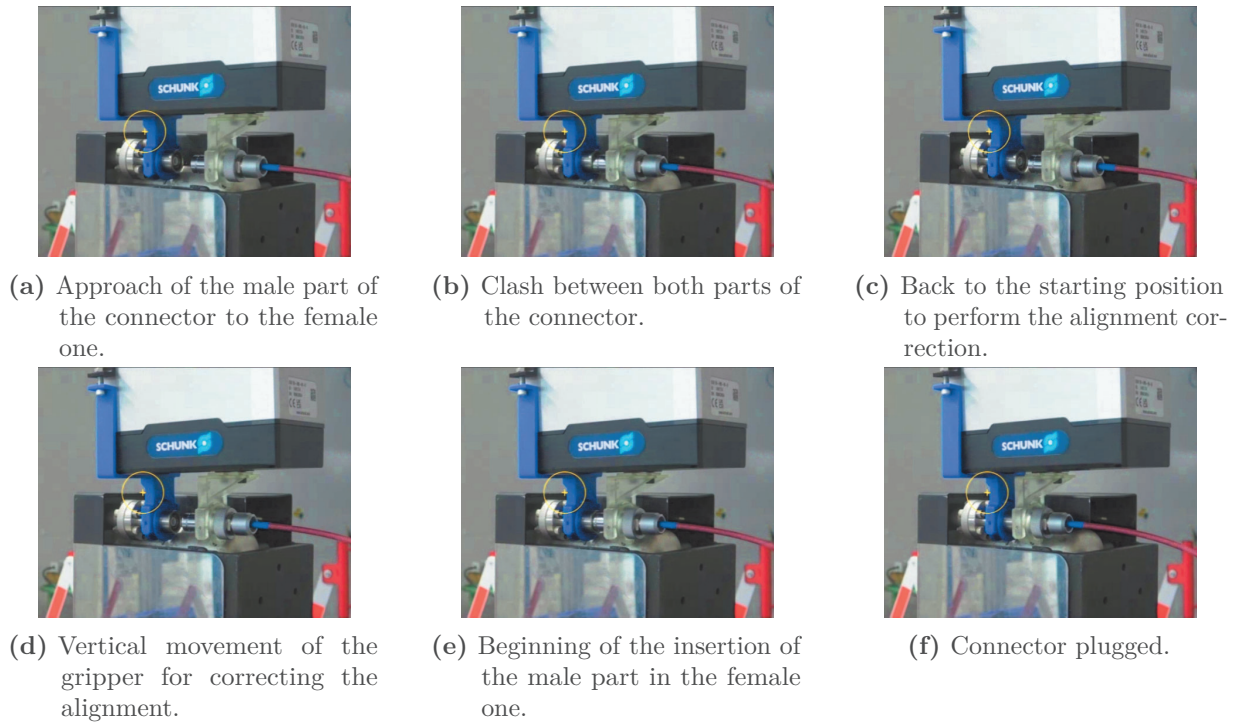


Figure 5.29: Images of the different stages of the connection during the test, taken by one of the cameras of the viewing system.

- **Correction.** The parts of the connector are separated and the robotic arm performs a vertical ascending movement to correct the misalignment. The operator knows how to correct it thanks to the visual feedback. There are no significative forces or torques in the TCP of the robot, as there is no contact between the parts of the connector.
- **Approach.** Once the correction is considered to be achieved, the approach can take place again. The characteristics of this phase are similar to the first approach.
- **Insertion.** Now the alignment is good enough to allow the insertion. During this stage, friction forces appear between the connector parts, as the male part has to adapt its position to fit inside the other half, causing reaction forces and torques in the TCP of the robotic arm. In this case, these forces and torques are smaller than they were in the first graph commented (Fig. 5.28), the reason for this is that the alignment now is better than it was in that other test.
- **Plugged.** As indicated by the peak in the gripper current, the insertion is completed and the connector is now plugged in. As was already commented for Fig. 5.28, the forces and torques in the TCP increase, due to the forced position where the too constrained system is. However, the alignment now is better than in that previous test and the levels are lower.
- **Extraction.** This stage is characterised by the minimum in the gripper current to overcome the connector security and the reaction forces to the fiction between both parts of the connector.

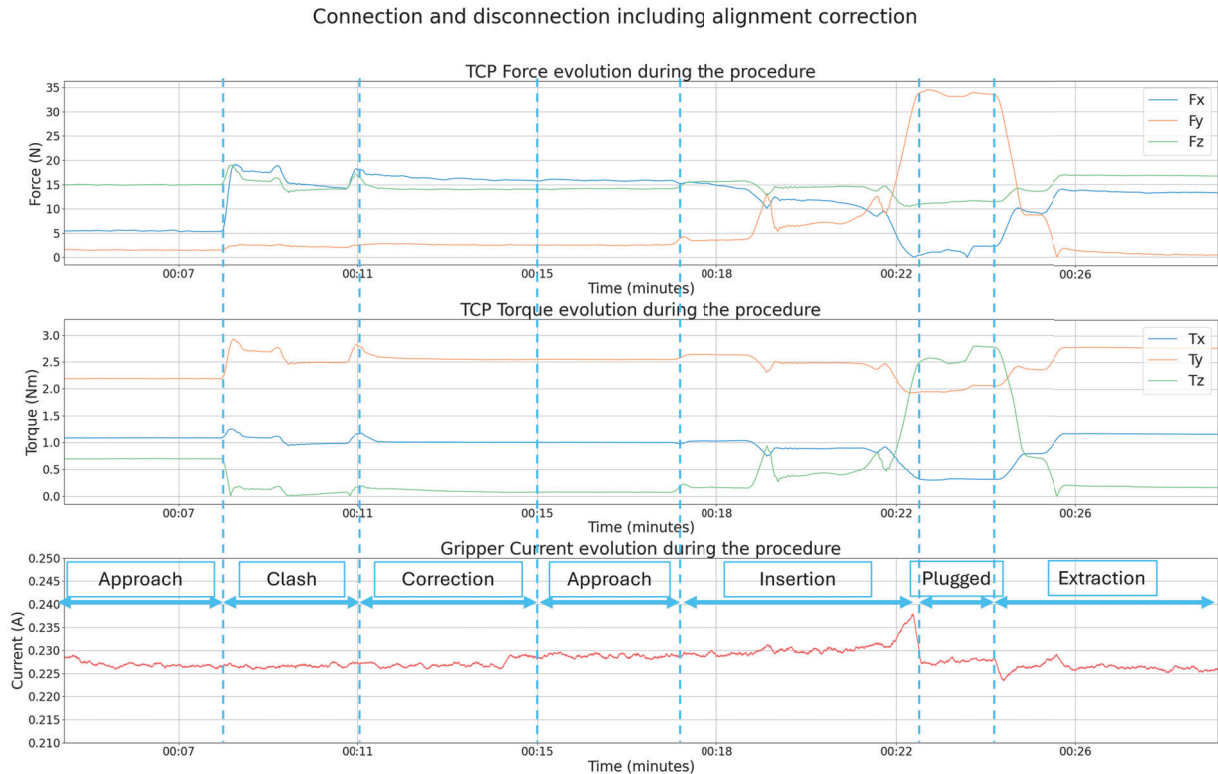


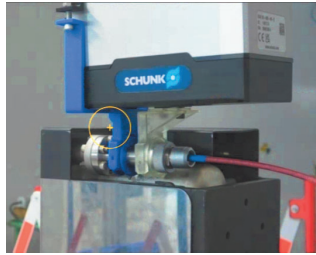
Figure 5.30: Graph showing the evolution of the forces and torques in the TCP of the robotic arm and the current in the gripper throughout the plugging and unplugging the electrical connector, including the alignment correction during the plugging.

Whole procedure including releasing the connector once connected

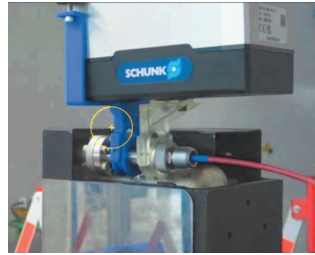
In this case, the connection is done without the need of correcting the alignment, and after achieving it, the robotic system releases the connector. Afterwards, it reattaches it to perform the unplugging. The steps of the connection are similar to the ones represented in Fig. 5.26, and the disconnection can be seen in Fig. 5.27. However the release and reattachment intermediate phases are displayed in Fig. 5.31 and Fig. 5.32.

As can be seen in Fig. 5.33, the stages of the procedure go as follows:

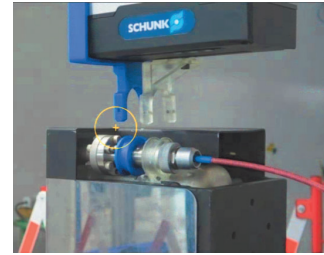
- **Approach.** This stage is similar to the approach phases commented in the previous types of tests. The forces and torques in the TCP of the robotic arm are more or less constant, as the gripper is getting both parts of the connector together, but there is no opposition to this movement, there has not been any contact between the parts yet.
- **Insertion.** As happened for the other tests, when the insertion starts, friction forces start to appear between the parts of the connector and reaction forces in the TCP of the robot, also caused by the constrained position of the male part of the connector that has to adapt its orientation to fit in the female part.
- **Connected.** This phase is also analogous to the previous tests, the robotic system is in a forced position caused by the over-constriction.



(a) The connector is plugged in and the robotic arm starts to move vertically to release it.

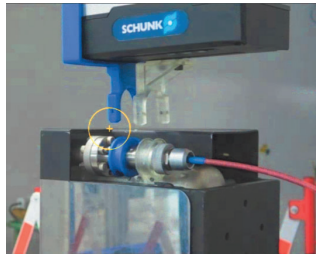


(b) The vertical movement continues as the gripper starts to release the connector.



(c) The connector is released plugged in.

Figure 5.31: Images of the different stages of the releasing of the connector, taken by one of the cameras of the viewing system.



(a) The robotic arm approaches the connector to attach it.



(b) The gripper attaches the connector thanks to the vertical approaching movement of the robotic arm.



(c) The connector is attached and the unplugging can start.

Figure 5.32: Images of the different stages of the attachment of the plugged in connector, taken by one of the cameras of the viewing system.

- **Release.** In this phase the robotic arm performs a vertical ascending movement to release the connector plugged in. High friction forces appear between the fingers of the gripper and the collars, this results in high reaction forces and torques felt in the TCP of the robotic arm. These forces disappear as the release is completed.
- **Gripper free.** During this stage the robotic arm is only carrying the gripper, so the forces felt in the TCP, are lower than before.
- **Attachment.** To perform the unplugging of the connector the robotic system has to attach it again. With this purpose the robotic arm performs a vertical descendent movement, opposite to the movement carried out in the release phase. The forces and torques in the TCP increase very quickly due to the friction between the fingers and the collars, and the reappearance of the over-constrained position for the system. The maximum force recorded in the TCP is around 120 N in X direction, and the highest torque around 6 Nm in the Z direction, both values are in the robotic arm working range, so they do not suppose any risk to the system.
- **Connected.** Now that the connector is grasped again, the forces in the TCP do not go back to the previous values. The reason for this is that, when released, the connector

adapted its position and orientation to fit perfectly inside the female part. And this new configuration is more forced for the robotic arm than before. Also, the vertical position of the robotic arm can be slightly different to the beginning, creating more reaction forces in this new situation.

- **Extraction.** During this final phase, the forces and torques in the TCP decrease as the position of the connector gets less constrained, and the friction forces during the extraction decrease too.

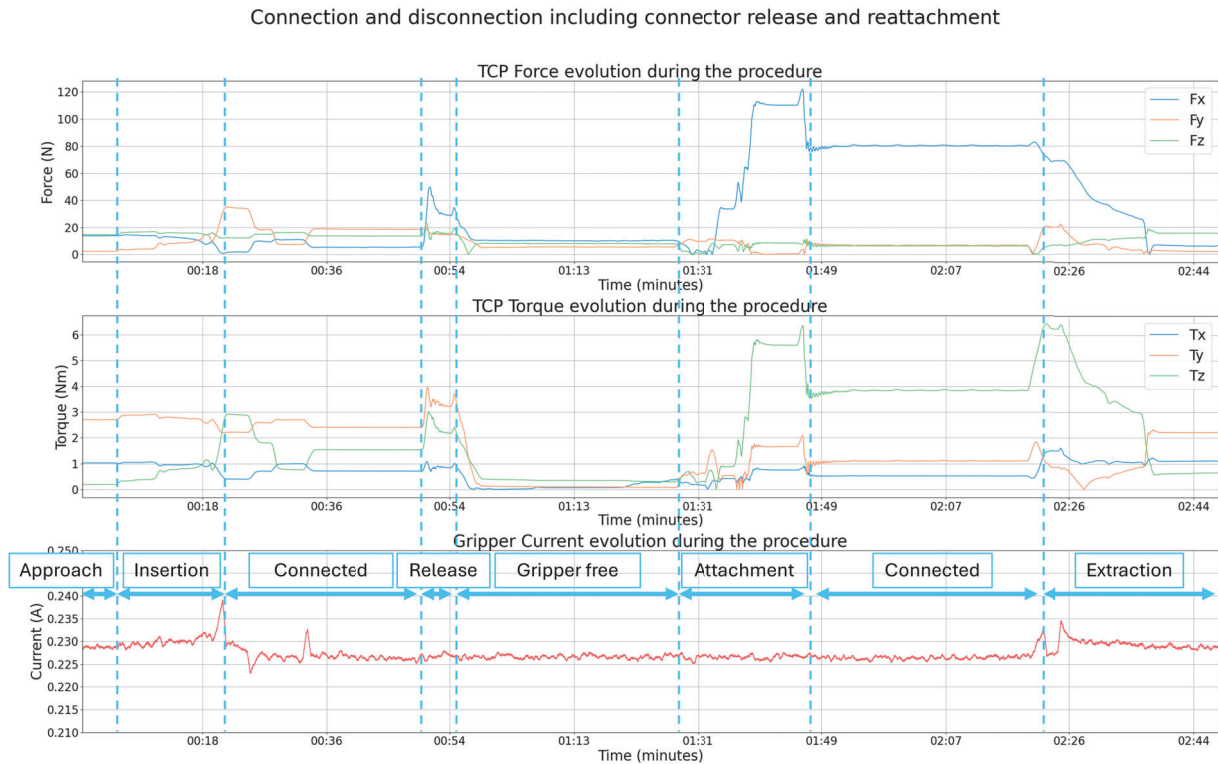


Figure 5.33: Graph showing the evolution of the forces and torques in the TCP of the robotic arm and the current in the gripper throughout the plugging and unplugging the electrical connector, including the release of the connector when plugged in and the reattachment before unplugging.

5.5.3 Lessons learnt

Seeing the results of the experiments, it is possible to conclude that the tool is capable of performing the task in different situations, such as the misalignment of the male and female parts of the connector. At all times the forces and torques felt in the TCP of the robotic arm are within the safe margin of the working range of the robot, so the procedure does not represent a risk for it.

This tool performs a passive gripping of both parts of an electrical connector. Using the female part that is fixed to the vacuum pump as a guide for the insertion and extraction of the male one. To enable this functioning, proper interfaces have been added to the connector, making it

adequate to be operated by the robotic system, and also the robotic tooling available has been customized, according to the requirements of this task. The result is a simple and modular tool that can be integrated in the available robotic equipment to carry out the plugging and unplugging of the electrical connector.

Also, this tool is designed to work in a teleoperated system, this means that the feedback to the operator is very important. In particular, the visual feedback, it has been improved from the initial versions of the tool to the one presented here, and keep improving it will mean less probability of misalignment when inserting the connector, so less risk of clashing between the components and saving time in the procedure if the alignment correction does not need to be performed.

Finally, it is important to remark that this is a preliminary concept, and as it has been validated, the design will get to the next iteration to improve it and make it more robust.

5.6 Examples of screwing

Tightening and loosening bolts using a robot is a key task in the RH procedures. Even though it is possible to find robotic bolting tools in the market, the aim of this design is to propose compact and modular tools capable of screwing at high torques without affecting the robotic arm. The modularity is a key aspect of the designs proposed in this section, as it enables adapting them to the requirements of different tasks and facilities as well as it facilitates the maintenance of the tools.

Different reaction torque limiters have been evaluated, these are devices added to the bolting tool that protect the robotic equipment from excessive reaction torque.

In particular, this work is focused on the IFMIF-DONES facility. The tools have been developed keeping in mind the remote maintenance of the accelerator system, with the corresponding environmental, mechanical and operational constraints. Two different configurations of a bolting tool have been developed, detailed explanation about their design can be found in Annex C. Main features of each are listed below:

- **Configuration 1.** This configuration was intended in particular for installing and releasing the pipe flanges in the rear cooling pipes of the beam dump (BD), Fig. 5.34. The elements in these flanges are quick disconnection system (QDS), a type of chain clamp that can be seen in Fig. 5.35 (Technetics Group, n.d.). The torque limiting devices included were designed to fit specially the QDS. The design developed is carefully detailed in Annex C, and the CAD model developed can be seen in Fig. C.1b. The radiation resistance of this tool has been analysed in Subsection 4.2.2, and the design and laboratory tests have been published in Ferre et al. (2023).
- **Configuration 2.** The intention with this configuration was to develop a bolting tool, that could be used in several tasks in the maintenance procedures taking place in the accelerator vault. This configuration is further explained in the Annex C, where is shown the CAD model of the tool in Fig. C.2. Details about this design and laboratory tests carried out have been published in Redondo et al. (2025).

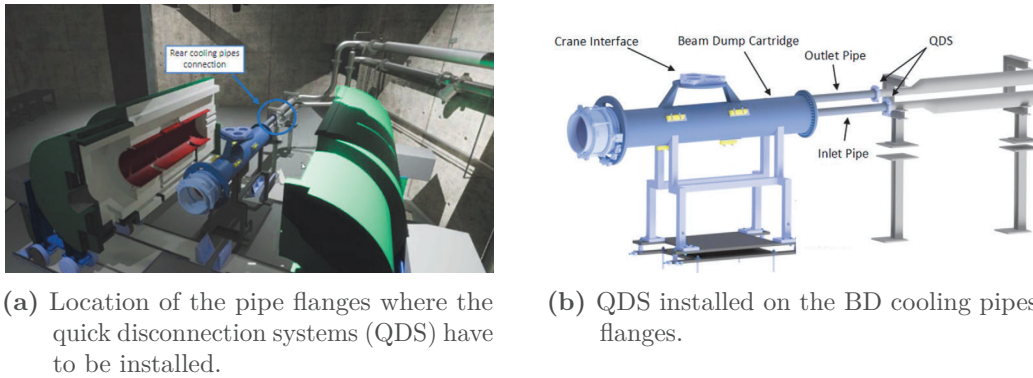


Figure 5.34: Views of the pipe flanges where the first configuration of the bolting tool has to operate.

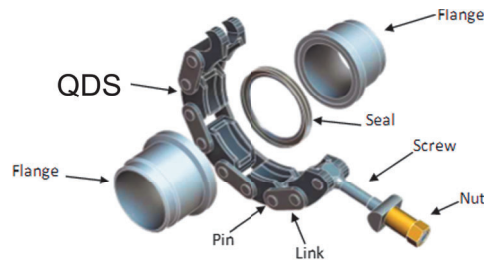


Figure 5.35: View of an open QDS. (Technetics Group, n.d.)

5.6.1 Laboratory tests

A mock-up of each configuration was created and used for laboratory tests in order to analyse the functioning of the tools and determine the efficiency of the reaction torque limiters, see Fig. 5.36. So in this subsection, this analysis will be explained, for each case studied.



(a) Test bench of the second configuration of the bolting tool. **(b)** Test bench of the first configuration of the bolting tool.

Figure 5.36: Views of the mock-ups and test benches for each configuration of the tool.

For the first configuration, the analysis of the screwing forces during operation has been published in Ferre et al. (2023). The most remarkable aspect of this analysis is that the tool succeeded at reducing the reaction torque felt in the wrist of the robot during the screwing.

This is an important result, because the wrist of the robotic arm is the weakest joint in the robot.

In Fig. 5.37 is displayed the comparison between the reaction torque with the limiters and without them, whereas the green line corresponds to the evolution of the bolting torque given by the actuator of the tool, at the beginning it is controlled in position mode to start tightening the bolt, and then, changes to torque control to achieve the desired tightening torque. The change between one control mode and the other can be noticed in the graph, as it corresponds to the rapid decrease in the green line in minute 1:42. Regarding the reaction torque, it is possible to see that without fingers the torque felt by the robotic arm goes up to the bolting torque, so the maximum tightening torque, will be the maximum torque the wrist of the robotic arm is capable of withstanding. However, when using the torque limiters the maximum torque felt in the wrist of the robot is around five times less than the bolting torque, this means that the robotic arm is protected when screwing at high torques.

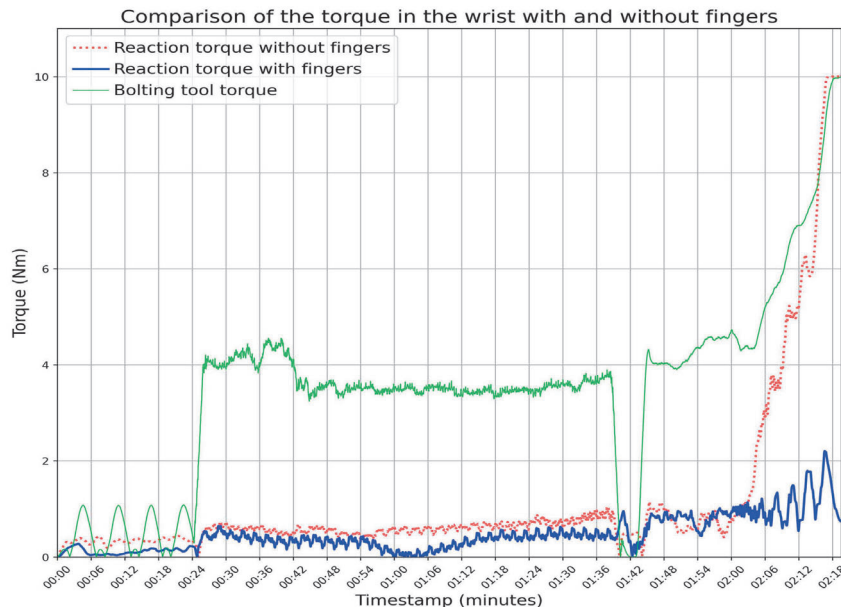


Figure 5.37: Using the first configuration of the robotic bolting tool to tighten a bolt at 10 Nm, in this graph can be seen the evolution of the torque in the wrist of the robot with and without the torque limiters. The use of the torque limiters result in a clear decrease in the reaction torque felt in the wrist of the robotic arm.

On the other hand, for the second configuration of the tool tests have been carried out, with and without the pins, for a tightening torque of 20 Nm, 40 Nm and 60 Nm. In Fig. 5.38, can be seen the joints and rotation axis, identified in the test bench used for this test, for an easier understanding of the following graphs. The procedure used for this tests was similar to the one used for the first configuration. At first the servomotor was controlled in position mode to start the tightening, and then changed to tightening control to achieve the desired tightening torque.

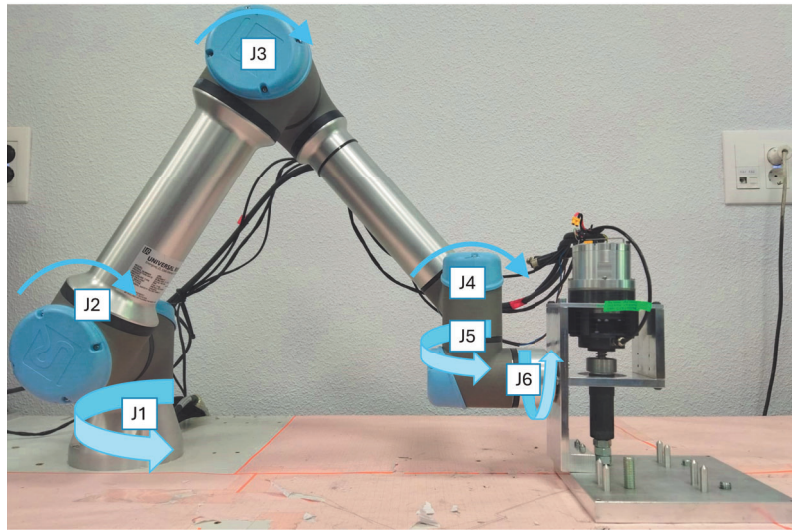


Figure 5.38: Joints and rotation axis of the robotic arm used for the screwing laboratory tests. The robotic arm used was a UR5e by Universal Robots. (Redondo et al., 2025)

In Fig. 5.39, Fig. 5.40 and Fig. 5.41, can be seen the evolution of the reaction torques in the joints of the robotic arm when carrying out the tests with and without pins. It can be noticed that for joints one to four, there is an improvement in the reaction torque when using pins for all the tightening torques. Even though when tightening at 20 Nm without pins, the reactions can be considered low, because of the low tightening torque and the design strategies to minimize them.

For the fifth joint, there is not a significant improvement in the magnitude of the reaction torque for any of the tightening torques. However, the pins prevent the oscillation of the robotic arm, helping it maintaining its target position and relieving stress from the robot.

Regarding the sixth joint, the improvement made by the pins is not noticeable when tightening at 20 Nm, as the pins force the robot to be in a determined position, slightly different than the desired position, creating little tensions in this joint. Nevertheless, when the tightening torque is increased, the reaction torque protection starts to be greater than the tensions created by the over-constrained system. This comparison can be seen in Fig. 5.42.

The aim of the tests presented in this section for each of the configurations of the bolting tool, was to understand the effects of the bolting reaction torques and explore mitigation strategies to protect the robotic arm. By protecting the robot, bolting at higher torques can be achieved with lighter robots. Both bolting tool configurations present a way of closing the force loop between the tool and the bolted component, fingers in the first one, and pins and slots in the second one. Also, the tightening axis, in relation to the last and most vulnerable joint of the robotic arm, has been changed from one configuration to the other to explore the effects. It can be concluded that the decrease in the reaction torques, while tightening at high torques, has been more significant with the second configuration. However, for smaller tightening torques, it did not present a clear advantage in the sixth joint, due to the creation of an over-constrained system between the robotic arm the tool and the component.

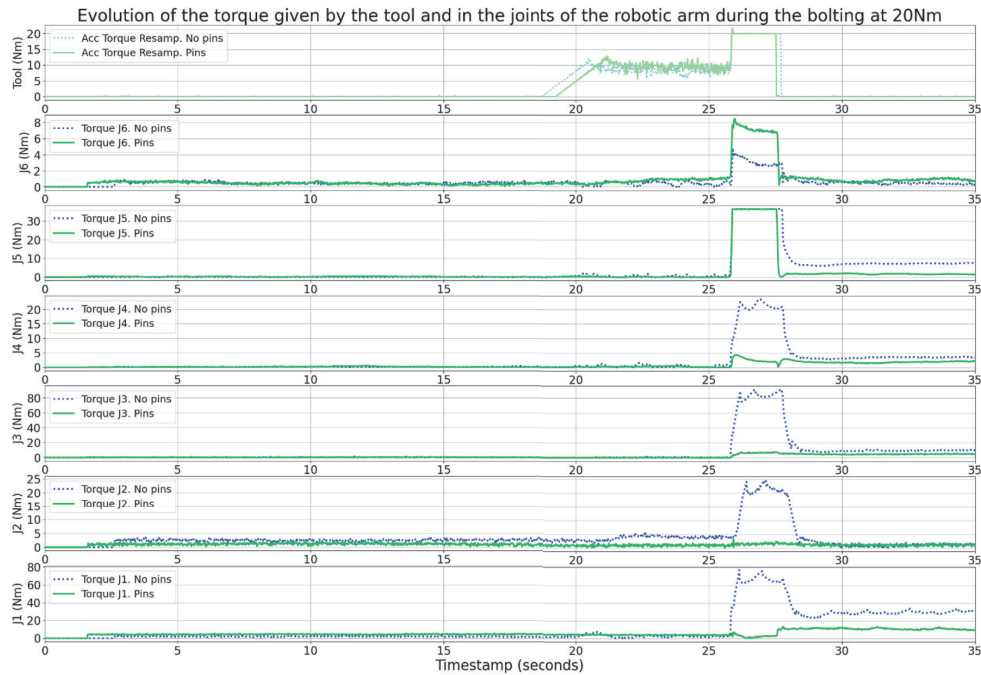


Figure 5.39: Evolution of the torques in the joints of the robotic arm when tightening at 20 Nm with and without pins with the second configuration of the bolting tool. (Redondo et al., 2025)

5.6.2 Lessons learnt

When comparing both configurations, it is possible to conclude that choosing a bolting axis perpendicular to the wrist of the robotic arm, creates less reaction forces and torques in the last joints, allowing a less stressful operation for the RHE.

Anyway, in both configurations it is possible to see the importance of deviating the reaction forces and torques from the last joints of the robot, which are more vulnerable than the bigger ones capable of withstanding greater forces and torques. This enables the tool to operate at higher torques without presenting a risk for the robot.

During the tests carried out for the first configuration, it was noticed that when protecting some joints from excessive reaction torques and forces, new reactions appeared in other joints. It is very important to analyse those and evaluate if the protection represents an improvement for the system as a whole. For example, in the second configuration of the bolting tool, the pins provoked an increase in the reaction torque felt in the sixth joint when tightening at 20 Nm, but an improvement for the rest of the joints. And for the sixth joint, the system was still working in a safe area, and the improvement in the rest of the joints was significant, so the protection given by the torque limiters was considered successful.

Regarding the increase of the reaction torque in the sixth joint, when tightening at torques lower than 40 Nm, due to the tensions created by over-constraining the system. These increment stays within the safe working area for the joint, and, when tightening at higher torques, the protection given by the pins is greater than the created tensions. So the pins are considered to be necessary when tightening at torques higher than 40 Nm.

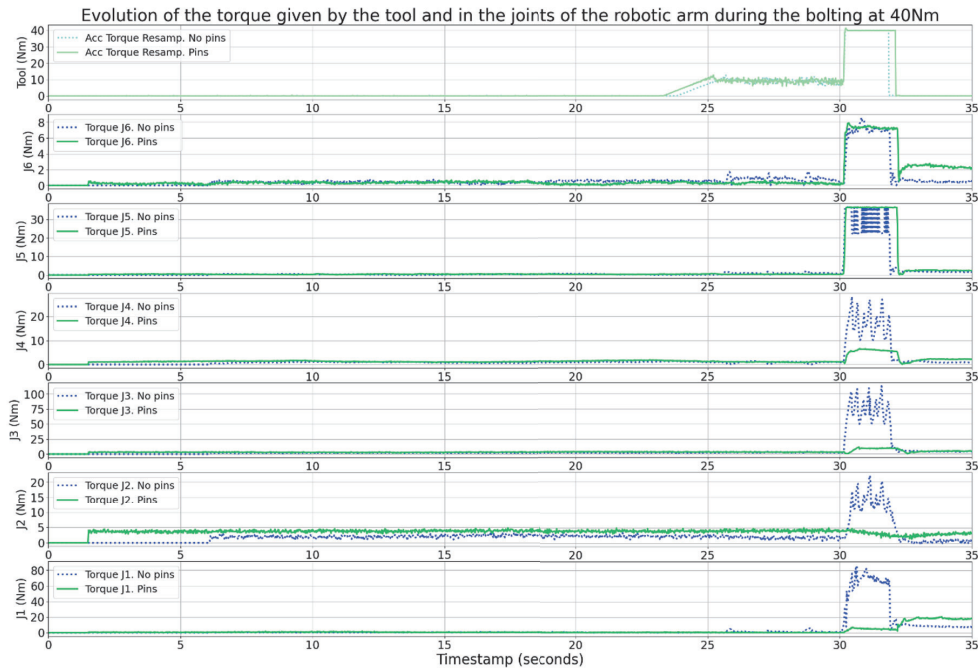


Figure 5.40: Evolution of the torques in the joints of the robotic arm when tightening at 40 Nm with and without pins with the second configuration of the bolting tool. (Redondo et al., 2025)

Also, it is important to remark that when using robotic bolting tools, whether they are automatic or teleoperated, it is a key aspect to include viewing systems capable of localizing the head of the bolt, and giving the corresponding feedback to the operator. In both configurations, it was used a spring above the socket wrench connected to a load cell, to inform about the fitting of the bolt in the tool, but this is not enough, as the tolerance for the fitting is very narrow.

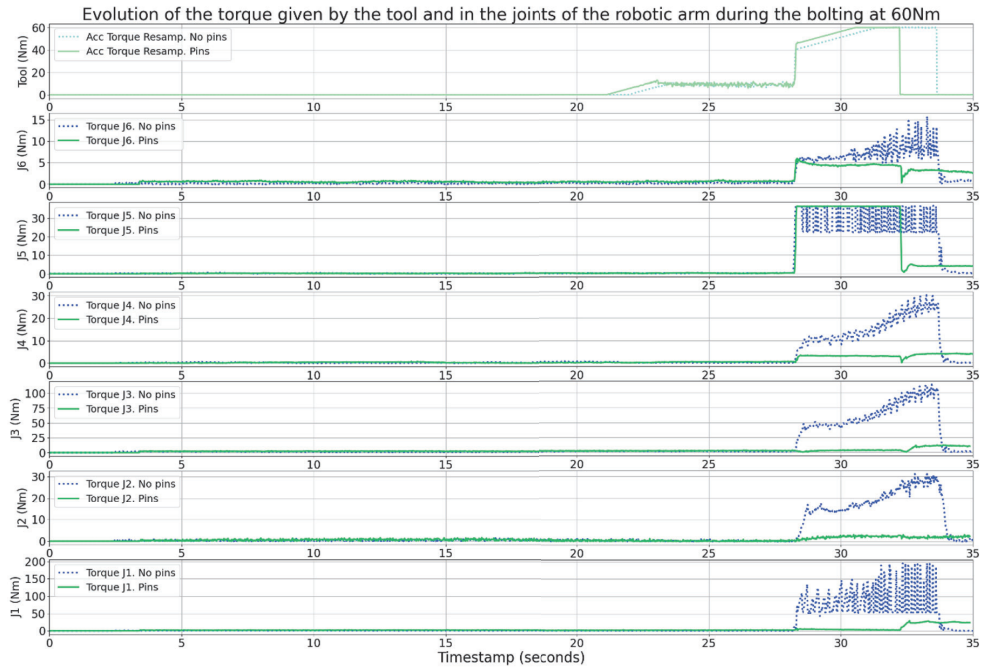


Figure 5.41: Evolution of the torques in the joints of the robotic arm when tightening at 60 Nm with and without pins with the second configuration of the bolting tool. (Redondo et al., 2025)

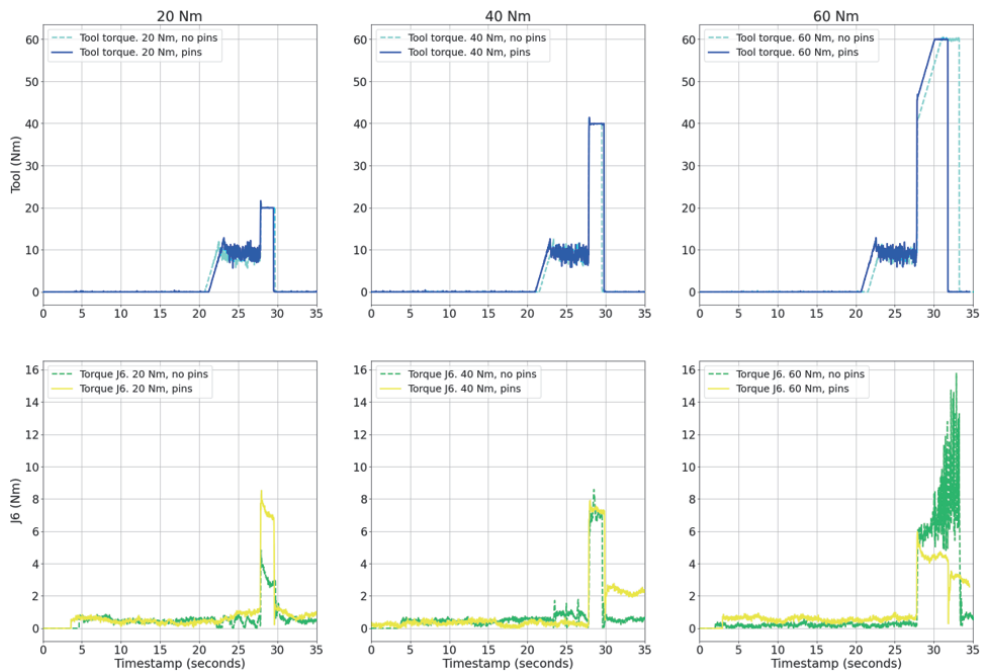


Figure 5.42: Evolution of the torque in the sixth joint of the robotic arm when tightening at 20 Nm, 40 Nm and 60 Nm with and without pins with the second configuration of the bolting tool. (Redondo et al., 2025)

Chapter 6

Conclusions

6.1 Discussion

Throughout this thesis have been presented advances regarding the modelling of RH procedures, the use of robotic equipment under radiation and the tooling design for RH tasks. These are considered key aspects for the progress of RH for the maintenance procedures in environments under radiation. Also, the ideas proposed have been applied to real life scenarios, as the implementation of the RH procedures in IFMIF-DONES, the contribution to the RH development at CERN and the definition of the preliminary version of the DEMO RHE.

On the subject of modelling RH procedures, it has been proposed a diagram for establishing the control architecture of a general procedure. It includes the fully automated flow that will take place when everything goes as expected and no errors or interruptions requested by the operator come up. Even following this path, the operator will be required to approve each step and confirm the progress to the following one. Besides this, it considers the event of interruptions or errors detection, where operator takes manual control of the system, and decides whether to the whole step manually and advance to the following, or going back to the previous one and solving the existing issues. This diagram has been applied to the maintenance procedures of IFMIF-DONES, in particular, in this chapter is presented the application to the replacement of the scraper and the Beam Dump.

Focusing on the radiation environments, in Chapter 4 has been analysed the effects of different types of radiation on different electronic components, and possible mitigation strategies have been explored as radiation hardening by design or protective shielding. This has led to proposing strategies for the robotic equipment selection, depending on the radiation conditions. Different scenarios have been considered, as medium or low radiation environments, as the accelerator vault in IFMIF-DONES, with the beam-off after the cooling down period and high radiation environments as hot-cells. This chapter has also remarked the importance of estimating the radiation resistance of components, first theoretically, as has been done with a bolting tool designed for the maintenance of the Beam Dump in IFMIF-DONES and, also, experimentally. Experiments to test the effects of exposing several microcontrollers and a 3 DoF custom made robotic arm to ionizing radiation are explained and the results carefully analysed. This enabled also studying and comparing the efficiency of different mitigation strategies used in the tests.

Regarding the tooling design for RH procedures, this thesis analyses the need of developing specific tools for each RH procedure that cannot suit the requirements in other areas or tasks. As a result, the different existing design guidelines and RH handbooks are studied, remarking the most important aspects to take into account. Thanks to the careful study of the state of the art done, is proposed an updated methodology to face the design of new components for RH applications. Additionally, it is presented a classification of the common RH tasks carried out in maintenance procedures, with the goal of identifying similarities in the design of the tools, corresponding to each group that could act as guidelines for new developments. Finally, successful applications of these ideas to the design of different RH tasks are explained. This applications illustrate the challenges of the different scenarios, which imply very different and demanding radiation and mechanical requirements.

Summing up, the new methods for RH procedures presented in this thesis evidence the research conducted in this field and the novelties introduced to contribute to its progress.

6.2 Conclusion

This thesis proposes innovative methods for implementing new RH applications in environments under radiation. It covers the entire development of the RH tasks, from the supervisory control architecture to the selection and design of the corresponding robotic equipment.

Moreover, thanks to an ongoing collaboration with major scientific facilities, as CERN and IFMIF-DONES, the ideas proposed in this thesis have been applied to real-life problems faced in the remote maintenance operations there. This has been very useful as it has enabled the iteration and improvement of the designs developed and the opportunity to test them in real life situations.

The contributions presented in this document, can be divided in three topics: modelling RH procedures, robotic equipment for radiation environments and tooling design for RH tasks.

Regarding the modelling of RH procedures, the focus has been set on supervisory control as it enables the automation of the RH applications while keeping the human in the loop. A supervisory control diagram has been proposed, it enables the partial automation of the procedure and ensures the validation of the advance by the operator. Partial automation means that it can be used even if not all the stages of the procedure are automated. When a manual step is reached this control architecture enables the operator to take control of the system and perform the corresponding step. The diagram also considers the manual control as a solution for different failures that might come up during operation as, for example, time out. In these situations the person can take the control to perform the failing action or to solve the issue and give the control back to the system to repeat the action. Related also to this topic, it is remarked the importance of taking into account the failure management and emergency scenarios and propose mitigation strategies and courses of action in case of failure since the design phase.

Moving to the robotic equipment for environments under radiation, first the effects of radiation on electronic components have been analysed, taking into account conventional and rad-hard devices, and studying the situations where each type can be more suitable. In addition to this, available mitigation strategies to minimise the effects of radiation have been studied, as for example, adding casings to the vulnerable components to reduce the radiation exposure. Theoretical and experimental tests of the radiation resistance of robotic equipment have been carried out. The radiation resistance of a customized modular bolting tool has been defined theoretically, by analysing the resistance of its components. Besides, experimentally the effects of radiation and exposure limits have been tested for different microcontrollers, servomotors and sensors. Also, real life radiation exposure experiments have been carried out to a three degrees of freedom robotic arm to analyse its behaviour and the effect on its trajectory as the absorbed dose increases. Finally, based on the information gathered from all the tests performed and a careful study of the related state of the art, recommendations are given for selecting robotic equipment for radiation environments.

Referring to tooling design, a new methodology is proposed for designing RH tools, emphasizing continuous improvement and operator training during development to reduce commissioning time and failures during operation. As the tooling used for RH is very specific due to the highly demanding requirements usually is necessary a particular tool for each task in each facility, in this thesis a classification of the main RH tasks has been proposed considering

the distinguishing features of the tools used in each group. The goal of this work is to serve as a guideline of the available designs and the features to take into account when designing a new tool. Also, several tooling designs made throughout this thesis are presented in this document, along with the performed laboratory tests. These designs are a gripping tool for transportation of a heavy load, a gripping tool for the plugging and unplugging of an electrical connector and two different configurations of robotic bolting tools including reaction torque limiting systems.

In conclusion, this thesis studies the available state of the art, and advances on it by proposing innovative methods and solutions for the development of new RH procedures and validates them in different challenging scenarios involving radiation exposure. All of these contribute to safer and more efficient RH procedures, enabling further advancements in scientific facilities.

6.3 Future work

Finally, this section proposes some ideas for future works.

In relation with the automation of RH procedures, in this text has been presented a diagram for the modelling of procedures, using supervisory control which considered the automation flow and operator interventions. It could be very useful to develop similar diagrams focused on the safety of the procedures, these diagrams would take into account emergency scenarios and failure managing, prioritizing safety aspects.

Regarding the implementation of RH procedures in environments under radiation, this thesis has remarked the importance of estimating the life span of a component exposed to radiation conditions. So, it will be very useful to advance in the development of a methodology for the theoretical and experimental testing for the characterization of electronic devices under radiation. This will enable accurately predicting failures and avoiding them.

About the tooling design, as it has been demonstrated that it would not be feasible to develop a generic remote handling tool, it will be very interesting to focus on the classification of RH tasks in maintenance procedures. Identifying more common characteristics of each group will enable the compilation of more helpful design guidelines and handbooks.

Appendix A

Gripping tool for transportation design

Tool Design

The first thing done for the development of this tool was looking for commercial solutions that met the requirements. However, no suitable option was found. So keeping in mind the design guidelines explained in 2.4, it was implemented a gripping tool.

The grasping location is from the top of the component, as the RHE descends from above. To get a balanced and reliable grasp, the tool consists in a top part with four fingers that attach the corresponding supports on top of the HFTM. The interface between the tool and the RHE is the standardised gripper change system included in all the components of the RHE. The expected radiation levels in the HFTM area, after one day cooling time, are around $10^7 \mu\text{Sv/h}$, according to Qiu et al. (2024). Because of the radiation constraints, it was decided to avoid motors for the grasping phase, only to add motors to block the gripping fingers during transportation. As motors were discarded for the grasping, the most feasible option was to add compression springs in the fingers and guiding paths. The leaning top surface of the supports helps the fingers to open and achieve the grasping, as the RHE descends vertically. The attachment is completely achieved when the fingers get to the end of the leaning surface of the supports, and close again thanks to the springs.

A simplified diagram of the gripping operation is displayed in Fig. A.1. The steps followed to achieve the grasping of the HFTM can be seen in Fig. A.2, and are listed below:

- The RHE approaches the HFTM from above.
- Thanks to the viewing system and the viewing aids, it is possible to align the fingers of the tool with the supports on top of the HFTM.
- The grasping starts as the RHE continues descending, and the matching guiding paths in the fingers and supports help the fingers to open. When the fingers get to the end of the leaning surfaces of the supports and close again thanks to the springs, the grasping is completed.
- The RHE can ascend again carrying the HFTM.

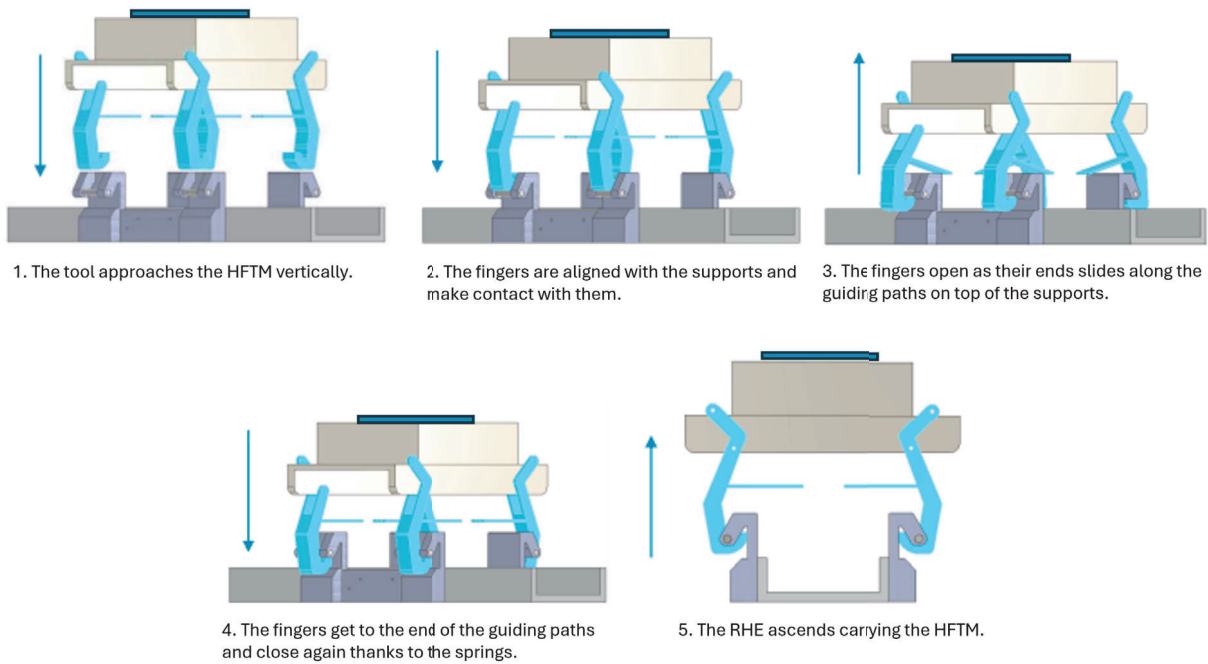


Figure A.1: Gripping operation using the designed tool. (Marín, 2024)

As mentioned above, the only motors in the tool are steppers to insert pins in the fingers and block their movement once the grasping has been achieved. This feature was added to minimize the risk of undesired movements of the HFTM during transportation and make sure that it could never fall.

The operations corresponding to the releasing of the HFTM is displayed in a simplified diagram in Fig. A.3. The stages of the procedure are presented in Fig. A.4, and more detailed in the following lines:

- The RHE descends positioning the HFTM in the TC or in the corresponding support.
- Once the HFTM is positioned in its support, the RHE descends a bit more, until the structure below the springs touches the top part of the supports.
- The RHE moves horizontally, until the fingers have completely released the supports.
- The RHE can now ascend again without the HFTM.

Focusing on the payload requirement, in Fig. A.5 is displayed a diagram of the Von Mises stress when applying the forces and constraints corresponding to carrying 1t weight to the fingers of the tool. According to this study, the maximum tension is 33,85 MPa in the springs, although the stress in this component will be temporary, so the breaking risk will be minimised.

Regarding the decontamination of the tool, to make it the most straightforward possible, the design includes mainly flat and smooth surfaces avoiding nooks. Also, its modularity enables the replacement of separate components without affecting the rest.

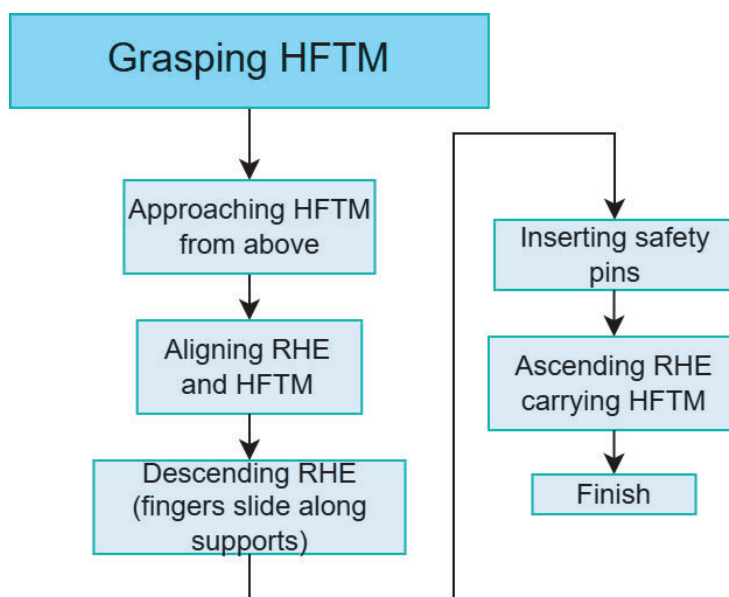


Figure A.2: Stages of the procedure to grasp the HFTM using the gripping tool presented in this section.

Mock-up

For the mock-up, the HFTM has been simplified, as the interest was to test the grasping operation, this means that the manufactured part consists only in the supports and the top part of the HFTM. Also, the interface between the tool and the robot has been changed to fit the robot that will be used in the laboratory tests. The mock-ups of the tool and the supports can be seen in Fig. A.6. They have been manufactured at a scale 1:3 in aluminium. In addition to that, as the main goal of these tests was to validate the grasping mechanism, the motors to insert the security pins have not been included in the mock-up, they will be inserted manually once the grasping has been completed, before the transportation starts.

Testbench

The test bench developed for validating the functioning of the designed tool, consisted in the mock-up of the gripping tool attached by a UR5e robotic arm and the mock-up of the HFTM within the workspace of the robot, so the grabbing and release can be performed, see Fig. A.7a. The datasheet of the robotic arm used can be seen in Universal Robots (n.d.). This test bench enable carrying out experiments in the laboratory to test the reliability of the grasping in different situations. Such as the rotation of the TCP while carrying the mock up of the HFTM, which is not expected to happen during operation, but performing this test enabled the analysis of the forces and behaviour of the grasping.

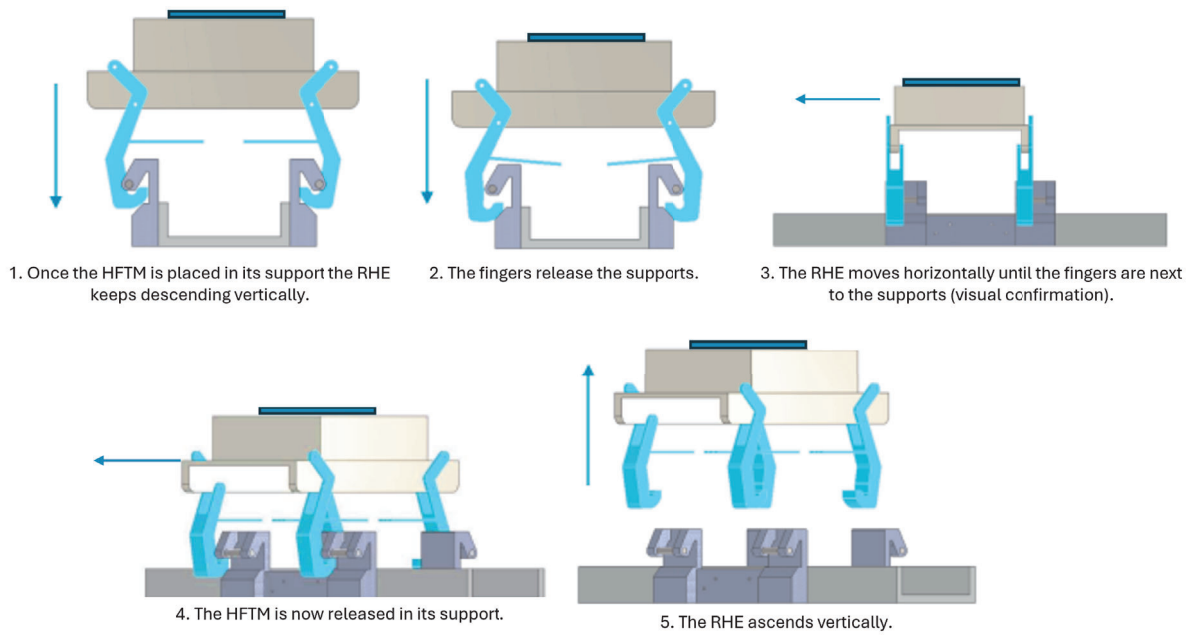


Figure A.3: Procedure for releasing the HFTM with the designed gripping tool. (Marín, 2024)

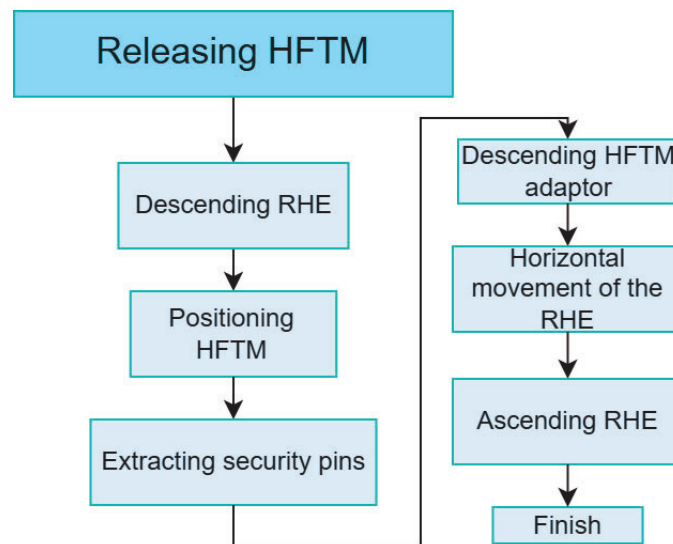


Figure A.4: Stages of the procedure for releasing the HFTM using the gripping tool presented in this section.

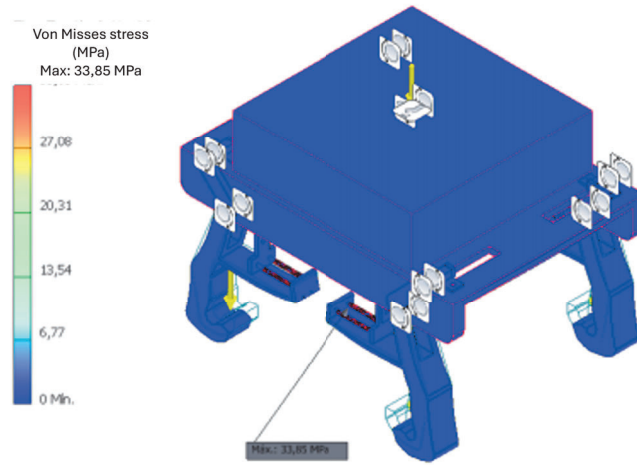
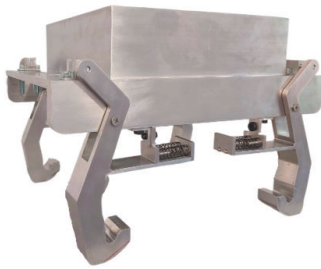
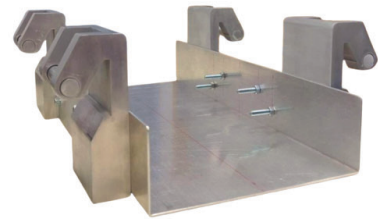


Figure A.5: Von Mises stress diagram corresponding to applying to the gripping tool the forces and constraints for transporting 1t weight. (Marín, 2024)

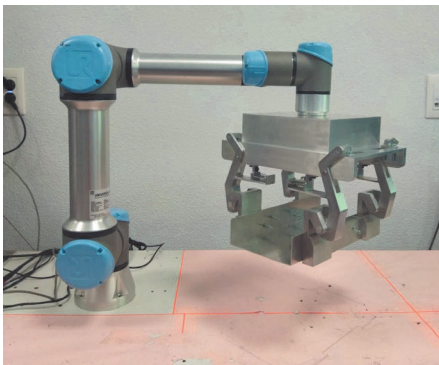


(a) View of the mock-up of the gripping tool.

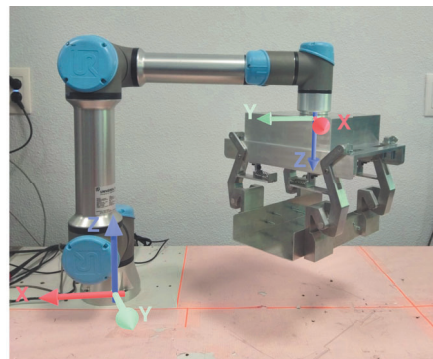


(b) View of the simplified mock-up of the HFTM.

Figure A.6: Mock-ups manufactured at a scale 1:3 in Aluminium for the tests of the designed gripping solution. (Marín, 2024)



(a) View of the test bench layout.



(b) Coordinates systems used for the tests.

Figure A.7: View of the test bench used for the tests of the gripping tool. The robotic arm used is an UR5e that attaches the mock-up of the tool. In the image the tool is carrying the mock-up of the HFTM, it corresponds to the transportation stage of the procedure.

Appendix B

Gripping tool for plugging and unplugging connectors design

Design and mock-up

The main requirements identified for this design are:

- **Environmental.** The procedure will be done by RH, however there is no need for rad-hard components.
- **Simplicity.** The designed system shall be as simple as possible, yet robust and failure tolerant.
- **Visibility.** It shall be adequate for teleoperation throughout the whole procedure. Vertical approximation during connection is preferred.
- **Accessibility and spatial constraints.** The robotic equipment and tooling shall be able to access all the necessary positions.
- **Compatibility.** The tooling designed shall be compatible with the available robotic equipment:
 - UR10 robotic arm.
 - EGK50 Schunk Gripper.
- **Position and orientation.**
 - The tool shall be able to grab the male part of the connector whatever its position and orientation is.
 - The female connector will be fixed at its position at all times.
 - The connection between both parts can be done regardless their relative orientation.

The design developed consists in modifying the fingers of the gripper to grab the connector, and to add to the connector an interface with the tool.

To enable the grabbing of the connector parts, the fingers designed have a "Y" shape, see Fig. B.1. It has curved edges for the precise positioning when grasping the parts of the connector. This shape is the base of the design, it has been adapted for each part, as explained in the following paragraphs.

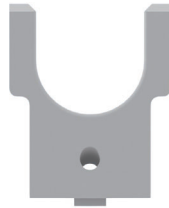
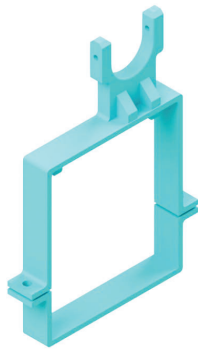


Figure B.1: The fingers designed have "Y" shape to enable the grasping of the parts of the connector.

One of the constraints was that the female part of the connector is fixed and cannot move, so the finger attaching this one will have to stay still during the connection and disconnection. Yet it is necessary that this part of the connector is grasped by the tool for alignment purposes. As it is not possible to move only one of the fingers of the gripper, that finger includes an structure to fix it to the side of the gripper, see Fig. B.2.



(a) View of the designed finger for grabbing the female side of the connector, including the structure to fix it to the gripper body.



(b) View of the fixing between the gripper body and the finger for the female part of the connector.

Figure B.2: Design of the finger to grasp the female part of the connector. As this side is fixed to the vacuum pump and cannot move during the plugging and unplugging, the finger will have to stay still too. So it has been fixed to the side of the gripper.

Whereas for the other finger, the one that will grasp the male part of the connector, to achieve a passive grabbing, spring plungers are used. This one will be fixed to one of the fingers positions in the gripper and move along the path when the gripper is open or closed, see Fig. B.3. Finally, the complete design of the tool can be seen in Fig. B.4.



(a) View of the designed finger for grabbing the male part of the connector. It includes spring plungers in its top ends to enable the passive grasping of the connector.



(b) View of the finger for grabbing the male part of the connector fixed to the gripper. It moves along the path when the gripper is open or closed.

Figure B.3: Views of the finger for grabbing the male part of the connector.



Figure B.4: View of the complete gripping tool designed.

In addition to the design of the gripper fingers, suitable interfaces have been designed for the parts of the connector to enable the grasping by RH. These can be seen in Fig. B.5a. In the case of the male part of the connector, this is not only an interface, but also thanks to its tight fixing and the gripping force, it will enable the unplugging. The reason for this is that the tooling will apply the necessary forces to unplug, according to the safety system.

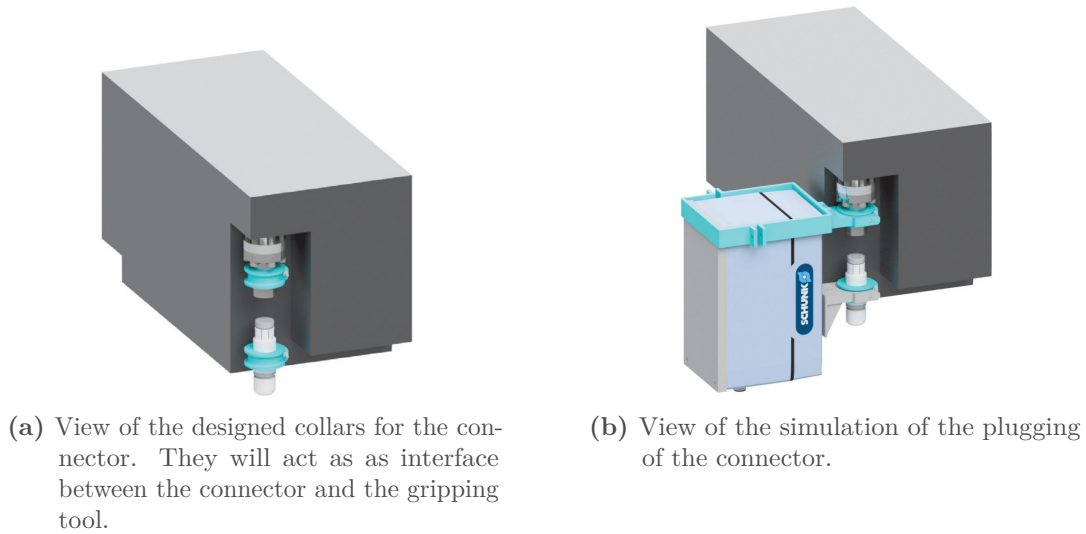


Figure B.5: View of the parts of the connector including the collars designed and the gripper performing the operation. (Redondo Gallego et al., 2024)

Procedure

The operation will be performed by teleoperation, so there will always be a person guiding the movements of the robotic equipment. The supervisory control architecture developed for this task can be found in Subsection 3.4.2. The foreseen procedure for the plugging goes as follows:

1. **Grasping the male part of the connector.** It will be laying in the floor in an unknown position and orientation. So the first thing to be done is to find it, and get the robot above it. Then the tool can be descended to achieve the passive grasping by the corresponding finger of the gripping tool. And finally, the robotic arm can be moved back up.
2. **Grasping the female part of the connector.** The position of the female part of the connector is known, as it will be fixed to the vacuum pump and will never move. So the operator will get the robotic equipment above the connector and align both parts. Once they are aligned, the operator can descend the gripper and grasp the female part.
3. **Plugging.** As both parts of the connector are grasped by the gripper, the operator can close the tool to perform the plugging. If the plugging cannot be performed due to misalignment between the parts of the connector, the operator will get the feedback and open the gripper again to realign the system.
4. **Releasing the plugged connector.** Once the gripper is successfully closed, plugging both parts of the connector, it can be released. To achieve this, the operator has to move the robotic equipment perpendicularly from the axis of the connector. The electrical signal getting to the vacuum pump will be tested, and if the connection is validated the plugging procedure is finished. Otherwise, the operator will fix the connection.

The unplugging procedure is detailed below:

1. **Grasping the parts of the connector.** The operator moves the robotic equipment to the position of the connector, and once they have aligned it with the component, the grasping can be performed.
2. **Unplugging.** The operator opens the gripper to separate both parts of the connector to unplug it.
3. **Releasing the female part of the connector.** The operator moves the gripper perpendicularly to the axis of the connector release it. Now the disconnection has been achieved.

Appendix C

Bolting tools for RH in the accelerator of IFMIF-DONES design

Designs and mock-ups

The main design requirements identified for this tool were integrating with the available RHE and achieving high bolting torques, while limiting the reaction forces and torques in the robotic arm. Additionally, following the design guidelines mentioned before, it is considered important to develop modular tools to facilitate the maintainability. Two different configurations for the tool were developed and compared:

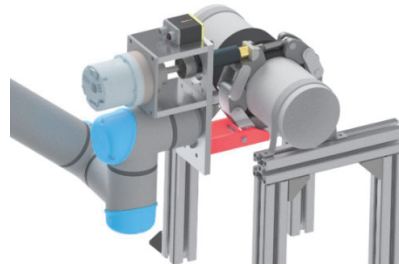
- **Configuration 1.** This tool was specially designed to operate the bolts in the QDSs located in the flanges of the cooling pipes of the beam dump in IFMIF-DONES (Fig. 5.34). As a consequence, some of its features are particularized to fit these devices, for example, the torque limiter system included in this design were developed to fit specially the QDS, as will be explained below. The overview of this design can be seen in Fig. C.1.
- **Configuration 2.** The intention with this configuration was to develop a bolting tool that could be used in several tasks in the maintenance procedures taking place in the accelerator vault. The key aspects of this configuration are that the bolting axis is perpendicular to the robotic arm wrist axis, and the reaction limiters consist in pins and slots. The pins will be placed in the component with the screws and the slots in the bolting tool. This design is shown in Fig. C.2.

The components of each configuration can be seen in Fig. C.3 and Fig. C.4. Both have some analogue functional systems, these will be explained below:

- **Bolt coupling system.** This consists of a spring above the socket wrench connected to a load cell. Informs about the coupling between the bolt and the tool. If the bolt is not inside the socket wrench, the spring will be compressed and the reading of the load cell will increase. If this is the case, the tool can rotate slowly while slightly pushing in the bolt direction to help the head of the bolt fit the socket wrench.

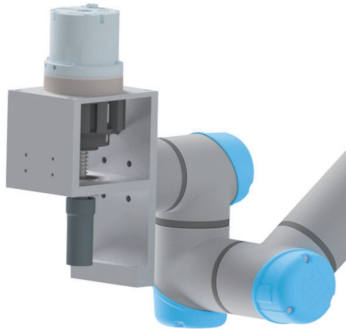


(a) The bolting axis is parallel to the rotation axis of the last joint of the robotic arm.

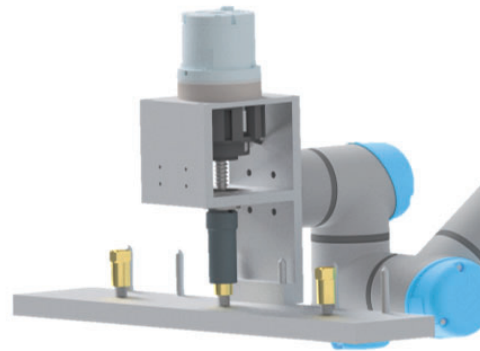


(b) CAD model of the bolting tool design for the QDS.

Figure C.1: First configuration of the bolting tool. This tool was specially designed to install Quick Disconnection Systems (QDS).



(a) View of the CAD model of the second configuration of the bolting tool.



(b) Simulation of the tightening of a bolt using the second configuration of the bolting tool.

Figure C.2: Views of the second configuration of the bolting tool.

- **Actuating system.** This is a servomotor that rotates to achieve the tightening/loosening of the bolts. It is a Qrob80 capable of achieving continuous torques up to 70 Nm and intermittent torques up to 110/143 Nm (ZeroErr, n.d.).
- **Torque transmission elements.** These are the elements that connect the socket wrench with the servomotor transmitting the torque.
- **Interfaces.** The interface with the bolt is the socket wrench, as the tool is modular it can be exchanged to fit different bolt sizes. On the other side, the interface with the robotic arm is foreseen to be a tool plate that will enable the attachment and release of the tool without human intervention.
- **Casing.** These correspond to the support elements bringing all the parts of the tool together. They are foreseen to be manufactured in Aluminium, because of its low weight and suitable mechanical properties.

- **Reaction torque limiting system.** This system has a different approach for each configuration. In the first one it consists of two fingers that limit the rotation of the tool, while bolting closing the force loop between the tool and the QDS. Whereas for the second one, it consist of two pins that have to be inserted in two slots in the component being bolted. This second approach provides a firmer coupling between the tool and the component.
- **Precise positioning system.** First configuration includes a camera that will be in charge of localizing the centre of the bolt very precisely. In addition to this, the fingers will also help positioning the tool. For the second configuration, pins and slots will act as the precise positioning system.

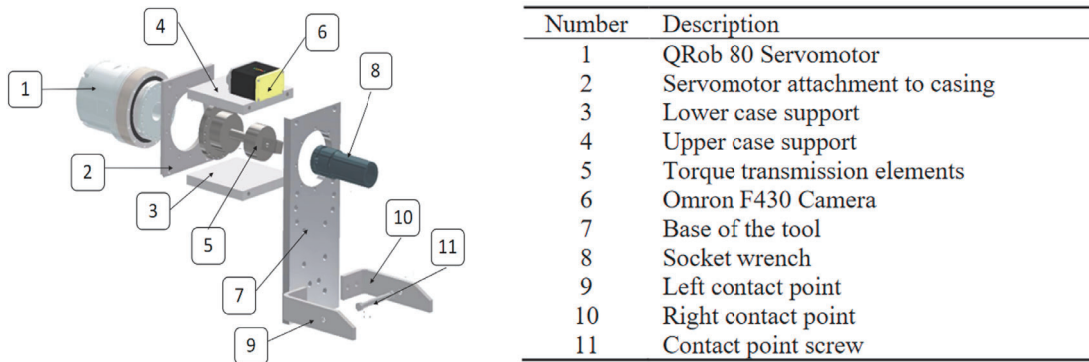


Figure C.3: List of components of the first configuration of the bolting tool.

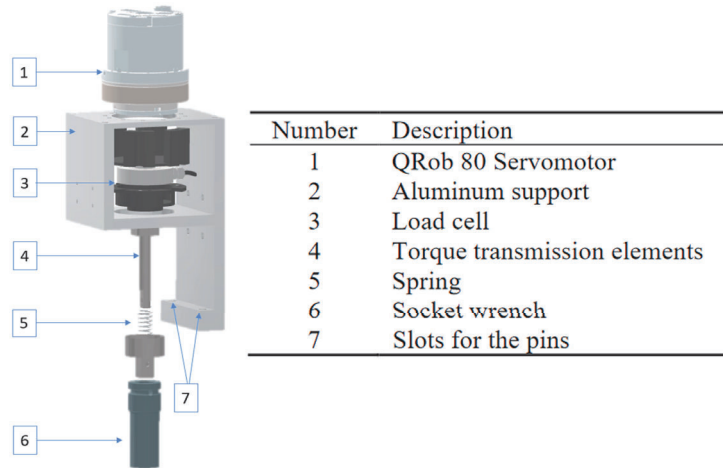


Figure C.4: List of components of the second configuration of the bolting tool.

Publications List

Journals

1. Micciché, Gioacchino; Arranz, Fernando; Mittwollen, Martin; Malloulli, Mariem ; Redondo Gallego, Violeta; Ferre, Manuel; Garrido, Jesus; Varga, Kornel; Rouret, Martin; Valuenzela, Elio; Cano Delgado, Abel ; Cammi, Antonio; Benzoni, Gabriele; Tripodo, Claudio; Wang, Yan; Dezsi, Tamas; Tadić, Tonči; Hoic, Matija; Siuko, Mikko; Rainio, Kari; Mitchell, George; Barranco, Francisco; Zsákai, András; Else, Christopher, Remote maintenance in IFMIF-DONES: current status and future development program, Nuclear Fusion. Accepted for publication 21 April 2025.
2. V. Redondo, N. Barbosa, P. Espinosa, M. Ferre, Design and evaluation of an advanced robotic bolting tool applied to IFMIF-DONES, Fusion Engineering and Design, Volume 214, 2025, 114877, ISSN 0920-3796, <https://doi.org/10.1016/j.fusengdes.2025.114877>.
3. Sofía Coloma, Paul Espinosa Peralta, Violeta Redondo, Alejandro Moroño, Rafael Vila, Manuel Ferre, The effect of ionizing radiation on robotic trajectory movement and electronic components, Nuclear Engineering and Technology, Volume 55, Issue 11, 2023, Pages 4191-4203, ISSN 1738-5733, <https://doi.org/10.1016/j.net.2023.07.041>.

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1. V. Redondo et al., "Development of a Remote Handling Intervention to Plug and Unplug an Electrical Connector of a Vacuum Pump at CERN," 2024 7th Iberian Robotics Conference (ROBOT), Madrid, Spain, 2024, pp. 1-6, doi: 10.1109/ROBOT61475.2024.10797438.
2. Ferre, M., Redondo, V., Barbosa, N., Espinosa, P., Sánchez-Urán, M.Á. (2024). Design and Radiation Resistance Analysis of a Robotic Bolting Tool Applied to IFMIF-DONES Maintenance. In: Secchi, C., Marconi, L. (eds) European Robotics Forum 2024. ERF 2024. Springer Proceedings in Advanced Robotics, vol 32. Springer, Cham. https://doi.org/10.1007/978-3-031-76424-0_2
3. Ferre, M., Peralta, P.E., Redondo, V., Barbosa, N., Sánchez-Urán, M.Á. (2024). Forces Analysis on Robotics Screwing Tasks. In: Marques, L., Santos, C., Lima, J.L., Tardioli, D., Ferre, M. (eds) Robot 2023: Sixth Iberian Robotics Conference. ROBOT 2023. Lecture Notes in Networks and Systems, vol 976. Springer, Cham. https://doi.org/10.1007/978-3-031-58676-7_45

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5. Redondo Gallego, V. et al. (2023). Design and Evaluation of a Passive Gripper for Remote Manipulation Tasks. In: Tardioli, D., Matellán, V., Heredia, G., Silva, M.F., Marques, L. (eds) ROBOT2022: Fifth Iberian Robotics Conference. ROBOT 2022. Lecture Notes in Networks and Systems, vol 589. Springer, Cham. https://doi.org/10.1007/978-3-031-21065-5_5

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