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**METHODS, STRATEGIES AND
APPLICATION CASES FOR ROBOTIC
TELEMANIPULATION IN
HAZARDOUS ENVIRONMENTS**

DOCTOR OF PHILOSOPHY

AUTOMATION AND ROBOTICS

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ELECTRÓNICA E INFORMÁTICA INDUSTRIAL
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To my mum and dad

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It seems like it was the other day that I started my PhD. At that time, I would not have imagined the beautiful things that I have lived and learned, as well as the magnificent people that I have been able to meet on this path.

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Resumen

Los sistemas robóticos son útiles en infinidad de sectores, otorgando un enorme potencial para el beneficio de las personas. Los robots pueden acceder a lugares recónditos y desconocidos, realizar tareas que requieran precisión sin agotamiento, o incluso operar en entornos peligrosos para el ser humano. Esto ha sido crucial para la evolución humana y sus descubrimientos, ya que se han desarrollado aplicaciones para el sector espacial, industrial, entornos nucleares u hostiles en general, tales como las complejas instalaciones de los aceleradores de partículas. No obstante, los entornos hostiles y desestructurados continúan teniendo multitud de desafíos que deben ser abordados. Estas condiciones hacen que sea complejo utilizar sistemas industriales y autónomos. Por ello, el uso de sistemas inteligentes y teleoperados continúa siendo preferible, ya que el humano controla el robot (esclavo) a través de dispositivos de control (maestro), lo cual permite al humano detectar peligros o riesgos más fácilmente y actuar directamente sobre el entorno.

La contribución principal de esta tesis se centra en el desarrollo de tecnologías para realizar operaciones de telemanipulación robótica o manejo remoto de equipos (Remote Handling, RH) en entornos peligrosos. Esta aportación profundiza en entornos con radiación ionizante, concretamente en aceleradores de partículas como la Organización Europea para la Investigación Nuclear (CERN) y la Instalación Internacional para la Irradiación de Materiales de Fusión – DEMO orientada a la fuente de neutrones (IFMIF-DONES). En primer lugar, esta tesis propone una metodología para desarrollar e implementar operaciones de RH en entornos con radiación. Esta metodología facilita coordinar el conocimiento de diferentes equipos multidisciplinares y unificar la información siguiendo un mismo camino para perseguir un fin común. Las fases iniciales de la metodología pueden determinar el éxito de la tarea remota, siendo un factor importante el diseño de la instalación. Por ello, en esta tesis también se ha desarrollado una guía de diseño genérica para instalaciones con aceleradores, la cual se enfoca en cómo deben ser los componentes, el edificio y los equipos de RH para ejecutar operaciones de RH seguras y factibles. Esta guía ha sido desarrollada en base a las necesidades de los aceleradores de partículas con altos niveles de radiación.

Por otro lado, las tareas de RH en entornos con radiación tienen la dificultad añadida de que la radiación afecta a los materiales y componentes de los equipos. Esto continúa siendo un hándicap que debe ser abordado en profundidad para un correcto diseño o elección de los equipos de RH (grúas, robots, etc.) necesarios para cada situación. Factores como el nivel de radiación en la sala, tiempo de operación, entre otros condicionantes, son decisivos para los equipos. Por ello, este trabajo ha contribuido

al conocimiento en este ámbito, realizando pruebas bajo radiación gamma para testear el comportamiento de dispositivos electrónicos y robots.

Parte del conocimiento mencionado se ha puesto en práctica en la etapa de diseño de la instalación IFMIF-DONES. La contribución en esta aplicación real se ha basado en definir, diseñar y coordinar soluciones ingenieriles para el mantenimiento vía RH de ciertos componentes de la instalación, como por ejemplo el remplazo de los materiales que son testeados bajo radiación neutrónica en la Test Cell (TC). El mantenimiento mediante RH tiene bastantes desafíos que deben ser considerados. Una de las dificultades principales es que los equipos deben tener herramientas que no necesiten asistencia directa por parte de los humanos, ya que en algunas áreas del acelerador hay elevados niveles de radiación. Esto implica hallar soluciones específicas que garanticen el éxito y seguridad del mantenimiento de los componentes. Adicionalmente, se debe considerar que estos equipos deben soportar ciertos niveles de radiación, y en el caso de fallar, un humano no podría entrar a rescatar o reparar el equipo. Por otra parte, el tiempo es un factor dominante, por lo tanto, las tareas deben optimizarse para conseguir agilizar las operaciones de mantenimiento.

Una contribución secundaria ha sido estudiar la interacción hombre-robot en el ámbito de la telemedicina. Siguiendo con la línea de aplicaciones en entornos hostiles, se ha implementado un sistema telerrobótico capaz de realizar ciertas tareas sanitarias básicas en pacientes con enfermedades altamente infecciosas, como la provocada por el virus Ebola. No obstante, esta aplicación puede ser extrapolable para pacientes con coronavirus (COVID-19) o tareas que requieran una alta destreza y precisión en entornos con radiación. Así mismo, este desarrollo también ha analizado que tipo de dispositivos, métodos de control, escalado y canales de comunicación son adecuados para tareas de precisión telemanipulando un humanoide.

Abstract

Robotic systems are useful in many sectors, mainly used to benefit and enhance people's lives. Robots can explore hidden and unknown places, carry out precise tasks without fatigue, and even operate in dangerous environments. They are considered of great importance to industrial evolution. Many applications have been developed for space, industrial, nuclear and other harsh environments like those in some particle accelerators. However, hostile and unstructured environments continue to present many challenges that still need to be addressed, and this could complicate the application of autonomous industrial systems. This is the reason why the use of intelligent and teleoperated systems continues to be the preferred choice for hazardous applications, whereby a human controls the robot (slave) through control devices (master). The teleoperation allows humans to detect hazards or risks more quickly and act accordingly.

The main focus of this thesis is on the development of technologies to perform telerobotic or Remote Handling (RH) operations in hazardous environments. This contribution delves into RH operations for environments with ionising radiation, specifically in particle accelerators such as the European Organization for Nuclear Research (CERN) and the International Fusion Material Irradiation Facility-DEMO Oriented Neutron Source (IFMIF-DONES). Firstly, this thesis proposes a methodology to develop and implement RH operations in radiation environments. This methodology facilitates coordinating the knowledge of different multi-disciplinary teams and unifying the information following the same path to pursue a common goal. The initial phases of a methodology can determine the success of the RH task. Therefore, there has to be a particular emphasis in the early stages, whereby the facility design can be a relevant factor as it can influence the results. For this reason, this thesis also presents design guidelines for facilities with particle accelerators. It is focused on how the components, the building and the equipment should be designed in order to perform safe and feasible RH operations. This guide has been developed based on the needs of these facilities since there were no general design guidelines for them.

RH tasks in radiation environments also have an added difficulty which is the effect of radiation on the equipment and electronic components. It continues to be a challenge that must be addressed in-depth. It is important to design or choose the most appropriate equipment (cranes, robots, etc.) for each situation. It depends on factors such as the radiation dose, time of operation, and so on. Therefore, this work has contributed to knowledge in this field, carrying out tests under gamma radiation to know the behaviour of electronic devices and robots.

Part of the mentioned knowledge is put into practice at the design phase of the IFMIF-DONES facility. The contribution in this real application has been based on defining, designing and coordinating engineering solutions for the RH maintenance of some components (for example, the replacement of the tested material under neutron radiation in the Test Cell (TC)). Nonetheless, the maintenance operations using RH have quite a few challenges that need to be taken into consideration. One of the main difficulties is that the equipment has tools that do not require direct human assistance since, in some areas, there are high levels of radiation. It involves finding specific solutions that guarantee safe and effective component maintenance. Additionally, this equipment must withstand certain levels of radiation, considering that in case of failure, a human could not enter to rescue or repair the equipment. The fact that time is a critical factor for this application implies that the tasks must be optimised to speed up the maintenance operation.

A secondary contribution has been studying human-robot interaction in the field of telemedicine. Continuing with the line of applications in harsh environments, a telerobotic system capable of performing specific basic health tasks has been implemented for patients with highly infectious diseases such as that caused by the Ebola virus. However, it can be extrapolated for the patients that have the coronavirus disease (COVID-19) or tasks requiring high dexterity and precision in radiation environments. Moreover, this contribution analysed what kind of devices, control methods, scaling and communication channels are suitable for precision tasks telemanipulating a humanoid.

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Acronyms and abbreviations

AC	Access Cell
ACMC	Access Cell Mast Crane
ADC	Analog to Digital Converter
AND	Activity Networks Diagram
ALARA	As Low As Reasonably Achievable
ARIEL	Advanced Rare Isotope Laboratory
AS	Accelerator Systems
AV	Accelerator Vault
AVR	Advanced Virtual RISC
BD	Beam Dump
BIT	BIinary digiT
BOR	Brown-Out Reset
BTR	Beam Transport Room
CAR	Center for Automation and Robotics
CB	Control Board
CERN	European Organization for Nuclear Research
CERNRHCOP	CERN Remote Handling Code Of Practice
CIEMAT	Center for Energy, Environmental and Technological Research
CMOS	Complementary Metal–Oxide–Semiconductor
COTS	Commercial Off-The-Shelf
COVID-19	COronaVIRus Disease 2019
CRC	Cyclic Redundancy Check
CSIC	Spanish National Research Council
CT	Current Transformer
DC	Direct Current
DD	Displacement Damage
DEMO	DEMOstration Power Station
DFMA	Design For Manufacturing and Assembly
DLR	German Aerospace Center
DONES	DEMO Oriented Neutron Source
DoF	Degrees of Freedom
D&D	Decontamination & Decommissioning
EDAC	Error Detection And Correction
EEPROM	Electrically Erasable Programmable Read-Only Memory
EU	European Union
EVEDA	Engineering Validation and Engineering Design Activity
F4E	Fusion for Energy
FAIR	Facility of Anti-proton and Ion Research

FRIB	Facility for Rare Isotopes Beams
GCS	Gripper Change System
GSI	GSI Center for Heavy Ion Research
GUI	Graphical User Interface
HDAPI	Haptic Device API
HEBT	High Energy Beam Transport
HEP	High Energy Physics
HFTM	High Flux Test Module
HMI	Human Machine Interface
HLAPI	Haptic Library API
HROC	Heavy Rope Overhead Crane
IAEA	International Atomic Energy Agency
IC	Integrated Circuit
ICRP	International Commission on Radiological Protection
ICSP	In-Circuit Serial Programming
IDE	Integrated Development Environment
IFMIF	International Fusion Material Irradiation Facility
IIEDR	IFMIF Intermediate Engineering Design Report
IMTS	Irradiated Materials Treatment Room
IP	Internet Protocol
ISAC	Isotope Separator and ACcelerator
ICSP	In Chip Serial Programmer
ITER	International Thermonuclear Experimental Reactor
ITHACA	InTervention in Highly ACtivated Area of HL-LHC
JET	Joint European Torus
J-PARC	Japan Proton Accelerator Research Complex
KIT	Karlsruhe Institute of Technology
LHC	Large Hadron Collider
M	Media
MBU	Multiple Bit Upset
MCS	Multi-Connection System
MEBT	Medium Energy Beam Transport
MLF	Materials and Life Science Facility
MOS	Metal Oxide Semiconductor
MUSE	Muon Science Establishment
NASA	National Aeronautics and Space Administration
N-MOS	Negative-Metal Oxide Semiconductor
NuPECC	Nuclear Physics European Collaboration Committee
NRC	Nuclear Regulatory Commission
LEBT	Low Energy Beam Transport
LS	Lithium Systems
LSP	Lower Shielding Plug
ORE	Occupational Radiation Exposure

ORNL	Oak Ridge National Laboratory
PC	Personal Computer
PCB	Printed Circuit Board
PCP	Piping Cable Plug
PDD	Phantom Device Drivers
PI	Proportional Integrated
PIE	Post Irradiation Examination
PKM	Parallel Kinematic Manipulator
PM	Profile Monitor
P-MOS	Positive-Metal Oxide Semiconductor
POR	Power-On Reset
PPE	Personal Protective Equipment
PSI	Paul Scherrer Institute
PWM	Pulse Width Modulation
QDS	Quick Disconnect System
QT	Quench Tank
RACE	Remote Applications in Challenging Environments
Rad-Hard	Radiation Hardener
RAR	Robotic Arm on Rails
RDS	Remote Disconnection System
RFQ	Radio Frequency Quadrupoles
RH	Remote Handling
RHE	Remote Handling Equipment
RHS	Remote Handling Systems
RIR	Radiation Isolation Room
RISC	Reduced Instruction Set Computing
ROS	Robot Operating System
ROV	Remotely Operated Vehicle
RS	Recommended Standard
RTM	Requirements Traceability Matrix
SCC	Super Conducting Cavities
SRAM	Static Random Access Memory
SD	Standard deviation
SEB	Single Event Burnout
SEE	Single Event Effect
SEFI	Single Event Functional Interrupt
SEGR	Single Event Gate Rupture
SEL	Single Event Latchup
SES	Single Event Snapback
SET	Single Event Transient
SEU	Single Event Upset
SMD	Surface Mounting Device
SNS	Spallation Neutron Source

TA	Target Assembly
TC	Test Cell
TCCP	Test Cell Cover Plate
TID	Total Ionising Dose
TIM	Train Inspection Monorail
TIR	Target Interface Room
TM	Test Modules
TRIUMF	Canada's National Laboratory for Particle and Nuclear Physics
TS	Test Systems
TTL	Transistor-Transistor Logic
UDP	User Datagram Protocol
UPM	Polytechnic University of Madrid
USP	Upper Shielding Plug
VERO	Virtual Environment for intelligent Robotics Operations
VIS	Vascular Interventional Surgery
VR	Virtual Reality
WDT	Watchdog Timer
WIPP	Waste Isolation Pilot Plant

Chapter 1

Introduction

This chapter provides a general view of the works developed during this thesis. It introduces the teleoperation, applications and drawbacks of this technology for hazardous applications. The motivation behind the benefits that teleoperation provides is exposed, to then, list the main goals and introduce the contributions and outline of this doctoral dissertation.

1.1. Overview

In recent decades, robotics has evolved to such an extent that some can carry out human activities and autonomously perform specific tasks (e.g., clean the house, bartender, guide in museums) [1], [2], [3]. Nevertheless, some applications still need human assistance during their execution, for example in dangerous, uncertain and unstructured areas. In these situations, the robots hardly control all the environment variables and factors, and the margin of failure is very small or null. Hazardous environments usually require teleoperation tasks, which means that the operators remotely perform or assist in those operations. The advantage is that the human is not physically in the area since the environments are characterized by representing a direct threat to life or unacceptable long-term health consequences [4].

Nowadays, teleoperation (or Remote Handling (RH)) is still necessary for some specific fields, such as space, nuclear, submarine or medicine [5], [6], [7], [8], [9]. Mainly, remote operations are highly demanded in nuclear reactors (fusion and fission) or particle accelerators facilities [6], [7], [J1]. In these places, facility components usually need to be frequently inspected and maintained to guaranty the safety and availability of the plant. The hazardous environmental conditions may be present in the form of high radiation, magnetic fields, high/low pressure, among others. These can accelerate deterioration and damage the equipment that performs the remote operations. However, other additional difficulties can appear for RH. For instance, limited accessibility, long distances, variable environment or components not easy to manipulate remotely. The way to reduce these complications is highly related to the following topics:

- The components and building design for remote operation.
- The equipment to perform remote operations under hazardous conditions. It includes from the operator side to the robot.
- The control software.
- The communication between the system.

The components and building design are essential factors to consider since it can facilitate the tasks. These have to take into account the equipment requirements and activities to perform. Depending on that, the Remote Handling Equipment (RHE) can waste more or less time during the operation. For example, the standard bolted flange is easy for a human to disconnect, but this can be tedious for a robotic arm, and it can increase the operational time and robot's functional requirements. For that, the elements to manage or be handled (e.g., bolts, nuts, clamps) must be suitable for the equipment to use. The problem with several facilities has been that they did not plan to carry out RH activities from the beginning, and they then had to find ways to implement solutions to perform Remote Handling operations [7]. A later implementation increases time and costs, and sometimes is not possible due to the incompatibility of the environment and building design. For these reasons, RH has to be considered at an early stage to achieve

adequate selection and implementation. However, this is not an easy task due to the unusual and personalised solutions that are required by these kinds of facilities.

Another relevant consideration is the equipment to perform remote operations under radiation. It must withstand environmental conditions and perform dexterity tasks without direct human assistance. Ionising radiation can influence and disturb the robot operational behaviour, damaging its electronic components and material [10]. That is why robots must have a robust design (hardware and software) against the radiation effects, besides having elements to allow easy radiation decontamination. However, the main problem is that there is no commercial equipment fully prepared for this type of hazardous environment. The available industrial robots are not created to operate in these kinds of facilities, and they cannot be easily adapted without investing a considerable amount of money and time [11]. Moreover, remote operations in ionising areas demand high precision and experience from the operators. To decrease the operator's training and experience requirement, it is crucial to have an appropriate and easy-to-use human-machine interface to perform the remote control, able to provide transparency to the process. If not, it can cause undesired overload, fatigue or stress to the operator. The main problem of most industrial robot control interfaces is that they are not intuitive and do not provide enough feedback for proper environment immersion. Thereby, the control software has to be configured depending on the application objective and be programmed to achieve remote control and adequate feedback. For better results, the communication channels and control architecture should be thoroughly considered to avoid communication delays [5], which is another issue of the telerobotics field.

This thesis presents extensive work to contribute new knowledge and applications for teleoperation. Most of the chapters have addressed different issues related to the operations in irradiated environments:

- A methodology and design guidelines have been elaborated on to implement RH operations properly in accelerator facilities.
- Study of the ionising radiation effects on a robot and sensitive electronic components. These have been tested in a real radiation environment to determine their response, behaviour and durability.
- Engineering solutions to develop RH Systems (RHSs) and perform specific RH maintenance operations at the International Fusion Material Irradiation Facility-DEMO Oriented Neutron Source (IFMIF-DONES) particle accelerator.

The last contribution is related to another type of application in a hazardous environment. A telerobotic system has been implemented for sanitary tasks in infectious areas. The work analyses and evaluates different control modes of a haptic interface and the performance of the operator performing precision tasks. The advantage is that the knowledge obtained with this contribution can be considered and applied in high precision tasks for radiation environments, which also demand high reliability and rigour.

1.2. Motivation

Robotics provides a host of benefits for humanity, from performing repetitive tasks without fatigue to accomplishing dangerous tasks. There is a great motivation to implement machines capable of performing tasks in hazardous environments since it prevents direct operator exposure [4]. However, robots are not totally reliable to carry out this type of work autonomously at the moment [12]. They continue to have some limitations in hostile areas. They still need supervision or telemanipulation by a specialised operator due to the number of variables to be addressed and the possibility of improvisation in unforeseen situations. For these reasons, human skills, knowledge and ingenuity are still necessary for some applications. It can also help to avoid mistakes, since any failure could be troublesome in situations where robots may be handling hazardous material (e.g., enriched uranium). Therefore, the equipment needed for these environments must meet strict requirements to achieve the objective of the task. Usually, these systems are made and implemented for a specific application, and there is rarely a generic or commercial solution.

The greatest motivation for a telerobotics application is to perform a remote task in the same way that a human being would. To achieve similar results, certain constraints and challenges must continue to be improved and solved [5]. The motivation of this work has been to continue investigating and deepening in the field of teleoperation. The aims are to enhance the RH operations in hazardous environments and develop new contributions that represent an improvement. In particular, the thesis has focused mainly on radiation environments, especially on the maintenance of particle accelerators. The implementation of remote systems and operations in radiation environments has the intention to avoid and reduce the amount of ionising radiation received by operators, which can cause cancer, or even death if they are high enough. The time and radiation dose received by remote equipment is also an essential factor in remote operations, as it can damage its structure and function. Therefore, efficient and safe systems must be implemented to reduce execution time, considering that the equipment has to bear and operate under radiation. The tasks runtime is also crucial for the facility; daily downtime is typically very costly (e.g., 0.3M to 0.5M € in IFMIF). In order to provide the best results, the investigation of how to facilitate and improve RH operations in radioactive areas should be continued.

During the development of this thesis, another specific telerobotic application has been implemented for hazardous environments, that is, patients with infectious diseases (such as Ebola virus or COVID-19). In this situation, the direct health care of the patients can pose a risk. The medical personnel must be specially equipped with Personal Protective Equipment (PPE) to care for the patient, although sometimes a minimal error can spread the virus. The incentive of this project was to implement a system capable of performing basic telehealth tasks to avoid the personnel exposing themselves continuously to this danger. In these cases, robots could help care for the patient without the risk of

the health personnel becoming infected, and thus minimising the spread of diseases. Currently, some robots perform a variety of activities, such as communication between patients and taking vital signs [13], [14]. However, there are no commercial nurse robots able to perform various types of health care operations with precision and dexterity on patients. This has lead to a gap in the market to develop a robotic system which can perform telehealth care tasks focused on patients with highly infectious diseases.

1.3. Objectives and contributions

The objective of this thesis is to provide advanced knowledge, useful applications and effective solutions for the field of teleoperation in hazardous applications, especially with regards to radiation. Several publications and congresses back up this thesis, see Appendix A. The work contribution is shown throughout five chapters, and can be summarized as follows:

1. A RH methodology that covers all the necessary aspects for the entire rigorous implementation and execution of remote operations in particle accelerators. The methodology is made up of a set of different stages and actions. These will be systematically executed to ensure the correct execution of a real remote task. The methodology principle is based on the initial cooperation among different teams or staff involved in the remote operation cycle. This approach leads to an iterative process that allows the optimisation and improvement of remote operation. It aims at accelerating the process with a safer and more robust concept of maintenance, simplified procedures, minimised breakdowns and reduced cost and time. Part of this methodology has been applied in the IFMF-DONES accelerator, which is in a design phase. The same approaches, tools and techniques can be implemented in another accelerator facility.
2. A basic design guide for RH operations in accelerators. This guide considers aspects of the facilities that must be evaluated and applied to facilitate remote tasks. It analyses the elements or mechanisms typically used during the RH operations, and it also proposes the most suitable for RH (for example, bolts, flanges and other items that are usually handled during the maintenance operations). This contribution tries to establish guidelines, so the facilities have a design adapted to the RH operations and equipment, avoiding systems that are cumbersome to be manipulated by robots. It is one of the problems and challenges that telerobotics has to continue addressing today in some facilities.
3. Analysis of gamma radiation effects on electronic devices and a robotic arm of 3 Degrees of Freedom (DoF). The radiation effect on hardware and software continues to be a challenge for teleoperation equipment, especially those with electronic devices, sensors, or actuators. This contribution performs tests under an irradiated

environment intending to know and understand experimentally more deeply the radiation effect and deterioration on specific sensitive electronic components, and how it disturbs on the operational performance of a robotic arm. Additionally, different techniques to alleviate or avoid the radiation effects have been compared. It leads to a real vision of which techniques may be better than others, or what factors should be considered when designing or purchasing a robot to the radiation environment.

4. Collaboration in the design and development of RH Equipment, tools and components that require remote maintenance of the IFMIF-DONES accelerator facility. The goal is based on providing and applying engineering knowledge to ensure that the most critical components and areas are maintained remotely most effectively and securely. The proposed solutions use parts of the methodology and design guidelines cited in contributions 1) and 2).

Another potential application in the field of telerobotics for hazardous environments and tasks that require high accuracy to act in the remote environment:

5. Development and implementation of a telerobotic system to perform telehealth care tasks, specifically for patients with a highly infectious disease. The goal has been to create a versatile system capable of remotely performing various functions with precision. In this case, a humanoid robot has been used to carry out telehealth care tasks such as taking temperature and oxygen saturation, ultrasound or rehabilitation. This contribution also studies the iteration human-robot testing different master-slave interfaces, control modes, types of escalation and number of communication channels architectures to provide the best performance to the operator during the execution of agility and accuracy tasks. [C3]

The last contribution is attractive to other RH applications due to the demanding requirements to interact and treat humans. The acquired knowledge concerning the human-machine interaction can be transferred to other fussy areas that require remote activities. For instance, where there is a radioactive material, and remote operations demand precision and dexterity (e.g., screwing, grasping, drilling, and so on), as the IFMIF-DONES facility.

1.4. Definition of some terms used

Some terms, also belonging to the “common” language, are used in the document. To avoid confusion, the definition of some of these terms are described below:

- Remote Handling: it is the synergistic combination of technology and engineering management systems to enable operators to safely, reliably and repeatedly perform manipulation of items without being in personal contact with those items [9]. The term “RH” is most commonly used concerning the nuclear industry, although also is used for other fields. The RH tasks in radiation environments are typically carried out using dedicated, modified equipment that is controlled and operated from a central control room [7]. It can be a robot or other equipment like a crane. These tasks are teleoperated, completed under supervisory control or carried out by automatic systems.
- Hands-on: any task that an operator performs manually in-situ (with hands or tools) when the environmental conditions are safe for humans. For example, connect electrical signals, activate drain valve or unscrew components during a technical stop.
- Remote Handling System: it comprises the whole set of Remote Handling Equipment, tool and devices for the execution of maintenance tasks. A wide range of technologies is involved such as special cranes, manipulator arms, lift interface frames, specialised cameras, operator control systems and Virtual Reality (VR) glasses [J2].
- RH Equipment: any crane, servo-manipulator or robot used during the remote manipulation.
- Accelerator component: it is a part of the accelerator, which is formed by different elements such as connector, gripping interfaces, and so on. The components have a purpose in the facilities. Examples of components on the accelerator facilities are the scraper, target lithium, cartridge, vacuum pump, etc.
- Commercial equipment or tool: any equipment or tool that has been developed and produced in the past, even if only one unit was commercialised.
- Modified-commercial equipment or tool: any commercial equipment or tool that requires some modifications in the design to be adequate for the particular operation.
- RH interface: the interface is the element of the component or tool that be in contact during the RH operation. For example, the bolted flange of a pipe has bolts, so these are the interfaces since the bolting tool has to tighten them.
- Indexing the workspace of the master device: it consists of performing unlinking when the master device reaches its mechanical limit. The master device is relocated then to a new position to continue with the guidance process.

1.5. Outline

The thesis structure is divided into eight chapters. These have been structured as follows:

- Chapter 1 introduces the context of this PhD dissertation to understand the problems of the teleoperation. It also presents the challenges, motivations and the contributions of this thesis.
- Chapter 2 gives an overview of the state of the art of the telerobotics for hazardous environments, making particular emphasis in the ionising radiation environments, like those in particle accelerators.
- Chapter 3 presents a methodology to implement a RH operation from the beginning to the end. This shows the different phases and the information to be considered in each to achieve a successful implementation. This work is the result of the collaboration in the IFMIF-DONES accelerator project and the acquired experience during the PhD Internship in the European Organization for Nuclear Research (CERN) particle accelerator in Switzerland.
- Chapter 4 proposes basic guidelines to consider in case of requiring remote tasks in the accelerators. This provides general suggestions and design recommendations so that the accelerator facilities will be designed to be maintained via RH Equipment instead by humans. It is the result of the work collaboration in the IFMIF-DONES project and PhD Internship in CERN.
- Chapter 5 presents experimental results of tested electronic devices and a robotic arm under ionising gamma radiation. These have been tested in the Van de Graaff accelerator at the Center for Energy, Environmental and Technological Research (CIEMAT) in Spain, under the collaboration of TechnoFusion project, which is funding by Community of Madrid.
- Chapter 6 presents the engineering work done in the IFMIF-DONES accelerator project. It applies the methodologies and guidelines presented in this thesis to provide the best RH solutions.
- Chapter 7 describes a telerobotic application to perform remote health care activities in an infectious environment. The tests carried out are used to know the feeling and performance of the operator depending on the software architecture. This work is the result of the collaboration between the German Aerospace Center (DLR) and the Center for Automation and Robotics (CAR) in Spain. CAR is a Joint Centre for Shared Ownership between the Polytechnic University of Madrid (UPM) and the Spanish National Research Council (CSIC). The collaboration has been carried out during the PhD Internship in DLR.

- Chapter 8 summarises the main contributions and conclusions of the work. It also proposes potential future research which could be performed bases on these.

Figure 1.1 represents an overview of the thesis. It illustrates in which part of a telerobotic system has been applied to each chapter.

Figure 1.1 - Thesis contributions for each area of a RH System

Robot communication also has been configured and implement for the works presented in chapter 5 and 6. However, it is not under the scope of this PhD dissertation.

Chapter 2

State of the art

The present chapter describes the context of the thesis, introducing the robotics and teleoperation fields. The origins, evolution, operation, development and application are specified. To later delve into concrete applications like the teleoperation in radiation environments, where a particular emphasis has been placed on particle accelerator facilities. This chapter concludes with the requirements and challenges that teleoperation has in this type of hazardous environments.

2.1. Robots evolution

The origin of the word “Robot” dates back to 1921, where the writer Karel Capek presented it in Rossum’s Universal Robots [15]. Years later, in 1942, the writer Asimov mentioned the word “robotics” in his short history Runabout. He defined robotics as the science that studies robots, creating three important laws of robotics [16]. However, science fiction finally became a reality [15]. Thenceforth, five generations have marked the evolution of robotics [17], wherein technology has evolved in all aspects and applications, creating a wide variety of robotic systems [16].

- 1st Generation (1950-1967). Robot manipulator based on multifunctional mechanical systems with open-loop control systems. It does not consider variations produced in the environment and performs pre-programmed tasks sequentially with simple control algorithms (Point-to-Point), like move objects from one place to another.
- 2nd Generation (1968-1977). Robots with rudimentary machine intelligence or closed-loop control systems with sensors. It allowed obtaining information from the environment to react and adapt to their performance. The robots were able to repeat a sequence previously executed by a human operator through a mechanical device.
- 3rd Generation (1978-1999). Robots started to be reprogrammable and capable of acquiring a perception of the environment using sensors to modify their control strategy. These already use powerful controllers like the computer. This generation is the beginning of intelligent robots and the development of programming languages.
- 4th Generation (2000-2017). Intelligent robots capable of controlling the process and capturing its environment in real-time with more sophisticated sensory systems. They can also analyse information, understand the situation, apply better-advanced control strategies and act on it using “model” concepts. This generation adapts and learns from the environment using knowledge such as diffuse and neural networks. Moreover, this generation began to include artificial intelligence and collaborative robots.
- 5th Generation (current). This generation aims to provide new technology with artificial intelligence incorporating behavioural models and innovative architectures. The goal is to create autonomous robots capable of meeting the needs of humans and mimicking the cognitive functions of the human mind, in addition to improving capabilities and working collaboratively with humans in the same environment.

The final goal of robotic systems is to be autonomous, that is, making their own decisions and acting on their own (without human control). However, autonomous robots are not safe for all applications [18]. Robots still have to improve and overcome different problems and challenges in design, control and planning since these are not totally safe when adaptation and intelligence are required. They do not have the same human sensory systems, nor the same motor skills in manipulation and locomotion. Furthermore, the autonomous robots have to overcome other drawbacks such as issues related to legal, security and privacy concerns [2].

In some applications, humans continue manipulating robots and other equipment through a partial (semi-autonomous) or full control (teleoperation). For instance, it is suggested in applications without a repetitive pattern of actions, or when the robot has to manipulate dangerous objects. The use of teleoperated systems in hazardous environments currently continues to be preferable [4], especially for tasks with a high level of uncertainty. Thus, the teleoperation takes advantage of the properties offered by machines and the human operator. Thereby, these systems achieve higher accuracy and security in task performance. However, as robotics advances, robots are expected to improve their capabilities and become increasingly independent in the future.

2.1.1. Teleoperation and telerobotics

The beginnings of teleoperation date back to the 1940s, wherein Raymond Goertz started to lead the first investigations on telemanipulation systems at the Argonne National Laboratory in the United States. The basic concept was to create a mechanism where an operator could provide position and orientation commands from a master controller to a slave-side system, replicating movements and forces in the remote area [19]. The patent (US Patent 2679940) is an example of the first electrical manipulator for the Atomic Energy Commission in 1951. The inventions of these decades have served as ancestors of today's master-slave teleoperation systems [20], [21]. Thenceforth, teleoperation applications have been developed mainly for nuclear, underwater and space environments. Although telerobotics has also spread to other areas, such as medicine, inspection, rescue, and maintenance [4], [5], [9], [22]–[28]. It is advantageous for situations or environments that are too dangerous, uncomfortable, limiting, or costly for humans [4], [18].

Telerobotics is a subfield of teleoperation and telepresence [29]. It was defined as a robot controlled remotely by a human operator, regardless of the robot's degree of autonomy. However, Sheridan (1992c) made a more precise distinction depending on whether: 1) all robot movements are continuously controlled by the operator (teleoperation), or 2) the human can control and monitor the robot, but it also has some partial autonomy [9], [18]. Unlike a fully autonomous robot, the operator has excellent control over the actions carried out by the robot. Figure 2.1 shows an overview of a telerobotic system following a bilateral control operation. As this image represents, the teleoperation system is based on a master and slave [9], [24]:

- Master: the operator control and supervises the robot through a Human Machine Interface (HMI) in a safe environment (local environment or control area). The HMI can include a wide variety of devices. It is possible to differentiate two types: control devices and the devices that provide feedback to the operator. Examples of these are screens, keyboards, VR glasses, lights, control devices with haptic feedback, control gloves, etc. The selection and quantity depend on the application requirements.
- Slave: the robot executes the master's orders in the remote environment, and in parallel, it transmits to the operator the environment information captured by the sensors and cameras.

Figure 2.1 - Example of a bilateral teleoperation system. The master is on the left side and the slave (robot) on the right. The operator controls the robot sending commands, and the operator receives the information captured by the robot in the environment

Telerobotics functioning consists of remote transmission of bilateral data [9], typically using the supervisory control architecture. The operator sends the orders remotely, and the robot reproduces the operator movements or other actions commanded (e.g., speed control). At the same time, the operator usually receives feeding back of the position and/or the interaction force of the slave robot with the environment [9], and other information of the sensors and cameras (see haptic feedback in [11] and other human interfaces in [23]). The feedback is beneficial to perform complicated motions in an unknown environment. In this way, the bilateral control loop allows the operator to interact with the place where the robot is located [9]. Systems with environmental feedback increase the feeling of telepresence and transparency of the system. The telepresence and transparency of the system are important factors because these allow the operators to feel as if they were operating in the remote environment, as if they were the robot itself. To achieve this, the control architectures, communication channels, control devices and receivers must be as suitable as possible for each application [9].

It is crucial to achieving a balance with the quantity of information transmitted, to avoid overloading the operator's sensory system and causing communication delays.

The delays in the control loop can introduce unstable behaviour and reduce transparency [9], [30]. There has been much work done on the stability analysis of control loops with delays [31]–[33]. Another research field telerobotics aims to improve is the robustness of those aspects which affect bilateral control system, space indexing, bilateral communications protocols and control of flexible manipulators [34], [35].

2.1.2. Operator master feedback

The brain collects all the possible information from the environment through the senses (hearing, smell, taste, sight and touch). The human being acts and takes decisions depending on the data obtained by the senses. The operator’s perception changes during the remote operations since a human cannot receive the same information as to when is operating directly in the environment. For example, sometimes the operator gets the force feedback though vision by means of a display. In this way, the mode of receiving the information changes, and the operator has to adapt and get used to this sensory modification. For this, it is essential to give operators the best possible immersion of the environment when performing remote operations, as if the operator is executing the tasks in the real environment. It is accomplished through appropriate control interfaces for each case and by the right stimulation of the operator's senses.

In general, the taste and smell senses are not usually used in handling tasks, unless the task requires the detection of some type of substance explicitly. This is why, when interacting with virtual stimuli, technologies have focused on developing devices for sight, hearing and touch. However, the concept of touch needs to be pointed out by distinguishing between three concepts: haptic, tactile and force. The term haptic designates the science of touch, which is of two types: tactile (e.g., smoothness, temperature, vibration) and kinesthetic (e.g., force) perception [36]. Both are necessary to form the sensations that are felt with the human hand [37]. Haptic devices such as Phantom Omni (Sensable Technology, Woburn, MA) are commonly used for telemanipulation tasks.

The operator must obtain adequate and functional sensory feedback from the environment. In telerobotics, the selection and quantity of the control and feedback devices depend on several factors. The choice should provide the operator with adequate and functional sensory feedback from the environment. Poor feedback of the senses can affect the perception, but this also occurs with an overload of the operator's senses. Some devices can cause fatigue, and the operator’s performance can become affected. For that reason, it is essential to make a correct selection of the devices to achieve a balance of information in the perception of the operator.

2.2. Teleoperation in hazardous areas

As subsection 2.1.1. has mentioned, teleoperation consists of operating a system or machine from a distance, although the term “RH” is also commonly used to refer to remote operations [6]. It separates the operator physically from the hazardous

environment, while the operator remotely controls the system. For that, it is vital to ensure that the operator has a realistic and natural perception of the situation, so remote management can be more productive during the performance of risky activities. As the following subsections detail, the teleoperation in the hazardous environment has additional challenges that depend on the type of activity and conditions [9], [38], wherein particular requirements and designs are usually demanded.

2.2.1. Hazardous environment

Work in hazardous environments presents many challenges for robotic devices [23]. Depending on the task and the risks, it can be an obstacle for the remote system performance. Hazards may be present in the form of temperature extremes, high radiation, toxic fumes, biological material, potential explosions, high pressure underwater, etc. The human exposure would either represent a direct threat to life or unacceptable health consequences. For those reasons, specialised robots and other machines have been developed over the years for these perilous conditions. The following paragraphs present relevant examples of hazardous environments applications [23], [39]:

- Underwater robots [40]–[42]: these perform underwater inspections, rescues and handling operations. The underwater challenges are mainly because of the low bandwidth and high distortion of the signal [11]. The vision system, mechanical design and their tightness also can be affected due to the depth and water pressure.
- Space [25], [26]: these robots have to perform multiple activities under different hazardous conditions, such as ionising radiation, storms on Mars, low gravity levels, etc. It affects the operation of the robot and its equipment, wherein if the robot fails, it usually cannot be repaired or recovered. Nevertheless, a significant challenge is communication delays in space. For example, there are 3-20 minutes of delay with Mars’s communication. For this reason, some robots have to be autonomous enough, although the operator continues to send commands and receive data every so often.
- Radiation [6], [7], [8], [10], [11]: robots are required to perform activities under radiation, for example handling radioactive material in nuclear fission facilities, or maintenance on particle accelerators. The main challenge is the ionising radiation, which can affect the material and electronic components of the RH Equipment.
- Highly infectious environments [14], [43]: robots can be used for situations where there are highly contagious diseases since it does not pose a risk to the robot. These robots can perform tasks in hospitals or laboratories with biological risk. The challenge is to implement and execute tasks for medical assistance because the robot-human iteration must be precise and safe.

- Harmful environments [44], [45]: robots can perform operations in places where there are toxic gases (carbon monoxide or nitrogen dioxide), asbestos fibres, etc. In these cases, the robot's material and devices must be compatible with the substances in the environment.

The main drawback of these applications is that it can cause malfunctions in the robot due to the deterioration of materials, electronic systems, communication problems, etc. Chapters 5 and 7 delve further into the drawbacks and challenges of operating in ionising radiation, which is one of the main themes of this thesis.

2.2.1.1. Handling of delicate and dangerous elements

Another factor to consider is the elements of the place. These can be dangerous, regardless of what the environment is like. For this, the elements must have a particular characteristic, such as the properties mentioned below:

- Fragile: the elements to be handled are delicate with the risk of breaking.
- Explosive: the material can detonate. A classic example is when a bomb deactivation has to be performed.
- Radioactive: the elements can be radioactive, and there is a risk of radioactive contamination or emission.
- Corrosive: specific material to be handled can be corrosive, like hydrochloric acid. For example, in some facilities, containers with acid have to be transported.
- Flammable: material that is dangerous since it can catch fire relatively easily.
- Heavy: weighty items that need special machinery to be handled or transported.

The manipulation, contact or proximity with these elements could cause human damage or undesired consequences. For this reason, a robot or special equipment is highly recommended. These have to have appropriate hardware and software to manipulate these types of elements, and also ensure proper and safe execution. In a similar way, when the robot interacts directly with humans (e.g., patients in a hospital), the basic requirement is to ensure a safe interaction.

2.2.2. Applications in environments with ionising radiation

The nuclear industry was the first user of teleoperation systems [38]. Goertz starts to develop the first unilateral manipulator to handle hazardous material for the Atomic Energy Commission in the 1940s [23]. Since then, the use and improvements of systems for radiation environments has been advancing in recent decades, which has helped drive significant developments [6], [7], [9], [11], [23], [46], [47]. Figure 2.2 presents the first mechanical slave-master manipulator device. Figure 2.3, Figure 2.4 and Figure 2.5 show

real examples of the RH operations in radiation environments. The images on the left show the operator area, and the pictures on the right the place where the robot is working.

Figure 2.2 - Raymond Goertz demonstrating the first mechanical slave-master manipulator device in 1949

Figure 2.3 - RH Mascot system at the Joint European Torus (JET) fusion tokamak reactor.
(Source: UKAEA and CCFE)

Figure 2.4 - Hot cell manipulators at Oak Ridge National Laboratory. (Source: OAK RIDGE)

Figure 2.5 - RH control room and Telerob EMSM 2B telemanipulator at Spallation Neutron
Source (SNS) (Source: ornl.gov)

The primary motivation to implement the RH System has been protected the workers, and avoid exceeding a specific dose limit, according to the set of regulations/standards of the countries. The RH System is a safe option because it helps to meet the safety measures of “As Low as Reasonably Achievable” (ALARA). It allows the operator to carry out RH operations from a safe place, avoiding or reducing the human radiation exposition [48]. It is more relevant for facilities that have to execute routine activities with high radiation levels or contamination. Examples of places or applications with these characteristics are listed below [39]:

- Civilian High Level Radioactive Waste Management.
- Decontamination & Decommissioning (D&D).
- Radiation Emergencies and/or Accidents.
- Environmental Restoration and Waste Management.
- Fusion Power System.
- Space Systems.
- Waste Isolation Pilot Plant (WIPP).
- Fission Power Plants.
- Fuel Reprocessing Plants.
- High Energy Physics Research Facilities (Accelerators).

In many of these examples, various tasks must be carried out to ensure a proper facility operation. It typically involves transport and the handling of radioactive material. A real example is that of Hanford, wherein it was necessary to recover and transport tanks with radiation higher than 5 Gy/h. The handling operation of hazardous materials is commonly required, especially during the dismantling of some facilities [49]. It usually happens when the components must be taken out to complete the final stage of the installation [8]. In the case of nuclear accidents, as they occurred in Fukushima and Chernobyl reactors, the tasks of cleaning up the waste have been essential, as well as

visualisation, inspection and rescue tasks [23], [28], [50]. These are fundamental to determine the state and conditions of the environment. However, these tasks are also performed to complement the routine maintenance of the facilities [8], [9], [51], [52]. Repair and maintenance are hugely important tasks in facilities such as Joint European Torus (JET) in the UK, International Thermonuclear Experimental Reactor (ITER) in France, CERN and IFMIF-DONES [J1]-[J5], [7], [11], [53], [54]. The robots execute different type of operation in these facilities [J2], [7], [9], [53], [55]. For example dexterity tasks such as unscrewing, grasping delicate components, drilling, sealing leaks, oil refilling, cutting, welding, etc. Cutting operations demand special consideration since it can release contaminated particles into the environment.

Interestingly, the demand for remote systems in nuclear facilities or accelerators has grown. One of the reasons is the ageing of the facilities, which require reform, inspection, partial dismantling, replacement of components, and so on. RH operation avoids or reduces the number of human operators with direct radiation contact, saving costs and time in the future. However, the requirements of remote operations are demanding in terms of flexibility, artfulness and perception. It becomes complicated and challenging for facilities that were not specially designed to carry out remote tasks [7].

2.3. Particle accelerators: definition, needs and application

As research expands, the number of particle accelerators is increasing worldwide. As a reference, 15.000 accelerators in the world were estimated in 2000 [56], and in 2014, there were already more than 30.000 accelerators [57]. A particle accelerator is a device that uses electromagnetic fields to accelerate charged particles at high speeds: magnetic fields are used to shape (focus and bend) the path of the particles, and electric fields to provide acceleration. In this way, the accelerator manages to generate collisions with particles or matter in a controlled way, which are executed for various purposes.

According to the Nuclear Physics European Collaboration Committee (NuPECC) and Faraz [7], the research carried out at particles accelerators facilities has a direct impact on the progress of society, such as medical imaging, cancer treatment, food processing, materials science, technology, microchip manufacturing, biology, clean energy, among others. Moreover, the high energy research communities and nuclear physics are expanding the limits of knowledge to understand nature at its most basic level, and thus, find answers about the evolution of the universe [58]–[60]. An example of the great scientific discoveries is the Higgs Boson at CERN in 2012.

2.3.1. Types and uses

Since the turn of the century, different accelerators have been developed. It has given rise to a wide variety of accelerators, as shown in Table 2.1 [61]–[64].

Table 2.1 - Different types of accelerators

DC Accelerators	<ul style="list-style-type: none"> - Cockcroft-Walton accelerator - Van de Graaff accelerator - Tandem Van de Graaff accelerator
Resonance accelerators	<ul style="list-style-type: none"> - Cyclotron - Linear accelerators (o LINACs)
Synchronous accelerators	<ul style="list-style-type: none"> - Synchrocyclotron <ul style="list-style-type: none"> ▪ Proton synchrocyclotron ▪ Electron synchrocyclotron
Storage ring accelerators	<ul style="list-style-type: none"> - Colliders

Two basic types of accelerators can be differentiated: linear and circular accelerators. Linear accelerators accelerate particles along a rectilinear path. The length of the apparatus limits the time available for particle acceleration and energy. Instead, circular accelerators allow particles to pass through radio frequency cavities many times along a circular path. Thereby, to achieve high energies in linear accelerators, it is necessary to increase the number of acceleration elements. Table 2.1 shows various accelerators used for engineering research and development of this thesis. These accelerators are:

1. Large Hadron Collider (LHC) accelerator of circular type from CERN (see chapter 4),
2. LINear ACcelerator (LINAC) from IFMIF-DONES (see chapter 6), and
3. Electron accelerator Van de Graaff type from CIEMAT (chapter 5).

2.3.2. Particle accelerators maintenance

Accelerators and their facilities require maintenance activities to guarantee their correct functioning. High energy ionising radiation speeds up the deterioration of the accelerator parts. During the beam circulation, the accelerator subsystems interact directly with the energy beam. The interaction can cause undesirable radiological activation of accelerator facilities and equipment [65]. It degrades the properties of the material more quickly, thus limiting its useful life. To ensure the correct functioning of the facility, accelerator facilities need maintenance, inspections and the monitoring of its operations. The three main types of maintenance activities are:

- Corrective maintenance: degradation can produce unexpected fails. The maintenance repairs the unscheduled breakdown of a component or equipment.
- Preventive maintenance: the regular use and environment conditions deteriorate the components or elements. This maintenance is scheduled to prevent bad functioning and undesired fail.

- Update maintenance: scheduled maintenance to update the components and accelerator technology. For example, during 2019-2021, extensive upgrades of CERN's accelerator have been underway in preparation for the next LHC run and the High-Luminosity LHC.

As a general rule, if the components have a probability of failure, these require preventive maintenance or scheduled replacement. If not, they do not require scheduled maintenance. But if there is an unexpected failure of these components, a repair should be done. Therefore, these unforeseen failures and incidents must also be anticipated and considered. The maintenance period implies a cost for the facility. For those reasons, maintenance operations must be carefully studied and optimised to obtain the best results in the shortest possible time.

Maintenance operations on accelerators can be tricky and risky due to the high radiation levels and radioactive materials. The personnel access is prohibited or limited in some areas of the accelerators because it can cause biological damage. The strategy to avoid or reduce that personnel being exposed to the radiation is using RH Systems. However, its utilisation can be an engineering challenge depending on the complexity and conditions of the facility [7].

2.3.3. The need for RH

Facilities with high radiation levels, such as those found in several particle accelerators (e.g., High Energy Physics (HEP)), have a legal obligation to protect the public and workers in their facility. The radiological protection is a multidisciplinary scientific and technical activity, whose purpose is to protect people and the environment from the harmful effects that could result from exposure to ionising radiation. The International Commission on Radiological Protection (ICRP) establish recommendations based on three basic principles. 1) Justification: the practice that implies the exposure to ionising radiations must always provide a benefit to society, 2) Dose limitation: the radiation doses received by persons must not exceed the limits set in the legislation in force [7], and 3) Optimisation or “ALARA principle”, that is, all exposures to radiation must be kept at levels as low as reasonably possible, taking social and economic factors into account. ALARA establishes three necessary safety measures for mitigating external radiation hazards and ensuring workers safety:

- Wait: the radioactivity decays over time.
- Shielding: the shield protects workers and minimises radiation levels in the room. The shielding should be developed from appropriate material and thickness.
- Distance between workers and radiation emission source: workers should be located as far away from radiation sources as possible.

The RH Systems are needed in some areas of particle accelerators to meet with the radiological protection requirements. The RH enables personnel to perform tasks safely and reliably, as the equipment can withstand radiation levels higher than the worker's safety limits (e.g., 2 mSV dose limit for personnel at GSI Helmholtz Centre for Heavy Ion Research (GSI), in Germany). The RH activities give various benefits to the staff:

- Reduce the exposure of workers to ionising radiation.
- Handling activated parts without biological risk.
- Optimise the general maintenance of the facilities.
- Minimise the cool-down period. It will be not necessary to wait until radiation levels are tolerable by humans. This time could take days, weeks, or even years.

The best idea is to carefully plan RH interventions at the accelerator and minimise the number of interventions. It is easier if the planning has been done in the design phase. However, as subsection 2.2.2 briefly mentioned, some older facilities did not consider performing remote maintenance during the accelerator's design or installation phases. These have had to implement subsequent remote systems, with the difficulty of adapting the systems to the accelerator's requirements. In these cases, there are often problems with access to some critical components, and they don't have a suitable design to be manipulated remotely. These problems hinder remote operations or increase the operation time. Therefore, new facilities should consider in advance the remote activities that need to be performed.

Defining RH tasks in advance has advantages. It allows validating the procedures defined in mock-ups or virtually. Moreover, the needs and requirements of all work teams are considered for facility construction, which is relevant to achieve the best solutions and reduces the difficulties of RH Systems in these environments. It saves time and cost, and beneficially avoids and reduces the frequency of exposure of workers to ionising environments. However, it is important to know that this early phase has several topics to consider, such as: the definition and optimization of RH procedures, the equipment selection, the RH design of the accelerator elements, the RH design adapted to the accelerator areas, etc. It is suggested to follow design guidelines and methodologies, but there is limited information for the RH accelerator applications. For that reason, this thesis has researched and studied this topic in depth.

2.3.4. RH applications

The reference [8] cited several facilities that progressively added RH capabilities over time. These have been the Paul Scherrer Institute (PSI) in Switzerland, the Oak Ridge National Laboratory (ORNL) in the USA, CERN, and GSI. Nevertheless, nowadays the RH is considered an essential requirement in new facilities such as the Japan Proton Accelerator Research Complex (J-PARC), IFMIF-DONES, the Facility of Anti-Proton and Ion Research (FAIR) in Germany and the Facility for Rare Isotopes Beams (FRIB)

in the USA. These types of facilities demand a wide variety of RH activities, such as inspection, maintenance, installation, replacement, decontamination, removal and storage radioactive elements. The following subsections describe detailed examples of RH applications in particle accelerators.

2.3.4.1. TRIUMF particle accelerator centre

TRIUMF is Canada's national laboratory for particle and nuclear physics, which houses the world's largest cyclotron. The facility is divided into several parts [66]. There are two facilities for rare-isotope beams: Isotope Separator and Accelerator (ISAC) and Advanced Rare Isotope Laboratory (ARIEL). Emphasising the ISAC facility [67], [68], it requires an effective remote system for the periodic exchange of targets located in the ISAC Target Hall (every 3-5 weeks) [69], where there are high levels of residual activity. The maintenance of the target component implies disconnecting the services and transporting the module with the crane to the hot cell [67]. The connection and disconnection of services are done manually since the target module is covered by shielding. In turn, the removal and transportation of the module must be done remotely, excluding personnel in this operation area. Vision systems allow personnel to supervise the remote operation, and operators control the position of the crane using a laser positioning system. The crane transports the module of 9 tons and 3.3 meters with a redundancy system integrated into the bridge, trolley drive and the hoist for security reasons.

Figure 2.6 - North hot cell of the ISAC facility. It has different remote equipment to perform accuracy operations to the activated components as Target Assembly (TA) [67]

Figure 2.6 illustrates the hot cell of the ISAC facility, which is a crucial maintenance area. The hot cell is made up of concrete, lead shield walls, glass windows, and sealable roof ports to allow crane access to the hot cell. It is equipped with master-slave manipulators, remote display systems, service equipment, and a platform to control and place the component being repaired. The hot cell allows performing various important tasks such as remote maintenance, replacement, decontamination and inspection of highly radioactive parts like targets. Repairs and replacement of components require from

2 to 4 weeks [67], albeit the preparation and work planning takes place several months in advance.

2.3.4.2. J-PARC proton accelerator facility

The J-PARC consists of a 400 MeV linear accelerator (LINAC), 3 GeV rapid cycling synchrotron (RCS) and a 50 GeV (currently 30 GeV) main ring (MR) [70]. JPARC allocates the Materials and Life Science Facility (MLF) [71]. It has a neutron and muon science facilities, wherein the most intense pulsed muon beam in the world will be produced in Muon Science Establishment (MUSE). The muon target and some components in the primary proton beamline in the vicinity of the muon target (M2 tunnel) are deteriorated and so highly irradiated. In this way, MLF has prepared maintenance activities to remove the radiated components and target of the line. The components that need to be handled and transfer by RH are: 1) muon target with a plug shield (target assembly), 2) monitors (Profile Monitor (PM) and Current Transformer (CT)), 3) scraper and 4) pillow seal. For that, a transfer cask and other elements, like a gripper, are used to transport the components to the hot cell (see Figure 2.7). The hot cell of J-PARC uses specific Remote Handling devices, that is a plug stand, exchange device, cutting tool, power manipulator, several master and slave manipulators, an in-cell crane, an attachment rack and a movable rack [72]. The operations can be observed through leaden windows and several cameras in the cell.

Figure 2.7 - RH procedures to replace the Target Assembly in JPARC. Image modified from [72]

Target assembly is the most critical component of JPARC. Figure 2.7 describes the complex transferring sequence required to RH transport the target assembly to the hot cell. As we can see, it needs to be temporally stored in a storage pod for cooling since it is a highly radioactive target. After that, the muon target is transported to a drying room for the water in the cooling pipes and then transferred to an underground storage room for long-term storage. The hot cell allows the handling and disassembling of the target

using the RH devices. For example, when the target was replaced in 2014, special equipment cut the target into pieces to enable efficient storage volume [73].

PM and CT monitors are also treated remotely in the hot cell. The monitors follow the same steps as the target, except the drying and the storage rooms treatment. In the case of the scrapers and pillow seal, these are stored inside the storage pod. If they break down after that, they must be inserted in a shielding vessel to be transported to the hot cell [72].

2.3.4.3. CERN high-energy particle accelerator

CERN is the world's largest research laboratory for particle physics. The LHC is the largest and highest-energy particle collider in the world (27 km of circumference). It collides proton beams at high energies (up 7 TeV). The LHC has different equipment that requires maintenance [74], such as Beam Dump (BD) and collimator [7]. These become radioactive as a result of particle collisions, so they need to be replaced remotely.

CERN is one of the facilities where remote maintenance was not fully considered initially. Only some critical components, as the collimator, were initially designed to be remotely replaced [7]. Nevertheless, the deterioration of the components and the need to maintain and update components in the accelerator has led to the gradual acquisition and addition of robotic systems. These have enabled the execution of some dangerous tasks, such as visual inspection, radiation dose measurements, leak inspection, water leak repair, installation and disconnection of the target, target dismantling, recovery and collimator inspection, among many others.

The great advantage is that robotic equipment can enter areas where a human cannot, and thus save radiation doses to humans. However, robots must operate in dangerous and unstructured environments, where there are no ready-to-use industrial solutions. These challenges have led to the development of a modular architecture for robotic inspection and telemanipulation in hazardous and semi-structured environments at CERN. A system called CERNTAURO has been worked up during the last years [55]. It allows operators to control different robots using the same human-robot interface, and additionally offers the possibility of performing tasks using multiple collaborative robots. Until now, various tasks have been completed successfully, such as assisted teleoperation, autonomous inspections, or dexterous tasks (i.e., grinding, screwing, sewing, cutting).

CERN has different robots to carry out the RH operations, most of which have already been integrated into the CERNTAURO architecture. Some of CERN's robots are commercial, and others have been designed and built at CERN [7], [11], [75].

- **CERNbot v1.0, CERNbot v2.0, CRANEbot**

Three different modular robotic systems have been created at CERN (see Figure 2.8). The different parts of the robot can be modified depending on the needs, easily changing one of the parts, such as the robotic arm. The objective is to guarantee autonomous inspections and to supervise the telemanipulation in the accelerator areas.

Figure 2.8 – CERNbots. Left: CERNbot v1.0 in single and dual arms configuration. Medium: CERNbot v2.0 with lifting stage in dual arms configuration. Right: CERNbot core (CRANEbot) in dual arms configuration [55]

These systems include the Schunk power ball robotic arm. Nonetheless, CERN also has other robotic arms and commercial systems that can be controlled using the CERNTAURO framework. Robotic arms like Kuka iiwa, Kukaubot, Schunk Powerball, Schunk Powercube, Kinova arms and Universal Robots.

- **Train Inspection Monorail (TIM) for the LHC**

The LHC tunnel has been equipped with the Train Inspection Monorail. TIM is made up of several wagons and is connected to a monorail on the roof of the LHC tunnel.

Figure 2.9 – Train Inspection Monorail in LHC accelerator from CERN [75]

Figure 2.9 illustrates the monorail. It includes cameras and sensors to carry out different autonomous missions. Examples of these tasks are visual inspections, radiation survey, civil infrastructure monitoring through photogrammetry, fire detection and survey

measurements of accelerator components. Depending on the mission, different mechatronic systems are deployed, for example, robotic arms.

- **Commercial Remotely Operated Vehicle (ROV):** Telex and Teodor ROVs perform tasks remotely with the required degree of care and precision. These are also used for inspections and unknown locations. The vehicle supports the operator in tasks such as 1) identification and processing of objects, 2) providing access to buildings and closed rooms, 3) eliminating dangerous elements, 4) recognition, monitoring and investigation, 5) use of various electrical and mechanical tools and 6) transport, positioning and remote use of measuring equipment. Figure 2.10 shows the Telex ROV performing remote operations in a part of the LHC accelerator.

Figure 2.10 - Telex ROV performing RH operations in CERN accelerator

Currently, there is an accelerator stop at CERN, which will end in 2021. During this stop, robotic equipment is being improved and updated to offer the best possible performance and results in RH maintenance tasks.

2.4.4.3. IFMIF-DONES particle accelerator

The IFMIF-DONES facility is currently under design phase. This facility aims at generating a neutron flux with an energy distribution close to the typical neutron spectrum of a (d-t) fusion reactor. The IFMIF-DONES will house a 40 MeV deuteron linear accelerator. The purpose is accelerating a deuterium beam that strikes a liquid lithium target to create the reaction and irradiate material samples [76]. The work conditions of the accelerator require RH maintenance activities in several areas to guarantee the availability and safety of the plant [J2]. This project is defining the RH activities and equipment needed during the design phase. It is done to anticipate or find problems and to coordinate the design of the plant with the rest of the RH requirements.

This preliminary phase defines which components are critical during the life of the facility and which need to be maintained remotely, and also the frequency of maintenance, location and radiation levels in the area. Other tasks focus on the necessary procedures to replace these components, how the components should be designed, and what is the best equipment to carry out maintenance tasks. Particularly, this facility

demands custom designs for specific RH operations. Chapter 6 of this thesis delves into the IFMIF-DONES project and the RH maintenance operations that are under developing.

2.4. Needs and challenges in an ionising radiation environment

Even though technology has advanced, solving and improving the telerobotics operations continues to be a challenge in irradiated environments since the hazardous conditions harm the remote equipment and its performance. It aims to solve different challenges to increase the level of reliability of the task in an environment with ionising radiation [10], [38]:

- The first challenge is the hardware system. This must be reliable and robust enough to survive the task execution period or at least a reasonable uptime. It is a relevant issue in environments with ionising radiation.
- The second challenge is to find methods to compensate for the hardware limitations, through an adequate selection and software implementation of the Human-Machine Interface to obtain a correct execution of the task.
- The third challenge is human-machine communication. This must be fast enough to act remotely in real-time.

The first challenge continues to be a problem. For that reason, it is explained in more detail in the following subsection 2.4.1. With regards to the second and third challenge, the software has an important role. It helps compensate for hardware deficiencies, and it can also help to minimise the delay in communications. Correct implementation and selection of the RH system can influence the operation performance. However, this thesis does not go into detail of the second and third mentioned challenges of teleoperation in irradiated environments.

On the other hand, the level of reliability during remote operations is fundamental, since failures can be costly. The remote system can also fail or be damaged. Still, there are different options to solve the problem. The first is to repair the system remotely with other equipment. This option is the most appropriate to protect the human from harmful radiation. If this is not possible, the damaged system must be decontaminated and removed from the environment, requiring human exposure. In the worst case, if the system cannot be removed from the environment, the system would require an on-site repair, which would prolong the intervention time due to the security measures that must be implemented. Therefore, reliable remote systems to perform these operations are necessary, in addition to a recovery system for the equipment. It prevents humans from having to repair or rescue equipment in dangerous environments. Thus, this should be considered for future installations that require remote operations.

2.4.1. Radiation effects on RH Equipment

The RH Equipment performing remote tasks on accelerators are directly exposed to ionising radiation. For instance, maintenance at fusion facilities can reach approximately 100 Gy/h with a run time that can range from 100-1000 hours [38]. It causes hardware and software affectations, for example, brittleness, loss of ductility, creep, ageing, etc [10]. The components of remote systems are affected, especially the mechanical and electronic components [9], [10]. These are seen to be degraded, and their life is shortened more quickly. Above all, the electronic components (e.g., microprocessors, memories, analog and digital converters, etc.) turn out to be even more sensitive to radiation.

During exposure of the devices to radiation, temporary or permanent failures may occur, leading to a malfunction or total equipment failure. Therefore, the equipment and its components must meet specific characteristics. The choice or design of the components is not trivial. It has to be highly linked to the exposure time, type and radiation levels, among other factors. The purpose is to alleviate the effects as much as possible and try to extend the operability time to comply with the planned operations. The best option shall be to select radiation-hardened components, but it is not always possible or even necessary depending on the operation conditions. Table 2.2 exposes the different radiation levels into four areas, where it is specified if hardened electronics are needed and in which real applications it is used.

Table 2.2 - Type of electronics and applications according to radiation levels [38]

Area	Dose	Electronics type	Applications
A	Low dose rate (< 0.01 Gy/h) and low total dose (< 10 Gy).	Radiation Hardener (Rad-Hard) electronics are not required.	The operations carried out in this area are aimed at light decontamination and maintenance work in areas with low radiation.
B	Intermediate dose rate and total dose (respectively < 10 Gy/h and < 1 kGy)	Rad-Hard electronics are required.	Hardened electronics can be found for most applications (within this radiation level range). Examples of activities under these conditions are decontamination, interventions and inspections.
C	High dose rate and total dose (respectively < 1 kGy/h and < 1 MGy).	Rad-Hard electronics is not always available.	Typically for interventions in the vessel reactor or hot-cells.
D	Extremely high dose rate and total dose (respectively ≤ 1 kGy/h and ≥ 1 MGy).	There are no Rad-Hard electronics available, and the selection of the remote equipment material (i.e., sensors, lubricants) is also critical.	It can be found in-core fission and fusion reactor maintenance, fuel handling, etc.

The use of hardware under radiation has led to various types of investigations. One is the development of special radiation hardener hardware, which today some delicate components can reach several MGy of the total dose. The other one would be the use of Commercial-Off-The-Shelf (COTS) components for applications with lower radiation levels and shorter exposure time. Selecting the most appropriate hardware based on the application is key to the success of the task. However, the costs are an important factor, and the drawback of Rad-Hard components is that these continue to be expensive due to its unusual design. For this reason, a balance between needs and requirements must be made, and the durability and effects of ionising radiation on the hardware of remote systems must be well known.

Another problem of remote operation is the reliable signal transmission for communications. When the communication is done by cable, it requires a balance between the number of signal lines in the umbilical link and the complexity of the electronics used [38]. The number of signals (associated with the number of sensors, actuators, etc.) must be limited for the umbilical link, since it must remain flexible and light, in addition to guaranteeing the signal throughout the entire line. A solution is to use multiplexors to process the signal data because it can reduce the number of signals on the line. Nonetheless, paradoxically, multiplexers should be avoided whenever possible in a radiation environment, unless they are particularly resistant to radiation. A similar problem happens with sensors, where these are needed for a better perception of complicated environments, requiring quality sensors. Nevertheless, for radiation environments and large workspaces, the number and quality should be limited. The problem is when sophisticated devices or sensors have radiation-sensitive components integrated [38].

Figure 2.11 - Design of the STÄUBLI RX170 based RH System for radiation environments [77]

Figure 2.11 exemplifies a RH System prepared for a radiation environment. The left part of Figure 2.11 is the operating area. It is a safe place for the operators and the radiation-sensitive components, as the control cabinets. A concrete wall and distance protect these. The RH System has a radiation-tolerant multiplexer to minimise the number of signals in the radiation area. The robotic arm has a radiation-tolerant encoder and a force/torque sensor. These sensitive components are radiation tolerant, resisting the radiation effect for longer.

Chapter 3

Methodology for RH operations in a radiation environment

This document provides a methodology to implement RH operations in a radiation environment, especially for particle accelerator facilities. The method is made up of a set of different stages to cover all the RH operation aspects from beginning to end. The aim is to create a known iterative process that allows the optimisation and improvement of remote operations, where cooperation between multidisciplinary work teams becomes essential in each stage. It is highly important when there are multidisciplinary work teams, being that the requirements of each one have to have a shared RH vision.

3.1. Introduction

A methodology refers to the set of rational procedures or methods to successfully achieve a goal. Usually, it is applied in an orderly and systematic way, avoiding random factors and improvisations. The purpose of the proposed methodology is to help structure, plan and control the process from beginning to end. Nowadays, these can be applied to a multitude of areas, such as health, education, computer, industrial and product design sectors [78]–[80], or even to design robotic systems [81]. However, no specific methodologies for performing RH operations in hazardous environments have been found, despite its difficulty, challenge and level of danger. For these reasons and the advantages that methodologies provide [82], this chapter presents a methodology for RH operations in irradiated environments. It has been made through scientific research together with rational knowledge and empiricism from different accelerators such as CERN and IFMIF-DONES particle accelerator.

The main goal considers all the common steps needed to prepare and complete RH interventions. Thereby, actions, sequence, rules, and suggestions have been proposed to complete each phase correctly, and thus mitigating and avoiding the common causes of failure in a project [83]. The purposes and benefits of implementing a defined methodology are several:

- Minimise the planning, development and execution time.
- Minimise costs.
- Improve communication and collaboration between work teams.
- Obtain efficient and straightforward implementation methods.
- Document the processes in a clear and orderly way.
- Maximise safety and results of operation.

Methodologies are advantageous in facilities or projects where there is a multidisciplinary work team. Each team has its requirements and conditions, so adapting and considering the needs of others is vital. For example, pipe designers have to take into account the RH requirements and vice versa. If not, the piping could cause problems or interferences during a RH maintenance. This example justifies the need to follow such strict design procedures as the one proposed in this chapter, which allows having an overview of the RH needs depending on the rest.

This chapter contains a detailed summary of the methodology [J1], including the stages, schemes and processes in each subsection. The intention is that the reader is able to identify the needs of each stage. The methodology presented can also be applied in facilities where previously RH interventions have been carried out. For that, subsection 3.9 includes an example request to speed up the first phases.

3.2. Life cycle phases of RH operations

A project can be defined as temporary entrepreneurship with a specific objective. It has a life cycle to define the entire implementation, from beginning to end [84]. It is based on a set of interrelated activities to achieve the defined purpose. The literature presents different life cycle approaches such as the control-oriented model, quality-oriented model, risk-oriented model, a fractal approach to the project life cycle, as well as other company life cycle projects [85]. The number of phases within each of these approaches differs, as do the names used to describe the phases. Despite this, projects often meet common phases in their life cycle structure, such as starting the project, organizing and preparing, carrying out the work and closing the project [85].

A complete life cycle of RH operations has not been defined so far [J1]. This section shows the first life cycle sequence and steps to completely implement RH operations in a radiation environment (see Figure 3.1 and Figure 3.2). Each phase strengthens and matures the objective.

Figure 3.1 - Steps and sequence to complete a RH operation in hazardous environments

Table 3.1 details the description of each phase defined in Figure 3.1. This methodology is composed of six phases, where there is an iterative process in the development. These must be completed sequentially but considering that it is possible to perform modification in each iteration. It aims to search the optimisation of the system according to the task progresses. In this way, different parameters of the system are progressively defined and adjusted during the development progress.

The division of phases into blocks are fundamental to carry out control and execute the activities in the most efficient way possible. All phases are important to complete the final operation successfully, but the definition and design stages are crucial to save time and money in the later stages. Therefore, special attention should be taken in these phases through clear, agile and collaborative working methods to prevent as far as possible, avoidable setbacks or errors. For that, it is highly recommended to have frequent meetings with different project members.

Figure 3.2 - Phases and subphases to implement a RH operation

Planning and evaluation procedures must be considered after each stage. It creates a clear roadmap in addition to establishing the needs of personnel, resources and other factors to achieve the objectives in time. Likewise, depending on the type of project or task, it is also necessary to plan and manage contracts, procurement activities, and other matters. Planning, evaluation and organisation are not going to be dealt with in detail in this methodology, only subsection 3.2.1 talks briefly about it.

Table 3.1 - Definition of the main phases/steps to complete the RH operation

No. Phase	Phases	Description of Phase
1	Initiation	In this phase, the idea of a new RH operation is generated, and a formal authorisation is evaluated. This phase does not require a formal project plan. However, the financial, operational and technical viability of the project must be assessed previously.
2	Definition	This second phase is the basis of the project. In this phase, the scope, description, specifications and requirements of the objective pursued are defined. It easily and directly transmits the necessary information to start working. Communication is the key in this phase, in addition to the subsequent decision making.
3	Design	The design phase determines the activities or actions to achieve the objective. It defines the necessary or available resources. In parallel, if necessary, the designs and manufacture of the equipment or elements selected for the task would be carried out. At the end, the RH operations and system would be validated through virtual simulations.
4	Construction	This stage is based on planning and acquiring the necessary elements for the operation, besides integrating them to validate their functionality and performance.
5	Operation	Prior to executing the RH operations, preparatory activities have to be done (e.g., transport equipment, protect sensitive material, etc.). After that, remote tasks are executed in the irradiated environment, and then post-operation activities are performed to conclude the phase.
6	Final	To complete all stages, the RH intervention is analysed and evaluated. It can influence future decision-making and ways of conducting remote operations. Depending on these decisions and circumstances, other tasks such as maintenance, modification or repair of equipment may be required.

3.2.1. Planning and evaluation

Planning is essential to organise the processes and resources necessary to implement the defined project or mission. It is crucial for decision-making, error prevention, and improvements of the project with a short, medium, and long-term focus. Moreover, evaluation is necessary to check the status and the implementation of each phase. The evaluation and planning normally are linked since one can influence the other. Poor planning and evaluation could lead to failure of the defined purpose.

3.2.1.1. Planning and scheduling

An essential part of the engineering design process is focused on planning future events and scheduling them. The purpose is to achieve specific objectives, avoiding or minimising delays. Detailed planning and scheduling are suggested for large construction and manufacturing projects [86]. Planning involves creating a set of plans to help guide your team through the different phases of the project, establishing a clear roadmap (for

example, plans to help manage and calculate time, resources, costs, risks, and other factors). These contribute to managing external personnel and suppliers, planning contracts and acquisition activities, as well as ensuring that the project is completed on time within the budgets and parameters set. During this process, it is necessary to guarantee proper communication and define the different roles (see reference [86] for more specific information). The following activities are some of the most important to consider before and during the definition of the phases [84], [86], [87]:

- Division of work: divide the project into activities and each one into tasks.
- Time: make a schedule and determine the beginning and end dates, as well as the project completion deadline.
- Costs: summary of the expected expenses and income.
- Communication: provision of communication platforms to guarantee fluid and efficient communication with all the members.
- Resources: create a resource plan to optimise performance.
- Risks: create a plan to identify potential sources of risk, consequences and mitigations.
- Project human resource: management and planning process of the people involved in the project. For instance, project manager, sponsors, customers, partners, individual contributor, project and team members, etc.
- Project: establish a project plan to serve as a baseline, providing an estimate of project tasks and resource needs.
- Rules and procedures: determine the rules, conditions and procedures of the project.

There are known techniques and tools to elaborate on some of the cited activities, such as the division of labour, the Activity Networks Diagram (AND) and the Gantt chart [84], [87]. Planning should be done considering the different phases, where it is advisable to review the planning and organisation after each phase to detect deviations and adjust it whenever necessary.

3.2.1.2. Analysis and evaluation

The evaluation process is essential for any project, regardless of its characteristics and size. The elements involved in the project must be periodically analysed and evaluated to determine their viability, feasibility and observe the possible risks to act accordingly. Considering the information provided in the stages, it is recommended to examine the results after each phase. It creates control and knowledge of the project evolution, detecting deviations and needs for improvement throughout the process. It is advisable to

carry out continuous monitoring to verify that the project is evolving according to the designed plan, in addition to detecting possible threats or opportunities for anticipating them and making the appropriate decisions. The recommended analysis or evaluation after each phase of this methodology is explained below:

- **Initial phase:**

The data provided in the initial phase allows us to know the operation. The responsible persons must make a preliminary analysis considering factors such as the economic, availability and work team's responsibilities, necessary companies, risks, etc. An initial feasibility examination may assess whether it is possible or feasible to perform this operation in the conditions described and examined. If not, the task must be dismissed or modified to meet the necessary conditions. Typical influencing factors are legal, money, or availability.

- **Definition phase:**

At this definition phase, a feasibility study is useful to decide the start-up of the design phase of the project. For instance, studies concerning the feasibility, economic and financial, technological, legal, environmental impact, among other studies. These allow analysing the elements that could harm the project and its objectives. Likewise, depending on the results obtained, decisions can be made to improve it or meet the feasibility requirements.

- **Design phase:**

This stage defines the most appropriate actions, equipment and tools for remote operations. In this way, the simulation phase has served to validate its operation and response. This phase requires an evaluation of topics such as:

- The equipment and tools selected are appropriate for the task, or if these can be acquired.
- Damage and lifetime of equipment and tools.
- Compatibility between operations, environment and equipment.
- Viability of the operation.
- The cost is acceptable for the project.

The evaluation is decisive since equipment and tools must be acquired and/or integrated with the system in the next phase.

- **Construction phase:**

Before proceeding to the operation phase, it must be determined whether everything is ready. It includes analysis and evaluation of topics such as:

- The correct acquisition of equipment and tools.
- The proper integration and operation between the hardware and software.

- The correct execution of the task in a virtual, mock-up or real environment.
- The availability of resources to execute the remote operation.
- The availability of personnel and time to execute the remote operation.

Once verified and guaranteed that the operation could meet the expectations and quality level, it is possible to proceed to prepare the operation phase.

▪ **Operation phase:**

The operation phase is composed of three fundamental evaluations. The first is whether the operator has enough experience and training to accomplish the task. The second analysis must be carried out before the execution of the task, where it is evaluated if all the elements have been considered, and everything is ready. The third analysis is after operating. The evaluation consists of analysing whether it has been carried out correctly, complying with the planned planning.

▪ **Final phase:**

A final evaluation must be done to conclude. This analysis can be recorded in a final report, which is useful to analyse whether the actions taken have been correct. Additionally, it helps to detect weaknesses or errors and to propose future solutions. It is also advisable to assess whether remote equipment fixes or modifications should be made before the next task.

3.3. Initiation phase

The initiation phase is the starting point to develop a project. It is composed of one step, as shown in Figure 3.3. The RH operation and characteristics are defined to know the basic information. It is fundamental to evaluate and examine the proposal, and receive a formal authorisation for its implementation [87].

Figure 3.3 - Stage of the initiation phase

The initiation phase of a RH operation is motivated by the risk or danger of the task. Other projects usually become motivated by other factors like economic viability and innovation.

3.3.1. Operation concept

In this initial process, the RH activity is described (multiple tasks can also be specified). The description defines the operations to be implemented and its basic characteristics. It should not be overly extensive. It should present a general idea to identify the main needs and problems of the desired RH operation. Figure 3.4 collects basic information about the RH operation. It includes the requestor, the operation goal, characteristics, brief

description, location, operation type (via RH or Hands-on), expected dates. Nevertheless, depending on the task, it also can include other descriptive information, such as preliminary requirements.

This information assists in studying the initial feasibility of the RH operation. This phase is the beginning, making a parallel planning and organisation process to consider decisions such as the team, staff or companies responsible during the RH process (see subsection 3.2.1). Concerning this last information, it is fundamental to know who is in charge of each part of the project (components and designers, technicians, robotic team, etc.). This information could be provided in a list with other useful data as the contact data (e.g., telephone number, address) or the work required. It is relevant to achieve rapid communication between the different groups or members.

ID/name RH operation	1010. Beam Dump operation				
Objective	Replace the cartridge component				
Description	The cartridge is covered by a shield. These shield have to be opened remotely. After that, the pipes ...				
Location	Main Characteristics	Required operation	Type of operation	Frequency	Data
Room (R113)	<ul style="list-style-type: none"> - Shield weight: 48000kg - Cartridge weigh: 1500kg - Cartridge dimensions: ~2552x940x1574 mm - Radiation room: 	Maintenance and inspection	RH and Hands-on	Only in case of fail	No data. Only in case of

Figure 3.4 - Example to complete the preliminary information about the RH operation

3.4. Definition phase

The definition phase is a crucial point for RH operations. The project specifications and requirements will be detailed, as clearly as possible. It also involves identifying the expectations or needs of the people who are part of the project/company. The staff, work teams or companies involved will have to include their specific information in each section (see Figure 3.5). It will be done iteratively until all the necessary information is collected for the next phase.

Figure 3.5 - Stages of the definition phase

The meetings are useful during the entire life cycle. However, it is especially recommended to have frequent meetings during the definition phase to understand all concepts properly. Reference [86] describes how to achieve productive meetings between different teams.

3.4.1. Purposes and objectives

This subphase aims to determine and specify expectations. The purposes and objectives must be identified and defined. The objectives help to centralise the information that is generated around the plan and, at the same time, these guide the decision-making. Moreover, when the entire process is completed, the defined objectives can be compared with the results (it is useful to see the effectiveness and efficiency of the implementation). It is important to differentiate two concepts for this subphase: the purposes and the objectives.

- Purpose: this describes what we want to achieve at the end of the work. It does not provide evaluable or measurable data within the project strategy. Main purpose example: development of a teleoperation system to transport contaminated items.
- Objective: these represent significant achievements on the road to the project's ultimate purpose. Once the main purpose is defined, the secondary objectives must be defined, examples of these are:
 1. Develop a strategic plan to implement remote tasks.
 2. Select and purchase a robot for a radioactive environment.
 3. Design tools to catch the contaminated element.
 4. Perform remote equipment test in a mock-up, etc.

Main purpose	<i>Develop a tele-operation system to transport, grab and handle contaminated items in the Beam Transport Room.</i>
Objectives	<i>1. Define the cartridge maintenance procedures. 2. Select and purchase appropriate equipment for BD maintenance. 3. Select or design tools for BD maintenance. 4. Select or design ... 5. ...</i>

Figure 3.6 - Example of the purpose and objectives

Figure 3.6 exemplifies how to prepare the objective list based on the established purpose. Note that the objective/goals are listed in chronological order based on the plan. Subsequently, it is necessary to consider how to subdivide these objectives to know all actions involved in the development or realisation of each objective.

3.4.2. Specifications

This subphase consists of defining in more detail the essential information to perform the RH operation. For example, the work environment, the components or elements that require RH, the required activities, the available equipment and tools, or the necessary personnel to control the equipment remotely. For the new facilities, some data could be unknown or not available at the beginning, so these will be completed with development.

▪ **Work environment:**

The characteristics of the environment have to be specified to implement the task correctly. It is relevant because the selection of equipment, tools or operations may differ depending on the environment. Therefore, it is initially recommended to indicate the location, description and the main characteristics of the place, such as dimensions and work area conditions (e.g., temperature, pressure, radiation levels, activation calculation, etc.). This information could be provided in a technical document (file with the basic description), in addition to providing graphic elements such as drawings or CAD models to visualise the places.

▪ **Component/element:**

It is recommended to specify descriptive information about the main components or elements involved in the RH operation, for example:

- Name of the component together with the elements that make it up (i.e., shields, pipes, cables), above all the elements that are involved in the remote task.
- Indicate if the component/element has RH interfaces.

This information must be followed accompanied by a description of characteristics (weight, dimensions, material, activation calculations, etc.), technical specifications and design (photography, technical drawings, CAD models, etc.) of the component's parts.

Part No.	Part Name	No. Parts	No. interfaces	Interfaces	CAD model	Material	Size	Radiation level	Link Technical data
1	Beam Dump	10	-	-	BD.step	M1	WxHxL	R1	/directory path
1.1	Cartridge	1	1	I1	CT.step	M2	WxHxL	R2	/directory path
1.2	Left Shield	1	1	I2	LS.step	M1	WxHxL	R3	/directory path
1.3	Right Shield	1	1						

Figure 3.7 - Example to describe components or elements

Figure 3.7 shows an example of how to integrate relevant information into a table. Additionally, it is advisable to provide technical documents and detailed drawings (see Figure 3.8). For example: technical data about the acceptance test, installation procedures, material certificates, components datasheets, and so on. The facilities that are being designed will be provided with the information as it is developed.

Figure 3.8 - Documentation example. Left image: description of the drawing elements. Right image: technical drawing of components (Source: IFMIF-DONES)

The number of parts and interfaces is related to the complexity of the task to be performed. It is recommended to simplify the maximum number of parts to handle during the RH operation. On the other hand, it is suggested that RH interfaces are compatible with RH Equipment. See chapter 4 for more information about these concepts.

▪ Operation:

Identifies the action required to perform the operation specified in the previous phase (Initiation). The information should specify step by step the tasks to perform, and if these actions are sequential or not. For that, it is recommended to have an identifier, and list them to show which task goes before or after. It is also important to indicate how the task will be carried out: the mode (that it is to say: manual, automatic or semi-automatic mode) and the time expected. Figure 3.9 details an example of task operation definition. It has relevant information about the task's specifications.

ID/name RH operation	1010. Beam Dump operation		
Operation	Cartridge replacement		
Type	Sequential		
No. Task	Task	Mode	Duration
1.0	Activate the lead shutter.	Remote actuation	5 min
..	...	...	...
7.0	Remove the cartridge	RH (manual)	120 min
8.0	Extract the container		

Figure 3.9 - Example of how to specify the tasks to complete the operation

Additionally, flowcharts complement this activity. They are a visual aid that facilitates the understanding of the tasks sequence and the search for inconsistencies in the process.

▪ RH Equipment and tools:

It is also necessary to specify the RH system for executing the remote operations. It demands information about the equipment and tools. For example, the identifier or name

of the equipment and tools, a description, status, among other descriptive characteristics. Figure 3.10 shows the information described.

This methodology can be implemented in facilities where RH operations have already been carried out previously. In these cases, the RH Equipment and tool could have been anteriorly purchased. If so, the status of the RH Systems has to be identified and determined (i.e., if it is available, broken, in a maintenance period, and so on). In the case of new RHS being required, it also has to be specified along with its status (e.g., if it is pending to design, under design, etc.). Other available technical documents could be useful to provide, for example, the datasheets, technical specification, acceptance test maintenance and operation manual, and additional relevant information.

ID/name RH operation	1010. Beam Dump operation					
Equipment	Description	Status	No. tools	Tools	Status	Technical documents
Overhead crane	Crane to transport heavy components	Pending to design	2	Tool 1 Tool 2	Pending to design	-
Robotic arm	Robot to perform dexterity operations	Pending to design	2	Gripper	Pending to	-

Figure 3.10 - Example of how to describe the equipment and tools for each task specified previously

- **Responsible and operators:**

The operator must meet certain requirements to perform RH tasks. Otherwise, all work done in the previous execution phases can be spoiled. If there are already operators working in the facility, they must be identified and registered with the following information: an identifier or name, experience, availability, skills. If there are not operators at this stage, the requirements have to be specified, indicating which ones are the most appropriate (skills, knowledge, experience).

3.4.3. Requirements

The requirements determine how the system will work and what characteristics it will have. The requirements definition requires knowledge of the conditions suggested by the different users. For this, the personnel involved (designers, engineers, architects, clients, etc.) must list the different requirements to define their needs formally. It provides the knowledge to establish a series of decisions that allow the organisation, rationalisation, compatibility and coherence of the different stages. There are different types of requirements, almost as many as there are elements involved in a project [87]. Albeit only the useful and dispensable requirements for project development will be specified.

Two basis requirements could be looked at: functional and non-functional. For example, a functional requirement specifies that the robot has to perform a welding task and non-functional requirement details that the robot should have an acceleration of 480 °/s in the final effect to perform the task. The requirements can start with a high descriptive

level and gradually become more detailed with requirements as more information becomes known [84]. There are tips and features to define requirements. For example, these have to be:

1. Unique. It can only be interpreted one way.
2. Specific. Two different requirements should not be mixed.
3. Clear, complete and well defined.
4. Viable (realistic and possible). It must be feasible under current restrictions on time, money and available resources.
5. Consistent and prioritised based on project objectives.
6. Necessary. A requirement is not necessary if none of the interested parties needs it or if its withdrawal has no effect.

The requirements listed will provide information about the different parts that make up the remote intervention such as the component's requirements, equipment, building and areas, maintenance, or others. Example of a part of the requirements list:

Crane requirements in a radiation environment:

- Transport contaminated components (meet with NUREG 0554),
- Transport heavy components (up 20 Ton),
- Self-recovery system, etc.

Robotic arm requirements:

- 6 Degrees of Freedom
- Load capacity of 20 kg.
- Force sensor to detect collisions, etc.

Component (Beam Dump) requirements:

- Design to be manipulated via RH (chapter 4),
- Electric connectors to be manipulated via RH (chapter 4),
- Positioning guides to place the cartridge, etc.

Once the requirements list has been obtained, it is subsequently recommended to use tools as the Requirements Traceability Matrix (RTM). It relates each project requirement to the deliverable or specification that satisfies it. The RTM requires several iterations and versions, from a simple relationship between requirements and specifications to a more complicated relationship [88], [89].

3.5. Design Phase

It is time to define in detail the elements and resources necessary to carry out the operation described in the previous phases. Figure 3.11 shows the three subphases of the design phase (operation tasks, RH system and simulation). The durability of these depends on whether the previous stages are in development. For example, the facilities

that are in the design phase have constant changes, as happened with the IFMIF-DONES accelerator project (2015-2020).

Figure 3.11 - Stages of the design phase

3.5.1. Operation tasks

This stage is made up of two steps. The first step is based on defining all the procedures/actions to implement remote operations. It should provide enough information to choose the equipment and tools correctly in the next step. The second step is the selection of the equipment, tools or accessories to carry out each task. This substage requires applying knowledge and ingenuity about the implementation of RH interventions in hazardous environments.

1. The operational procedures to perform the task:

This section determines the sequence of the tasks/actions needed to implement the RH operation completely, wherein the equipment and tools are linked for each task. The tasks should be listed as Figure 3.12 (or in a similar way), showing more detailed information.

ID/name RH operation	1010. Beam Dump operation						
Operation	Replace the cartridge						
Pre-conditions	<ul style="list-style-type: none"> - Beam off completed. - Tools available on the box tool station. - RH System is available and ready for operation. 						
No. task	Task	Description	Characteristics	Control Mode	Graphic model	RH System	Duration
...	...	...	...	...	...	...	...
7.2	Attach the cartridge	The crane has to ...	<ul style="list-style-type: none"> - Shield open - ... 	RH		Crane + grasping tool	15 min
7.3	Lift the cartridge	The crane has to ...	<ul style="list-style-type: none"> - The crane must hold 1500 kg in motion 	RH		Crane + grasping tool	5 min

Figure 3.12 – A detailed description of each task. It includes more specific information as characteristics, control mode, graphics, and so on

It is convenient to add other relevant information as a description, the control mode, characteristics (restrictions or physical parameters such as weight and torque), graphic models (photo, video, CAD models), type of equipment or tool required for each task and the duration time (the total time can be included at the end of the table). It is also useful to know the preconditions of the task (for example, if the accelerator is shut-down or if the shielding has been removed).

2. RHS: equipment, tools and accessories for each task

The equipment, tools or other accessories have been specified in more detail according to each task. It is important to consider the task characteristics to a proper selection. For that, it is suggested to include the information shown in Figure 3.13. It includes the RH systems along with specific details of the sensors, cameras and other necessary accessories. In addition to other descriptive characteristics that help to select or design the elements described (e.g., radiation-resistant, load capacity, etc.), and technical documents (if available).

No. task	Interface component	Equipment	Tools	Sensors	Camera	Other	Specific characteristics
7.2	Eye lifting shackle	Overhead crane with telescopic	Grasping tool	Proximity	CID8825D	-	Rad-hard components
...				...		...	...
7.4	Grip interface	Robotic arm	Gripper	Force sensor	CID8825D		Rad-hard

Figure 3.13 - The RH system needed to complete each task

3.5.2. Equipment and tools

The second substage of the design phase specifies separately, and in detail, each element of the RH system. Most of the time, multiple equipment or tools may be candidates for completing the task, so all solutions must be carefully considered. If there are several options, the following guidelines should be followed:

1. Summary description of each alternative.
2. List of the aspects that must be met by each alternative.
3. For each alternative, a summary of the reasons for being accepted (pros) or rejected (cons) as a possible solution.
4. Evaluation of each alternative.
5. Selection.

The equipment and tools selected have to be described, as shown in Figure 3.14. It specifies the main characteristics (i.e., dynamics and kinematics), design, status and price. Other useful information can also be included, providing or acquiring detailed data such as commercial catalogues. Concerning the status of the equipment and tools, it can be dissimilar in the function of each situation (facility, project phase, etc.). The status of the RH systems may vary depending on the following cases:

- It has already been acquired, and they are available for use.
- It has already been acquired but needs modifications (adapt or redesign).

- It has not been purchased and a) is available on the market, b) exists in the market but require modifications, c) it does not exist on the market and must be custom designed.

ID/name operation	1010. Beam Dump operation				
Operation	Replace the cartridge				
Equipment	Characteristics	Design	Cost	Status	Technical documents
Overhead crane	<ul style="list-style-type: none"> - 16 Ton Load Capacity - Span of 30 m - ...		50k€	Under design	/directory path
Tools					
Grasping tool	<ul style="list-style-type: none"> - 4 grasp points - Stainless steel material - Twistlock interfaces - ...		5k€	Under design	/directory path
Robotic gripper	<ul style="list-style-type: none"> - 85 mm aperture - Grasp force 130 N - Adaptive grip		5k€	Available to buy	/directory path

Figure 3.14 - Detailed description of the equipment, tools and other devices need to complete the RH operation

In the case of modifying and design some RH Equipment and tools, it is recommended to follow design guidelines that allow improving the aspects of manufacturing and assembly, respecting the essential requirements and functions of the product. The guidelines advise on structuring and design, reducing costs and manufacturing difficulties. For example, there are adequate books and guides such as engineering design concepts and recommendations [86], Design for Manufacturing and Assembly (DFMA) [90], assembly automation and product design [91], design of service robots [81]. Depending on the product and objectives, the most appropriate design and manufacturing process guide will be selected for each case. Nevertheless, it is suggested to follow the design recommendation to make them suitable for RH operations (see chapter 4).

3.5.2.1. RH control system

To perform RH operations in hazardous environments, master control devices for the operator have to be considered to achieve adequate remote control and communications with the remote equipment. Figure 3.15 exemplifies how to capture this information, where it is necessary to specify the control and feedback devices that the operators will use, in addition to their communication mode.

Equipment	Additional equipment	Control devices	No. Senses feedback	Feedback devices	Communication	Specific characteristics	Technical document
Overhead crane (ABUS)	Camera CID8825D	Control panel	0	- Display	Cable	-	/directory path
Robotic Arm	Camera CID8825D	Phantom devices	2 (visual and haptic)	- Display - Phantom	Cable MODBUS	-	/directory path

Figure 3.15 - Information related to the RH control system

3.5.3. Simulation analysis

Simulation is the process of designing a model of a real system, as shown in Figure 3.16. Simulation and VR systems can facilitate the preparation of ad-hoc mechatronic tools and robotic interventions, including the recovery scenarios and failure mode analysis [11]. It allows for analysis, evaluation and verification of the behaviour of the system or new strategies within limits imposed [92]. Thereby, the simulation validates the hypotheses established during the previous stages and checks the operations defined with the system (robots, cranes, tools) in the defined environment.

Figure 3.16 - Simulation of a real environment at CERN. It allows analysing the viability of remote tasks (Source: CERN)

Simulators have three distinctive characteristics: 1) it imitates reality, 2) it is not real in itself, that is, it is a simplification of real life, and 3) it can be modified. The simulation also gives us the following advantages:

- Possibility to experience the RH System without the need for physical construction. It avoids damage and extra costs.
- Experiencing a new unknown situation and better anticipating unforeseen results.
- Study and observe the effect of different variables and changes in the system.

- Simulate complex systems to understand the system operation and area better. It is useful to suggest strategies that improve the operation and efficiency of the system.

Figure 3.17 shows the sequence of five steps (at a high level) to complete the simulation from beginning to the end. Sometimes an iterative process is required with the previous subphases until obtaining the correct combination. It has to be done until the correct and safe planning of the RH intervention is achieved because it is crucial to execute the next phases. Figure 3.18 illustrates an example of an iterative sequence when the simulation has to be validated, and the risk analysis is performed.

Figure 3.17 - Simulation steps to analyse and validate the defined RH operations. It is an iterative process that ends when valid results are achieved

Figure 3.18 - Example of a flowchart to validate the simulations

In nuclear plants and other hazardous environments, it is mandatory to do several studies in the simulations, such as: analyse the available space in the environment, kinematic and dynamic studies, human radiation absorption, risk analysis, most efficient route calculation, etc. The simulation behaviour has to be as real as possible, achieving a high level of fidelity to be acceptable for the study required. Regarding simulators, the number of simulation tools has increased in recent years, along with computing capabilities. The selection of the most appropriate simulator depends on the needs and characteristics of each system. For example, there are several simulators and tools to recreate RH robotic operations: Gazebo, Blender, V-REP, Webots, Delmia, etc. Some of them can be

combined with ROS for robotic functionalities or use physical motors. Other 3D modelling software as Autodesk Inventor, also includes the possibility of simulating, both kinematics and dynamics. For example, CERN uses the Virtual Environment for intelligent Robotics Operations (VERO) module. It creates a virtual environment for simulation using Unity. It is used for the design of the robotic procedures, tools and recovery scenarios [11].

Virtual Reality can be combined with the simulation to produce an immersive environment. The user can use different systems to replace real-world sensations. For example: the use of the headset, audio phones or devices with tactile feedback. It is also used in other radiation environments as Tokamaks, JET and CERN [11], [93], [94]. It is beneficial for design robotic operations and also for training. The realism has increased in VR. Nowadays, it is possible to add real picture features as textures of the virtual environment [95]. It helps to decrease the fatigue and stress using the VR.

3.6. Construction phase

The purpose of the development phase is the construction and integration of all the components that make up the RHS. Three main stages are considered for the development phase (see Figure 3.19):

- Logistics for the equipment and material acquisition.
- Hardware and software integration
 - Planning and design the software to implement.
 - Software development.
 - Integration of hardware and software components.
 - Testing and validation.
- Validation and testing of the RH System.

Figure 3.19 - Stages of the definition phase

In some projects or installations that already have the equipment or tools, some steps can be omitted or reduced. For example, the acquisition may be omitted, although logistic considerations could be required to have the RH System available. For the software/hardware integration, sometimes it is necessary to implement software improvements for the available equipment and tools. It adjusts them to the new tasks, and the validation tests of the RHS are always recommended before carrying out the final operation.

3.6.1. Logistics and acquisition

The equipment and tools selected in the previous phases have to be purchased/acquired. It requires planning time and takes into account specific steps as those specified below:

1. Analyse the needs, specifications and requirements of the requested hardware and software. (i.e. flexibility of adaptation, operating time, security, support, etc.)
2. Identify suppliers.
3. Analyse and study the feasibility acquisition.
4. Negotiate with suppliers.
5. Payment and acquisition of the requested hardware and software.

The acquisition of hardware and software components requires a logistics plan that takes into account various issues related to custom designs, vendor limitations, resource availability and integration plans, costs, etc. All these factors determine the critical routes for the development of the project, which must be identified to avoid delays. Robotic tools are a basic example of components that may require a custom design, wherein specific planning must be done to guarantee its availability in the defined time. The logistics plan can be described in a Gantt chart or similar. This plan must be periodically verified until its final acquisition, and certain actions must be taken in the event of significant deviations. Figure 3.20 shows a basic table to track the product. It contains the main information that must be known by the personnel involved in the project.

Product	Commercial availability	Company (supplier)	Acquisition time	Price	Status	Viability
Overhead crane	Yes	ABUS	3 months	50k€	Under negotiation	Yes
Gripper 2F-85	Yes	Robotics	1 month			

Figure 3.20 - Example of how to define the acquisition status of the products

3.6.2. Hardware/Software integration

The equipment, tools and accessories need to get ready for the RH operation. These steps are mandatory for the new acquisitions and the RH System that needs modifications. Three main tasks are recommended: 1) installation and/or assembly, 2) software and hardware integration, and 3) RH validation and test.

3.6.2.1. RH System installation and assembly

The equipment can require installation and assembly operations. It depends on the type of equipment and mobility. The overhead cranes need an installation in the work area when they are acquired, but other cranes are mobile and do not need to perform any

installation. The robots can be mobile, but others need a fast installation on a surface. Thus, two types of RH System can be distinguished depending on the mobility:

- Non-mobile equipment. It requires to be mounted and installed in a place (i.e., real environment, mock-up, laboratory). This installation process could demand delicate tasks for a radiation environment such as weld, screw or cut elements.
- Mobile equipment. It does not need to be installed in a specific place. These are capable of being inserted and removed without prior installation.

However, custom equipment normally needs installation and assembly operations. For example, when a commercial robot is purchased and improvements must be implemented by adding additional accessories. It is important to remember that assembly and installation procedures need to meet with the rules and regulations of the facility and country.

3.6.2.2. Software and hardware integration

The RH System is composed of hardware (processors, drivers, microcontrollers, etc.) and software (operating system, applications, firmware). The RH Equipment and accessories need to be configured and tuned-up by specialised staff (analysts, programmers, operators, etc.). The hardware and software integration stage includes various steps to accomplish with the defined functionalities of the RH System. These can be shown in the flowchart of Figure 3.21.

Figure 3.21 - Generic high-level sequence to integrate the software and hardware with the functionalities defined (It can be an iterative process)

The first step is to implement and develop the software according to the specified tasks. The software can implement several RH functionalities, such as move the robot to a defined position, develop bilateral control, detect the obstacles, automatically recognise risks, etc [11], [96]–[98]. When the software is ready, this must be integrated with the equipment hardware, and after that testing and verification must demonstrate a correct and robust implementation.

Figure 3.21 represents a generic sequence phase due to the wide variety of methodologies for the software development process. These methodologies divide the work

into distinct phases to improve the design, product management, and project management. There are different software engineering methodologies: agile, waterfall, spiral, and others as V-model (improvement of waterfall methodology) [99], [100]. Each one has different procedures and advantages, and it must be chosen depending on the type of project.

3.6.3. RH Validation and test

The validation and tests are, in some cases, the continuation of the verifications carried out during the integration phase. Moreover, all defined robotic functionalities have to be carried out and tested by using the defined tools. It is required to define a set of tests to evaluate the performance of RH System under different conditions of the installation. This step will provide a final version of the documentation related to the operation of the Remote Handling Systems and include guidelines for operator training. These tests can be performed in different types of environments. It will depend on the project conditions.

- Mock-up. The equipment or other operation elements are validated in a similar environment to the real one. It occurs in situations where it is not possible to enter the environment. It normally occurs in hazardous environments such as when the accelerator is on, and the radiation is too high to test.
- Real environment. Sometimes, the equipment can be installed and tested in the real environment. However, this is possible under certain conditions. For example, when there are no dangerous elements or there is not a hazardous environment condition (low/high-pressure level, ionising radiation, electromagnetic fields, etc.).
- External environment. The RH operations are validated in other places such as laboratories or outdoors. It is possible when tasks can be recreated and validated regardless of the scenario. For example, when a robotic arm performs an operation that requires loosen bolts and nuts.

Figure 3.22 - Nuclear Fusion Tokamak mock-up from JET

Figure 3.22 shows the tokamak mock-up used in JET. The reactor has installed the robotic arms to carry out the tests without risks.

3.7. Operation phase

The operation phase is carried out once the previous phases are completed. Figure 3.23 presents the different stages needed after and before performing the RH operation. The RH operation will be done when everything is ready to be finally executed.

Figure 3.23 - Stages of the operation phase

3.7.1. Operator training

Operator training and experience is fundamental for achieving satisfactory RH interventions. The training gives the operator security and knowledge of the remote area. Thus, the operator can understand the process of the task better and act more safely [101]. Training has multiple advantages:

- Become familiar with the RH control and remote working space.
- Increase operators' ability and skills, as much as the reaction capacity and agility.
- Optimisation of the actions of the task, minimising the operation time.
- Minimise the operation time. Additionally, it reduces the equipment exposition to radiation environments.

The operator's training sessions can be done in mock-up, real environments, virtual environments or others. It is highly recommended to train in scenarios as similar to the

real ones as possible, as long as they are safe. Most of the irradiated facilities have mock-ups to allow operator training. However, sometimes the training is done or complemented with VR reality applications [11], which can reproduce the RH maintenance operations and simulate special conditions. VR is advantageous to provide the necessary skills and operation knowledge in a safe way and cost-effective option [101]. Operators can practice with a simulated robot as a preparation for the real intervention.

3.7.2. Operation preparation (pre-operation)

Before the execution of the RH intervention, preparations must be made. It includes logistic operation, area configuration and equipment set-up. Examples of the activities to perform are:

- Availability: check if all the RH elements for the RH intervention are available and ready.
- Un/packing: some elements may need to be packed for transportation, and others may require special packing.
- Transportation: transport material and equipment until the work area.
- Protection: special protection has to be considered for susceptible or weak elements. Especially these that can be damaged and contaminated.
- Installation and tuning: some equipment has to be prepared or set-up. For example, plug in the equipment connectors, protect the equipment, install cameras, etc.
- Area configuration: technical personnel can prepare the work area (depending on the environment conditions). The preparation operations can include: loosening screws or removing the bolts of a component covered with shielding, open-drain valves, activating the lead shutter mechanism to isolate the accelerator beamline, etc.
- Test: the RH System must be previously tested to verify its functionality.

These are highly dependent on the RH operation features and location. For example, 1) if the equipment and personnel cannot be accessed to the work area, 2) if the facility has special rooms for the equipment, 3) if the robot is mobile or non-mobile, etc.

3.7.3. Operation execution

Once the previous stages have been completed, and everything is ready for execution, the RH operation will be running on the stipulated date and time. The expert operator carries out the task until it is successfully finalised, considering the pre-established sequence actions.

Figure 3.24 - RH operations at CERN. Left: Robots in operation dismounting a Beam Dump water disconnection [55]. Right: operator controlling the master-slave bilateral system

The operator performs and supervises the operation in a safe place, where the radiation and other hazardous factors are not. Some facilities have a control room to manage all the RH control system. However, other facilities or scenarios do not have a control room. In these cases, the remote control is performed in a mobile or makeshift control area. Normally, near the work area but safe enough for operators.

Figure 3.25 - RH inspection task at CERN [55]

Figure 3.24 and Figure 3.25 show a real scenario on the particle accelerator at CERN, where the operator is manipulating a mobile robotic arm. Figure 3.24 shows as the robotic arm is doing a skill task. In some cases, additional tasks are to carry out to finalise the RH intervention. For example, when the High Flux Test Module (HFTM) is RH replaced in IFMIF-DONES, the crane has to place the shielding plugs to isolate the Test Cell (TC). The same happens with other components, which have to be cleaned and decontaminated after being replaced. In other cases, acceptance tests have to be done before concluding the RH operation. That is, tests to validate the functioning of the new components. Therefore, the RH task ends when all the operations to be performed via RH have been concluded.

3.7.3.1. Types of tasks in a radiation environment

The accelerator and other nuclear facilities demand a wide variety of RH operations (see Figure 3.26). Examples of these activities are un/screw, drilling, assembly, dismantling, lift heavy loads, cleaning, grasping and handling, transport elements, vision and inspection, radiation measurement, recovery and rescue.

Figure 3.26 - Telerobotics operations with different tools: screwdriver (left, source: weber-online.com), ultrasonic cutting (medium, source: robotics.org), grasping, handling and transport a piece with a robotic gripper (right, source: CERN)

Cutting and welding are also done, but these tasks demand special conditions to guarantee safe operation in a radiation environment. These can produce contaminated dust, and this has to be cleaned to avoid spreading it. In addition to this, it is recommended collect environment data in parallel. For example, take photos, videos or data measurements of sensors.

3.7.3.2. Operation mode

The robot can actuate under remote control, semi-autonomously or autonomously. The autonomy degree depends on several factors, as was mentioned in subsection 2.1. Teleoperation continues to be preferable for nuclear or radiation facilities. The differences between control modes are:

- Remote control (telemanipulation): the operator controls the robots or other equipment manually in a remote way.
- Semi-autonomous: the operator controls the robots, but they are also programmed to have some specific tasks.
- Autonomous: the robots perform the task by themselves since they are programmed to perform specific tasks.

3.7.3.3. Operation scheduling

The RH interventions can be of two types: scheduled or unscheduled operations. Scheduled operations have enough time to be prepared, and so achieve the best results.

Conversely, unplanned or unexpected tasks in radiation facilities can be a challenge because these have a limited time to be prepared, and in some cases, limited resources.

3.7.4. Post-operation

To conclude with the RH tasks, some activities could be requested. These are not trivial when there are contaminated elements. A radiological team has to evaluate the situation, and depending on that, there will be distinct procedures. The following paragraphs expose relevant activities to take into consideration:

- Radiation evaluation: the environment and components should be previously evaluated to know the radiation levels and remaining contamination. If not, the radiological team can measure the radiation levels and stipulate the special treatment.
- Disassemble and uninstall the work station: disassembling and uninstalling operations can be required due to equipment fails, extraction of non-fix equipment, final dismantling, etc. Depending on the environmental conditions, there are three options: a) RH operations, b) wait until the radiation levels decay, or c) contaminated elements are removed.
- Package: some elements are extracted from the radiation area, and others transported to another place. These elements can be packaged for transportation. The problem is when these are contaminated. In this case, the package will be special, complying with the radiological rules. For example, use a cask or containers to be safely transported [102].
- Transport: the transport can be done by different equipment (trucks, cars, conveyor belts, cranes, forklift, lifts, etc.). However, transport can require different specifications and conditions depending on the element contamination:
 - Contaminated elements: these have to be protected or isolated. These require special transport considerations to be cleaned or removed. These must always comply with safe and strict regulations and protocols, which will depend on the country [103].
 - No contaminated elements: the transport is done without special requirements. The elements transported will be stored or discarded.
- Acceptance test: tests to verify the performance of the facility components. Recommended before starts the plant/facility operation or start-up the system.

Normally, different work teams can be involved in the cited considerations (e.g., radioprotection, Remote Handling and logistics teams).

3.8. Final phase

A final evaluation is advisable at the end of the RH operation life cycle. As Figure 3.27 represents, the first step is to make an analysis report and then actuate according to the analysis done. It prepares the RH System for the next RH interventions.

Figure 3.27 - Stages of the final phase

3.8.1. Operation report

The RH intervention should be reported and analysed after finishing the intervention. It is mandatory to evaluate task performance and results. It is useful to determine possible breakdowns, weak points and efficiency. This evaluation can help to make decisions about potential improvements and modification of the RH System and future RH operations.

3.8.2. RH System preparation

It involves the actions to prepare the personnel and RH System for the next RH intervention. These depend on the report prepared previously. For example: repairing equipment, replacing damaged parts, hiring new personnel, investigating new techniques for remote manipulation, etc.

3.9. RH Intervention Request

The facilities where RH interventions have been carried out previously, and they have RHS and work teams, the “Robotic Intervention Request” can be done to speed up the initial phases of the methodology. It summarises some of the previously defined phases (initiation, definition and design), concentrating the most relevant information. In case of requiring more detailed information, it can be specified as described in the subsections 3.3, 3.4 and 3.5. The robotic Intervention request can be a first approximation between the requestors and those responsible for the RH interventions. Table 3.2 shows an example of how to concentrate and summarized this information.

Table 3.2 - Example of RH intervention request for facilities that previously had to perform RH interventions

Requestor	Accelerator Team. #Requestor 1
Description	The request consists of remote support for the maintenance to the ATLAS detector. The mobile robot has to provide visual support using multiple cameras and VR support for feasibility studies.
Requirements	Live stream from the cameras and VR simulation.
Robots (hardware checklist)	CERNbot
Material checklist	Cameras, VR glasses and Personal Computer (PC) controller
Software checklist	Cameras Graphical User Interface (GUI) and VR GUI
Procedure	Insert the robot, move the robot until the ATLAS detector and provide visual support
Impact	NONE
Location	ATLAS
Main responsible	#Responsible 1
Second responsible	#Responsible 2
Operators	#Operator 1 and 2
Intervention supervisor	#Supervisor 2

This RH intervention request also serves as a final report to record the interventions carried out. Although, it is also necessary to notify the problems occurred or the improvements to be made.

Chapter 4

Basic design guidelines for RH operations in the accelerators

This chapter presents basic recommendations and general guidelines for RH on accelerators. It suggests how the accelerator components, building areas, equipment and tools have to be to achieve easy and safe RH operations. This chapter also includes an analysis and comparison between tools and elements (e.g., electric connectors, flanges, etc.) in order to determine which is the most suitable for RH. The guidelines are in base on the experience and other reference sources available, such as the well-known ITER Remote Handling Code of Practice [104].

4.1. Introduction

Access to hazardous areas is not allowed when it compromises the health of the workers (for example when the radiation doses exceed the established limits or personnel protection systems are insufficient). Under these situations, RH operations (maintenance, rescue and recovery, inspections, etc.) are required for components and equipment of accelerators. RH Equipment (crane, servo manipulator, mobile robot) has to perform this sort of tasks. The problem is that RH Equipment, like robots, do not have the same ability as a human. The robots usually need more time to complete tasks without human assistance. It depends on the equipment characteristics, but it is also related to the facility design. Three recommendations must be carried out in order to minimise the operation time and facilitate the RH tasks in hazardous environments:

1. The design of the facility (rooms, components or modules) must allow easy and secure RH operations.
2. RH Systems must be suitable for RH operations. For example, equipment and tools with good manoeuvrability and dexterity for accuracy task. These characteristics depend on several factors, such as environmental conditions, activities, budget, and so on.
3. The work environment must be adequate for RH operations. For example, enough space to access the accelerator components with the robot or cranes.

The problem with some radiation facilities is that they did not take into account the necessary design requirements to perform RH operations. This fact increases the complexity of future RH implementation. So, whenever possible and feasible, design considerations for the RH activities should be considered from the beginning of the facility design. It will avoid subsequent design modifications, which are sometimes costly or even unfeasible. A well-known example is the fusion reactor of JET. RH was not considered at the beginning of the project, causing a significant impact on RH tasks and teams [105]. For this fact, the RH requirements were considered during the future design processes of JET. The importance of proper components design has been confirmed and determined in JET [105] and other nuclear facilities [106]–[108]. Some of the advantages of adapting the design to RH operations are [109]:

- An increase in the availability of the facility. It reduces the maintenance periods.
- A reduction of operative, upgrading and training costs.
- A decrease of human occupational exposures.
- An increment of installation flexibility.

This strategy is being applied across multiple facilities. A good example in this regard is a methodology based on the development of codes of practice for an adequate design of

the components, implemented especially for ITER [104]. In the case of the accelerator facilities, CERN and IFMIF-DONES are applying solutions to facilitate the RH operations. CERN is developing a code of practice document, named CERN Remote Handling Code Of Practice (CERNRHCOP) [11]. It is a basic document for the Intervention in Highly Activated Area of Hi-Lumi LHC (ITHACA). Part of the internship of this thesis was dedicated to collaborating in CERNRHCOP.

4.1.1. Goals

This chapter shows basic guidelines to implement a suitable design of particle accelerators, especially for those that require RH operations due to harsh environmental conditions. It has been elaborated by considering information provided in other manuscripts (see subsection 4.1.2), researching information in this field and based on the experience gained at CERN and IFMIF-DONES accelerators.

The basic guidelines include general recommendations and concepts to be applied to the components or equipment of the facility, considerations such as standardisation, modularity, simplicity, among others that are presented in subsection 4.2. The chapter also focuses on more particular components and tools, providing suggestions on the component's elements as connectors, fasteners, flanges and so on. The guidelines aim to achieve secure, reliable and easy RH operations. It pretends to simplify and speed up the execution of RH tasks and minimise the exposure time of the remote equipment in a harmful environment. Additionally, it also aims to reduce the requirements of the equipment and prolong its durability.

Nevertheless, it is important to find a reasonable balance between the application of the guidelines, along with other installation requirements, such as costs, maintenance periods, availability, etc.

4.1.2. Related work

Some documents from written in the past provide guidelines for the design of remotely maintained components or equipment. The guidelines and recommendations presented have been developed by reviewing some relevant manuscripts:

- ITER Remote Handling Code of Practice [104].
- ‘Design Guides for Radioactive Material Handling Facilities and Equipment’ [108].
- ‘Design Guidelines for Remotely Maintained Equipment’ [107].
- ‘Remote maintenance design guide for compact processing units’ [110].
- ‘Designing equipment for use in gamma radiation environments’ [111].
- ‘A perspective on fusion relevant remote handling techniques’ [106].
- ‘Remote handling on fusion experiments’ [112].

- ‘Development of Key Fusion Technologies at JET’ [113], and many other publications and information from the JET experience [53], [114].
- ‘International Fusion Materials Irradiation Facility: Preliminary Remote Handling Handbook for IFMIF Facility’ [105].
- ‘Basic guidelines for the design of remotely maintained components in the Test Facilities of IFMIF’ [109].
- ‘A novel robotic framework for safe inspection and telemanipulation in hazardous and unstructured environments’ [11].

This chapter covers basic considerations and concepts related to the design of the accelerator components, equipment and building. Design rules (safety, environmental impact, mechanical and electrical calculations, licensing, etc.) are out of the scope of this work. Still, they must always be followed or applied depending on each country or project.

4.2. General and basic design guidelines

Accelerator facilities with high radiation levels should follow and apply design guidelines, given that RH is usually carried out during the facility lifetime and decommissioning. The building areas, equipment or accelerator components need to be defined in concordance, considering some recommendations to facilitate the RH operations and satisfy the RH needs. The proposals in this section involve issues related to properties as accessibility, modularity, standardisation, among other considerations presented in Table 4.1 and Table 4.2. These tables show a summary of the features and topics to consider during the design phase.

Table 4.1 - Summary of relevant characteristics to consider for the design of accelerator components, building and equipment

Properties	Definition
Modularity	Modularity aims to divide the accelerator into smaller parts, that is, into separate modules. It facilitates fault diagnosis and makes it more manageable in terms of weight and volume. Modularity should be applied whenever it is possible, but without compromising the safety of the installation.
Accessibility	The accessibility criterion recommends geometric and visual access. It involves avoiding obstacles to the components to prevent collisions or low vision during operations.
Simplicity	Simplicity encourages the use of simple and reliable elements. The compatibility between RH Equipment and components must be respected, and it is preferable to avoid radiation-sensitive parts in designs.

Standardization	The elements and equipment used should be standard, or at least try to meet the standards as much as possible. It avoids high cost due to the availability, and the characteristics are well-known since these are registered and defined.
High reliability	Systems have to have high reliability to avoid failure. For this, quality and safety are essential. It is recommended to follow the established standards, perform maintenance, work in the right conditions, among other measures.
Easy decontamination	Components or equipment can require decontamination. It is suggested to use easy to decontaminate surfaces and shrouds, or removable coatings.
Radiation resistance or hardening	The accelerator components and equipment must bear certain levels of radiation. If not, whenever possible, protection strategies should be applied, such as protecting elements with local shielding or locating sensitive elements outside the danger zone.
Replaceability	The components/elements most likely to be replaced must allow a quick and straightforward replacement through the use of RH Systems.

Table 4.2 - Summary of important topics to consider for the RH operations

Other considerations	Definition
Labelling	Labelling is recommended because it helps to differentiate something characteristic of the component. For example, the insertion/extraction position, the type of elements (electrical and hydraulic connectors), and so on. Labelling should be permanent and completely visible.
Positioning aids	These systems guide during the positioning or removal operation of various components or elements. An example is the pins and holes of the male and female electrical connectors.
Viewing and illumination	An adequate visualization and lighting system is essential to carry out remote operations. The vision largely determines the success of the operation, as it is one of the primary sources of operator information.
Enough diagnostics	Diagnostics allow detecting faults in the system. For this reason, the number of diagnoses must be sufficient for fast, reliable and specific fault detection.
Material	Correct selection of the materials prolongs the life of components and equipment. It highly depends on the environmental conditions and the time of use.
Storage	Storage zones are required in some accelerator areas. This space has to take into account the facility requirements.
Recovery and rescue	The RH Equipment located on restricted or prohibited areas for the humans must be able to be recovery and rescue by other equipment or by it-self.
Adequacy for the RH Equipment	The accelerator components and building have to have an adequate design to guarantee the correct integration and operation of the RH Equipment. In turn, the RH Equipment has to be appropriate to actuate in these harsh environments.
Electronics devices	Electronic devices are sensitive under a radiation environment. The correct selection of device or the mitigation strategies applied can extend the durability of the equipment and components with electronic devices.

4.2.1. Modularity

Modularity is based on dividing a system into smaller parts, forming subsystems. It is advisable because usually it simplifies or reduces the operations to perform. The design and characteristics of the module play an important role. For example, a lighter and small module is preferable to be transported with the crane than a full component or system. Figure 4.1 illustrates a real example of a modularized system on the DONES accelerator.

Figure 4.1 - Example of modular components in DONES accelerator

Various design recommendations for modules are listed below, wherein the iteration process between the modules and equipment has been emphasised.

- The module must be designed to be correctly manipulated with the RH Equipment. For that, consider module properties (weight, volume, etc.) and the characteristics of the equipment or tools (load capability, weight, precision, etc.).
- Modules must have proper RH interfaces, which must be in tune with the capabilities of the RHS. It is advantageous because it facilitates the operation between the module and the RH Equipment, and additionally can help to decrease the execution time.
- Elements with similar lifetime are preferable for the design of the modules.
- The module should be designed using standard elements to avoid the need to use special tools (whenever possible).
- The interfaces of the module must be accessible for the RH Equipment.
- Mark and label the modules and their elements (e.g., connectors). It allows clear identification and avoids confusion.
- The module must be correctly oriented and visible during the RH operation.

- The module maintenance has to meet with the maintenance periods and the accelerator operating availability.
- Consider beforehand the order of components/elements removal (electrical connectors, pipe disconnect) surrounding the module.
- Try to avoid obstruction between modules and the rest of the accelerator elements.
- Consider the transport path and storage places of the module.

Modularised design reduces maintenance time and saves costs. The different advantages and reasons are exposed in the following paragraphs:

- The modules have less weight and dimensions than an entire system. It facilitates and streamlines the transport operation. Moreover, it reduces the requirements of the RH Equipment (e.g., the load capacity).
- Modularisation allows to extract the module and replace this with a new one. Thereby, there is no need to spend time repairing a fault (if not necessary).
- The module can be replaced or repaired without the need to remove other parts of the accelerator.
- Modularisation makes it easier to diagnose and remedy failures.
- Repairs are easier and faster. It helps to reduce costs, the number of maintenance tasks and their complexity.
- Modularity reduces the inventory of spare parts and contributes to the possibility of standardisation in the installation.
- The configuration in modules facilitates the improvements on the accelerator (flexibility and adaptation). Whenever necessary, these could be replaced by improved modules and new technology.

4.2.2. Accessibility

Accessibility is a key factor for RH operations because it is related to the results and execution time. Good accessibility must include enough space and enough visibility. Space can facilitate RH procedures since the RH Equipment can reach the components or modules faster, and in turn, finish the task earlier. The visibility is also relevant, being that the visual sense is needed for the operator when performing RH operations in hazard environments.

Avoiding obstacles and interferences is essential to achieve good results. In this way, designers of accelerator facilities must ensure correct spatial and visual access to the critical components. Accessibility recommendations for the accelerator areas have been summarized below:

- Foresee and provide enough space and visibility at the operations areas.
 - Consider the space that RHs need to carry out the RH operation. For example, space for disassembling or disconnect the connectors.
 - Provide good visibility of the workspace, especially in the area where the RH operations are required. Preferable from several points of view (see Figure 4.2), either through cameras, windows or periscopes.

Figure 4.2 - Cameras from different points of view [11]. Different perspectives make easy a remote operation with robotic arms

- Foresee and provide enough space for:
 - RH Equipment mobility (manipulators, cranes, articulated arm or boom). For example, an accessible path between the equipment storage zone and the work area.
 - Components or modules. For example, cold and hot paths to transport the non-contaminated and contaminated parts.
 - RH Equipment maintenance. For instance, space for repairing or checking the equipment.
 - Recovery and rescue operations in the accelerator areas.

Figure 4.3 clarifies the differences between a workspace with accessibility and without. The example on the right shows how it would be impossible to execute a remote maintenance operation with the robotic arm. The RHS does not have spatial either visual access.

Figure 4.3 - Example of good and bad practices about the accessibility designs

Design practices to increase accessibility:

- Avoid obstructions or interferences to reach the components. It is recommended to evaluate it in a simulated environment.
- The interfaces of the components (magnetic surface, eye lifting bolt, and so on) must be in an accessible position for the RH Equipment (preferable from multiple locations).
- Accelerator systems, components or modules should be designed or selected to cause the minimum environment disturbance.
- Accelerator components design must consider the available space on the accelerator areas.
- The marks and labels must be visible to vision systems (cameras), periscopes or windows.
- The equipment or accelerator components colours must be discernible from the environment area. Remember that the colours in high radiation environments tend to fade.
- Component interfaces must be easily visible with the available or selected vision means.

4.2.3. Simplicity

Simplicity is essential to increase the availability, reduce the cost and facilitate the maintenance of the facility. Simplicity is the result of product reduction and the elimination of non-value-added tasks. In this way, the RH maintenance or replacement

of accelerator components should be as simple as possible. The following lines propose recommendations to consider:

- The number of accelerator elements should be reduced as much as possible. For example, try to avoid (unnecessary) redundant RH interfaces.
- Use few, well-verified and straightforward elements.
- A simple, reliable and easy mechanism is preferable to a complex element.
- Whenever possible, simplify the cable lines with multiplexor.
- Locate sensitive components such as the electronic devices outside of the radiation area or in places where the level of radiation is smaller. It simplifies the complexity and requirements of electronic devices.
- Try to use natural law (i.e., gravity) to transport, assembling or disassembling process.
- Minimise the number of RH tasks. Avoiding unnecessary or redundant operations but guarantees the safety and success of the complete process.

4.2.4. Standardization

Standardisation creates common codes or standards. It has two main aspects: 1) it makes the best practice available to everyone, thereby ensuring efficiency and safety, and 2) it promotes interchangeability and compatibility [86]. Standardisation reduces or eliminates unique and little used custom components and processes, which can lead to additional costs and quality problems. It also avoids high cost due to errors or lack of information since the characteristics are well registered and defined. In this way, the use of standards elements increases the availability, assurance of a level of quality, security, robustness and reliability of components. Additionally, it reduces the design and construction costs of a custom system and minimises spare parts inventories and fixtures. The accelerator elements and RHS should be standard or compatible with the others. General standardization guidelines for the designers include the following recommendations:

- Use standard design solutions, wherever possible in preference to creating new solutions.
- Commercially purchased components and eventually modified are preferred to specially designed and fabricated components.
- Limit and reduce the number of different sizes for the same type of component or fixture.
- Use the same component and process in different applications at the facility.

- Limit the number of different types of commercially purchased components for a remote handling environment.
- Limit and reduce the number of different methods and processes in the facility.

On the other hand, standardisation also minimises the requirements for special remote equipment and tooling. For example, the same robotic gripper could be used to handle similar element sizes.

4.2.5. High reliability

Reliability is a measure of the capability of a system to operate without failure [86]. The design of the systems must preclude errors and accidents. In the accelerator facilities, the accelerator components and RHS must be highly reliable due to the environmental conditions and the availability requirements of the plant. The fails or malfunction can delay the accelerator operation and maintenance, producing extra cost. In such a manner, facility systems must be highly reliable in design. Design practices and recommendations for high reliability are proposed below:

- Use redundant elements on sensitive radiation devices. For example, a redundant system of electric drives, electronics, lifting crane devices, etc.
- Practise careful design. Use commercial components or well-proved concepts.
- Establish the working conditions somewhat below the nominal values of the component. For example, limit the power of the motor to some secure value.
- The load capacity of the RH Equipment must have a safety margin of 10%-15%. It is defined based on the weight of the components to be lifted by the equipment.
- Supervise and monitor the working conditions of the components/elements, which have a significant probability of failure. For example, monitoring the temperature of critical motors.
- Carry out periodic maintenance, tests and inspections.
- Critical components or RH Equipment with a significant probability of deterioration or failure need preventive and periodic maintenance.
- Perform extensive tests to know the degree of component reliability before final assembly.

4.2.6. Decontamination

Decontamination refers to the process of cleaning radioactive material. This process diminishes the radiation exposures, facilitates the waste management and the reuse of components. The decontamination is demanded during the decommissioning, but also it can be required when the accelerator facility is operational. For example, after a RH

intervention where a mobile robot can become contaminated. Adequate design and material for decontamination can reduce the costs and decontamination maintenance time. The design requirements may vary according to the components and facility conditions. The following paragraphs show a series of recommendations and design practices to ease decontamination:

- Smooth or polished surfaces are favourable to decontaminate. For example, electro-polishing is fast, inexpensive and effective for complex structures.
- Try to avoid holes, deep grooves, discontinuous welds, cracks, crevices, porous materials and joints that trap dust.
- Apply coatings or liners on porous materials, such as concrete.
- The component cleaning should be greater when the probability and degree of contamination are higher.
- Avoid plastic material. It is not suitable for radiation nor the decontamination process.
- Provide protective covering for sensitive material or components, preferably if the covering can be readily removed.
- Install shrouds in components that are complicated to decontaminate. Example of these components: bearing, connectors, wheel, etc.

Figure 4.4 shows examples of the decontamination unit and the reference [108] different decontamination methods.

Figure 4.4 – Decontamination unit [115]

General recommendations for RH Equipment:

1. Protective covering: some equipment's elements must be protected in contaminated environments, such as the wheels of the mobile robot. Especially if 1) they require manual maintenance by the operator, 2) they are in direct contact with

contaminated surfaces, or 3) they are difficult to be decontaminated. Protective coatings must be removable and replaceable, and these do not have to impair the operation.

2. Decontamination: the equipment parts that are not covered and cannot be easily replaced, must be decontaminated until acceptable radiation levels. Equipment parts that may be damaged by decontamination solutions, such as bearings or connectors, could be removed and replaced by new ones.
3. Material: the elements/devices that cannot be reused after RH operations may be lower quality materials, must not necessarily be resistant to the decontamination process. Although it also depends on more factors like environmental conditions. In contrast, the material should be radiation resistant if it will be reused. The material to be decontaminated must resist the degradation produced by the fluids and decontamination procedures.

The last recommendations for the RH Equipment also can be considered for the accelerator components.

4.2.7. Labelling

The components and elements should have a visibly mark or label. These provide useful information when the operator is performing the RH operations. As Figure 4.5 exemplifies, marks indicate the correct place to insert the connectors, or labels can help to identify the type of connector. It can be beneficial when there are several elements. Design practices on this matter are:

- Marks or labels must show information about the component or element, such as the correct assembly orientation, type of component, etc.
- Permanent and clear marks and labels. For example, labels could be stamped in stainless steel
- The type of label depends on the environment, dimensions, visual system, etc. For easy identification, it may have an identification number.
- The labels and marks must be placed in locations that are fully visible to remote cameras and humans.
- At least one label is required, but more than one may be required on large components.
- The material of the labels should be compatible and resistant to the environment.
- Avoid reflective or shiny material. It can reflect, and so affect the vision of the camera.

Figure 4.5 - Example of labels and visual marks. The labels show where each male connector should be connected, and the markings help to know in which orientation the male connectors should be inserted with the female connectors

4.2.8. Positioning aids

Many tasks consist of positioning, assembling, inserting and removing accelerator parts. These actions require precision. However, it can be challenging during remote activities since the perception of the environment is often limited and confusing. The use of positioning aids between components or elements is useful in this regard.

a) Electric connector (Source: Lemo)

b) Different positioning guides

c) Positioning guides for DONES TC components

d) Positioning aids for DONES accelerator component

Figure 4.6 - Different types of position aids. The images c) and d) show drawings of two components of IFMIF-DONES facility: HFTM and scraper

The positioning aids consist up of mechanical limits, guides and reference surfaces. The guides are elements as pins, spigots, dowels, surfaces. These elements must be inserted into slots or holes (i.e., blinds and through). An example of positioning aids can be visualized in Figure 4.6 and Figure 4.7. The element surface has holes and the other one pins, wherein the position between them must coincide. Usually, each part has several positioning aids through which the element makes contact. These aids can also restrict freedom degrees. This design technique aims to simplify processes, decrease execution time, facilitate maintenance, as well as gain precision and speed in task execution. Besides, these systems also allow the components or elements to be kept stable and stationary in place.

Figure 4.7 - Positioning sequence of a component with position guides. Image modified from ITER design [116]

Design practices for positioning aids:

- The guide selection depends on the operation, component to operate and its characteristics, such as shape, surface, material, etc.
- Avoid redundant positioning pins and guides. It could produce mechanical jamming due to many constraints.
- Several designs require staggered guides since it reduces the number of Degrees of Freedom in sequential stages. It avoids tilt, seizing or damage to components during installation and removal.
- Try to have a clear view of the guides during the remote assembly. Avoid blocking the view of the guides.
- Staged positioning may be recommended for some components. The positioning elements of the first stage allow a rough positioning of the components (first approximation). Subsequently, the second positioning set allows for more precise positioning for proper engagement, where these must be designed or selected for finer tolerances.
- The guides must be located on both contact faces of the elements to be assembled.

- The correct choice of the guidance system can avoid the use of external systems for alignment assistance.
- The guide system combination (between two or several components) must be in a strategic and correct place to allow adequate positioning.

4.2.9. Viewing and illumination

The visualisation and lighting system is crucial in the workspace since the RH operations are highly dependent on them. These must be integrated with the building layout, accelerator and the RHS. For that, it is necessary to take into account considerations as the shadows, accessibility, degree of visual detail for the RH activity, the cameras and illumination support in the building, among others.

Figure 4.8 - Control area with telerobotics system. This area has windows to visualize the interior of the hot cell (Source: nuclear.ro)

Some facilities have a direct view through periscopes or windows with special lead glass, see Figure 4.8. However, in other cases, the RH operations have to be done via a remote visual system, which can be composed by cameras, computer screens, VR glasses, etc. Figure 4.9 shows the remote control area of the JET reactor. It is composed of several monitors that visualize the tokamak reactor from different points of view. It allows the operator to telemanipulate the Mascot robot remotely [117].

Figure 4.9 - JET control area. The operator is visualizing the work area of Mascot robot (tokamak reactor) by means the visual monitors (Source: race.ukaea.uk)

Adequate lights and cameras should be placed from several different angles so to provide good feedback of the task. The cameras can be fixed or portable inside of the critical areas. Fixed cameras are located on walls or mounts. Movable cameras can be integrated with RH Equipment like cranes or robotic arms, as Figure 4.10 shown.

Figure 4.10 - Robotic arm equipped with a camera and lights. (Sources: [105] and industrial.omron.co.uk)

It is possible to distinguish three types of cameras to obtain as much information as possible from the environment during the RH interventions. These cameras are RGB (red, green, blue) to visualize the environment in 2D, RGB-D to visualize the environment with depth (3D) and thermal camera to visualise the temperature. For radiation areas, there are special radiation-resistant cameras, which can be observed in Figure 4.11. Nevertheless, radiation cameras are not always needed. It depends on several factors such as the time of use, radiation levels and budget.

Figure 4.11 - Commercial Rad-Hard cameras from Remote Ocean Systems, (Source: rosys.com), Brooks Associates Inc. (Source: rbrooks.com) and Diakont (Source: diakont.com).
For example, D-40 can bear a max. accumulate dose of 2×10^8 rad (2 MGy).

Design practices on this matter are:

- Movement: the pan and tilt movements are often necessary to provide different views of the area.
- Quantity: it is often preferable to have multiple cameras to get different views of the work area. However, the number of cameras will be defined depending on the type of task, environment, cost, etc.

- The quality of the vision system must be suitable for the RH operation. It is related to the type of camera and the lighting system. The quality of the light must be ideal for each work area and task.
- Some factors can disturb the visualisation and reliability quality of the camera. Consider the following environment conditions to select the camera:
 - Radiation doses.
 - Reflective surfaces. Try to put anti-reflection painting.
 - Colours. It is suggested to differentiate the elements or components with different colours.
 - Light. It is preferable lights that can be dimmed since it allows adjusting the lighting to each area and RH task.
- The accelerator design should allow visualising the RH operations from several locations. If it is not possible, the components and also the tools have to have specific features.
- Use commercial cameras and lights since these have high availability in case of failure.
- Depending on the situation, the use of a non-radiation resistant camera is more profitable than use especial radiation-resistant cameras, being that the latter have a high price.
- Avoid delays in the image retransition, providing real-time information.

4.2.10. Enough diagnostics

The accelerator must be designed with enough diagnostics for reliable and fast failure detection on accelerator components or modules. It avoids wasting time detecting failures throughout the accelerator.

4.2.11. Material

The selection of the materials is fundamental for the correct accelerator performance. The material has an important role because this can cause failures and require more frequent maintenance. It leads to an increase in maintenance costs and accelerator stops. Designers must take into account the degradation and lifetime of the materials depending on the environment conditions. Preferably, the material must be considered at the design stage.

4.2.11.1. Radiation-resistant materials

The material exposed to ionising radiation can absorb high-energy particles. It can produce microscopic changes in the composition and structure of the material, which is accentuated by the continuous exposure of the material to radiation, even being able to change the properties of the material. The radiation accelerates the deterioration of some materials. There is an extensive bibliography that talks about the effects and mitigation techniques under irradiated environment [10], [107], [111], [118], [119]. The effects of radiation depend on several factors: 1) type of material exposed, 2) the amount of radiation absorbed, 3) the environmental conditions, 4) the physical application of the material [107]. Other specific factors are the type of radiation (gamma or neutrons), spectra and intensity of the radiation and exposure time. A correct selection of materials or electronic devices can prevent or avoid unexpected failures in a short time, although there is a trade-off between the material and cost. Materials radiation-resistant can reduce the frequency of maintenance operations, and they ensure longer life, reliability and availability of the plant. In general, the metals and ceramic are far more radiation-resistant than other materials [120]. However, some care must be taken with certain alloys as some are subject to brittleness.

Other components and materials are especially sensitive to radiation [10], [107]: electronic and electrical components, and also organic materials such as some elastomers, oils, and plastics may be severely affected and may have very limited use in areas of high radiation. The effect on electronics is so critical for some components that the radiation can produce transient as well as permanent changes in electronic circuits and equipment [107]. Therefore, the type of material in electronics is also relevant. For example, some microcontrollers with radiation hardness properties are made by a ceramic material instead of plastic.

In the case of non-radiation-resistant components or electronic devices, it is possible to cover them with materials that act as shielding to prevent radiation from passing through the materials. The material of the shields depends mainly on the type of radiation. For example, 0.04 m of lead can be an estimation to reduce about ten times the radiation for common ~ 1 MeV gammas [109]. The lead acts as a shield for gamma radiation, but it is not enough for neutrons.

Some recommendations for components and equipment located in a radiation environment are:

- Use resistant material to the radiation such as the stainless steels type 316, ceramics, etc.
- Avoid materials no resistant to the radiation, such as plastics.
- Shield components or devices that are highly radioactive or sensitive. The type of material shielding depends on several factors, such as space, cost, availability of the material, type and levels of radiation.

- Try to design or select materials with a similar lifetime for the elements of the components or modules.
- Cooling could be considered in some parts of the facility where the radiation is intense for the material and component.

4.2.11.2. Corrosion-Resistant Materials

Designers must also consider corrosion on materials and anticipate unplanned events such as leaks, which occur in the form of liquid or gas. As mentioned in subsection 4.2.6, RH Equipment can be periodically decontaminated. Materials must be resistant to damage from decontamination methods and processes. Thereby, the choice of compatible materials and coatings to resist the corrosion and decontamination is fundamental to assure the availability and performance of the plant. Depending on the characteristics and factors of the accelerator, different options to address the problem of corrosion can be chosen:

1. Select anticorrosive material, preferably if it is compatible with the needs and environmental conditions of the accelerator. For example, the stainless steel material provides a long service life and minimizes the corrosion effect.
2. Sometimes there are incompatibilities between materials. In this case, corrosion and radiation-resistant coatings and sealants can be applied to less qualified materials to improve performance.
3. In some cases, economic compensation can accept the corrosion effect. Sometimes, it is preferable to regularly replace the component, rather than apply an aggressive and expensive decontamination procedure. This option depends on factors of operability, useful life, ease of replacement, downtime and general cost (initial cost, operating delay costs and disposal costs).

4.2.11.3. Materials Resistant to Galling

The galling problem is not readily detected with remote inspections in the early stages. Galling is most prevalent between mating parts of heavily stressed screw fasteners. As document [107] cites, there are three main galling causes: 1) poor surface finish, 2) inadequate lubrication, and 3) improper selection of materials. It is generally avoided by specifying the use of dissimilar mating materials. For example, stainless steel is highly prone to galling between mating parts, so be attentive to design against galling. The following design suggestions can help to avoid galling:

1. Avoid cross-threading. Blunting the starter threads is a common practice.
2. Improper alignment. Misalignment when starting to engage threads or when tightening fasteners will increase the possibility of irritation.

4.2.12. Electronics devices

Electronics is a sensitive element in radiation environments. It may be affected as radiation can cause temporary or permanent failure. Chapter 5 presents a detailed study of the electronic effect under radiation. It details further the concepts of this subsection.

Figure 4.12 - Techniques to reduce the radiation effect on robots. Blue boxes represent electronic devices. These control the robotic arm located in a radiation environment

Some recommendations to lessen the effects of radiation are listed below:

- Locate rad-sensitive components out the radiation areas. For example, the controller devices with microcontrollers.
- Use radiation hardness electronic components. These are specially made to resist more the radiation dose and to avoid failures due to the Single Event Effects (SEEs).
- Use redundant devices to avoid soft errors, such as the Single Event Upset (SEU) error. It produces changes in the values of the microcontroller memory.
- Shield the electronic devices with a material able to attenuate the radiation of the accelerator areas [10], [121].
- Use architectures and software specially designed to resist or solve typical SEEs.
- Use non-radiation resistant components if these: a) are not a key element in the operation of the equipment, and b) can be periodically replaced.

The cited recommendations have been illustrated in the drawing of Figure 4.12. It shows different techniques to reduce the radiation effects in electronic devices.

4.2.13. Replaceability

The accelerator modules or components must be designed so that they can be replaced during the installation lifetime, being preferable easy replace. It also can be considered for the RH Equipment, which needs periodic maintenance activities. This topic is relevant since a fast and simple replacement decreases both the RH maintenance and accelerator shutdown times. Some recommended design practices are exposed bellow:

1. Preferably divide the components in modules. RH Equipment can handle and replace more easily modules than complete systems.
2. Design or select modules considering a remote replacement with a RH Equipment. It is preferable to use commercial and standard solutions and avoid special tools or accessories.
3. Consider simple RH interfaces to be remotely handled. For example, the Quick Disconnect System (QDS) flange from Technetics company (technetics.com).
4. Provide enough accessibility to replace the components or elements of the accelerator. Wherein it is necessary to consider the building, accelerator and equipment characteristics.
5. Mark and label the elements to faster and correct identification.

4.2.14. Storage

Storage areas are often required for locations where remote operations must be carried out. The storage space allows the deposit of material, such as tools or temporarily replaced components. The design considerations for storage are the following:

1. Identify the components or elements that should be permanent or temporarily stored, and check if there is enough space in the rooms.
2. Storage areas must be accessible to new and old components, RH Equipment, and staff.
3. The storage areas must bear the weight of components or RHS to be stored. For example, heavy plugs of 120 tons can be deposited in a stored area, and the floor and structure have to resist the heavyweight.
4. Add visual marks to delimitate the storage areas. It is useful to view it remotely.

Figure 4.13 - Storage areas in the Access Cell (AC) area of IFMIF-DONES

Figure 4.13 exemplifies the storage area of IFMIF-DONES's maintenance room. This room has reserved a space on the floor to deposit the shields, new components and tooling. Additionally, this room has space assigned to perform maintenance and decontamination operation on the RH Equipment (overhead cranes).

4.2.15. Recovery and rescue

Recovery and rescue is an important consideration that is often overlooked for RH Equipment. The RH Equipment must be able to be recovered or rescued in case they fail, either by other equipment or by workers. The downside is that robots or cranes must perform these tasks because workers cannot enter in some rooms. The following lines present several recommendations:

- Reserve an area or space for possible equipment recovery. This area may have robots to perform repair activities or low radiation levels to allow manual repair.
- The equipment must have its recovery and rescue system. For example, if the robot falls, it must be able to get up on its own. Another option is that the equipment has an auto-mechanism to move by itself to a safe area (recovery and rescue area) in case of breakdown.
- If the equipment does not have a self-recovery and rescue system, other equipment has to perform the rescue. It would have to transport the equipment to another place (e.g., maintenance areas or safe areas) or repair in situ the equipment. The recovery equipment must have the appropriate capabilities and characteristics to perform RH tasks.
- Consider enough space to transport the equipment in case of failure.
- Consider equipment with modular design to facilitate the equipment reparation.

If recovery and rescue are not considered, the equipment may be not rescued due to high levels of radiation. The accelerator must be turned off until humans can safely enter. It represents a high cost for the installation, and sometimes it is not possible to enter, or there is a long wait until the radiation levels drop over time. For this reason, recovery and rescue is a relevant factor to consider in places where RH is required.

4.2.16. Adequacy for the RH Equipment

The accelerator components must be designed with specific requirements to allow their RH manipulation with the defined equipment in the accelerator zones. For that, it is necessary considers the weight, dimensions, interfaces, positioning and accessibility, and other characteristics mentioned in this chapter.

Equipment and tools can be commercial or modified but must be selected or designed according to the requirements of the RH operations demanded. Detailed recommendations and characteristics of the equipment to use in gamma radiation environments can be found in the document [111].

4.3. Guidelines for particular elements

The design and properties are relevant for the performance and timely execution of the RH tasks. For this reason, it is not convenient to use interface or mechanism designed to be manipulated by humans, since these do not usually meet the requirements to be operated by robots or other equipment, and need more time to complete the tasks. For example, a robotic gripper will have more difficulty to grasp connector with a circular design (the common one) than a connector with flat surfaces.

For these reasons, the accelerator components design and RH Equipment have to follow some guidelines to streamline and facilitate the RH operations. This second part of the chapter analyses specific elements and tools for the RH operations. It presents recommendations and design guidelines in order to improve RH interaction and provide the best results.

4.3.1. Gripping devices

Gripping operations must take into account: 1) the equipment to grasp and handle the component, typically performed by a robotic arm along with a gripper, and 2) the component that must be grasped by the equipment. The robotic grippers types are not analysed in this subsection, for more information, see subsection 4.4. It is focused on parts where the robotic gripper grasps it, that is, the interface or surface of the component. These must allow a correct and secure grasp operation with the gripper. Figure 4.14 shows a specific commercial connector for RH. It has a flat surface and a cable to be grasped by a robotic gripper. Instead, the component of Figure 4.15 has a special “gripping interface”. The piece has been added to be easily grasped with the gripper. As subsection 4.2 mentioned, the interface of Figure 4.14 and Figure 4.15 has

positioning and grasping aids (pins and limiters) to assist during the positioning of the gripper.

Figure 4.14 - Commercial connector from Stäubli company. It is designed to be handled by a robotic gripper (Source: staubli.com)

Figure 4.15 - Component with a unique gripping interface to be grasped by the Mascot Manipulator at JET. Image modified from source: [120]

Design practices for gripping devices and components gripping interface:

- The gripping part of the element or the gripping interface must be suitable for being grasped. Commercial parallel grippers are preferable.
- The gripping surface or gripping interfaces must be correctly positioned to allow good manipulator access. Preferably, avoiding interference to grab the component.
- Try to avoid cylindrical surfaces or irregular shapes. Flat parallel gripping surfaces are recommendable for the typical flat grippers.
- Try to use a standard gripping interface for RH.
- The gripping surfaces or gripping interfaces should be knurled or rough surfaces; this helps prevent slippage.
- Define guides and limits on the grip surface for a faster and reliable engagement of the gripper. For example: fastening pins or borders.

- Robotic arm and gripper must have adequate properties and capacities to grasp the element or gripping interface. For example, enough force, dimension, etc.
- The best solution for a correct a safe operation has to be found when there is not a suitable gripping interface or surface for RH.

4.3.2. Lifting Devices

The lifting devices are considered one of the elements that make possible the transport of the accelerator components in radiation facilities. The transportation is generally done with cranes because these can grasp, hold and transport components with more load capacity than other equipment. There are multiple types of commercial cranes systems, although sometimes specific solutions are required depending on the facility characteristics. These are often demanded in areas with high ionising radiation, and critical components (e.g., heavy or contaminated components), wherein particular and complexity solutions are implemented to transport components via RH. These exigent conditions give rise to engineering challenges and solutions with high reliability and security to prevent unexpected and undesired accidents, considering the U.S. Nuclear Regulatory Commission (NRC) regulations, such as NUREG: 0554, 0612, 1774.

Figure 4.16 – “Single Failure Proof Cranes” for critical operations such as nuclear power plants
(Sources: konecranes.com, americancrane.com, ecms.emech.com)

Figure 4.16 shows various examples of Single Failure Proof Cranes. These cranes have a special and safe mechanism for areas that need high reliability when the critical loads must be transported in a radiation environment. Figure 4.17 presents an example of a peculiar tool to transport casks in a nuclear facility. This tool has a compatible design with the critical component that needs to transport.

Figure 4.17 - Special tool to transport the transfer cask in a nuclear facility. This tool applies NUREG-0554 (Source: americancrane.com and [122])

The lifting devices are a tool made up of the interfaces or elements that crane has. Instead, the component has fixed or removable interfaces as lifting bail (lifting eye, lug, eyebolt, wire loop), threaded hole or other similar elements. It depends on the type of tool or crane system, which allow lifting, transport and position the component. There are multiples types of lifting tools and interfaces. These can be commercial or custom. For RH operations, the preferable are those that can perform the attaching operation by self-actuation since the humans cannot assist during the operations in most of the accelerator areas. Different common models of lifting devices for RH are documented in [107]–[110]. Figure 4.18, Figure 4.19 and Figure 4.20 present commercial and custom tools systems to attach the components with self-actuation.

- Automatic hook

Figure 4.18 - Automatic hook from Elebia company. The engage sequence is: 1) place the eye bolt with the magnet, 2) introduce the hook and 3) close the hook. (source: elebia.com)

- Pneumatic system

Figure 4.19 - Vero-S Quick-Change Pallet System from Schunk company. It has a pneumatic system to attach the clamping pin (Source: schunk.com)

- Twistlock system

Figure 4.20 - Twistlock mechanism with a motor and gearbox system. System designed for RACE company for IFMIF-DONES [123], [124]

Design guidelines for lifting devices are recommended for successfully transporting accelerator facility components. It is suggested the use of one or multiple lifting devices on the components, keeping enough access and vision. Design practices for lifting devices and components:

- Try to use commercial RH solutions or adapt commercial solutions.
- Lifting devices with self-actuation are recommendable in areas where the human cannot directly assist during the operation. Figure 4.18, Figure 4.19 and Figure 4.20 show examples of lifting devices.

- The strength analysis of the lifting devices must be carried out under the worst abnormal lifting operation. The lifting devices must have a security margin in the load capability respect to the maximum load to be transported.
- The location of the lifting interface is important for a feasible and fast attachment. The recommendations to place it are the following:
 - The lifting point must be on the proper side of the component to be lifted in the correct orientation.
 - Try to locate the lifting interface in a visible and accessible location for the RH Equipment.
 - Try to situate the lifting interface over the centre of mass of the component to facilitate removal and installation operations.
 - Locate the lifting interface in a position that does not interfere with other components, equipment or other RH operations.
- Redundant lifting interfaces are recommended for delicate lifting and transport operations with a critical load. Read NUREG-0554 to know more details.
- A single lifting point is preferable than multiple lifting points when there is a risk of jamming.
- Multiple lifting points (two or three) are suggested if a rotation of the component along the horizontal axis is needed.
- Remote cameras must be able to display the component and the lifting interface during the engagement/disengagement operation. Try to avoid items that interfere between the camera and component.
- The component must be designed to remain stable when the lifting interfaces release it in the mounting position or storage areas. If not, extra supports or interfaces must be added to grant this stability.
- Install permanent lifting devices where possible. Permanent lifting devices reduce maintenance time. It avoids the necessity to install and remove the lifting interfaces all the times.
- Threaded holes should be provided if components with permanent lifting devices have interferences with other systems, assembly or the operation of the system.
- Provide enough access around the lifting interface for a feasible and fast attachment.
- Consider enough space to transport the component along with the facility.

- Consider storage place to locate the lifting device when it is not being used and storage the components transported.

Other recommendations to facilitate the placement of components with the lifting devices:

- Use aids (subsection 4.2.8) during the positioning and placement of the component.
- Design components in a way that only vertical forces are needed for dis/assembling. Note that horizontal forces cannot be applied with a crane equipped with vertical ropes only.

NUREG-0554 or NUREG-0612 includes specific information about the transport of critical loads (heavy loads and radioactive components) in areas with ionising radiation. Mostly when the load being handled by a crane can be a direct or indirect cause of radioactivity emission and provoke undesired accidents.

4.3.3. Electrical connectors and cables

Cables for transferring power and signal have two parts: the cable itself and the connection element, so-called connector. Figure 4.21 clarifies the configuration and types of electrical cables. The choice between alternative 1) or 2) depends on the application and the cost of the electrical device, connectors, cable and jumper.

Figure 4.21 - Connector configuration. 1) It is attached to an electrical device (such as motor, diagnostic, camera) and has a connector on the other side, and 2) both ends of the cable have a connector, it is denoted as “jumper”

This section is specially focused on electrical connectors. There are several connectors, and Table 4.3 shows three types:

Table 4.3 - Type of electric connectors (Photos source: lemo.com, staubli.com and [105])

Type	Description
<p>Conventional connectors</p>	<p>There is a wide variety of conventional connector types. The inconvenient is that the design is not friendly to be used by RH Equipment, as a robotic arm. Depending on the shape and material, a particular interface or gripping tool may be required to be remotely grasped.</p>
<p>RH connectors</p>	<p>The special commercial connectors for RH have a series of characteristics to be manipulated by a robotic arm. For example, a flat surface to easily grip the connector.</p>
<p>Multi-connectors</p>	<p>Multi-connectors can include multipin signal power, and coaxial connectors installed in a sole structure. Typically, they are specifically designed for each application.</p>

Within the variety of connectors, the connector can be angled (90°) or in-line straight [118]. The preferred selection depends on the equipment, space and placement the connectors.

Figure 4.22 - RH connector from LEMO company. The image details design recommendations for RH connectors like flat and knurling surface and alignment guides to correct positioning. (Source: lemo.com)

Design practices for electrical connectors, cables and electrical service penetrations:

- Commercial and RH solutions are preferable for cables and connectors. It increases availability and compatibility, and in turn, the price decrease. However,

depending on the requirements, it may be necessary to modify commercial designs or create specific ones.

- The connector must be compatible with the RH Equipment capabilities (force, dimensions, etc.).
- Try to select connectors with a compatible design to be manipulated with RH Equipment (see an example in Figure 4.22). Using connectors with a suitable interface or grip surface results in easy and quick dis/connection operation.

Design recommendations are exposed below:

- Connectors with flat and parallel surfaces are preferable to grip with a robotic manipulator. These are easier than cylindrical bodies (see photos of Table 4.3).
- Knurling on the gripping surfaces aids operability, especially for rotary motion connectors.
- A connector with a lanyard design introduces a potential tangling hazard.
- Push-pull connectors are preferable to that requiring rotary motion.
- 90° angled connectors are sometimes preferable to in-line straight connectors because the cables do not interfere with the manipulator and the gripping of the connector.
- The connectors that do not need a specific position during the insertion operation are easier to handle. However, this is sometimes not possible due to the requirements and application of the connector. Some electrical connectors must be introduced in a unique position.
- Alignment key or guide pins are recommended for the connectors that need to be connected in a specific position. These must be visible. Otherwise, the operation becomes more complicated.
- Permanent alignment marks are helpful. If alignment guides are not visible on the connectors, the marks must be mandatory for the engagement of the connector.
- Visual marks with labels or colours are recommended to identify where the connectors must be connected.
- Minimise the number of cables and connectors. It saves space and simplifies the system.

- Signal and power cables usually have separated connector to avoid noise and electrical interference. However, this is not always convenient in places that need RH operations. For example:
 - If there are a lot of signal lines and power, the use of different connectors is recommendable.
 - If there are a few lines, it is necessary to evaluate the use of a connector.
- Sometimes the use of multipin connectors is preferable to handle several individual connectors. The main drawbacks are customization and the higher cost.
- The connectors must have enough space to be grasped by the gripper. The minimum distance between connectors should be 40 mm, but it depends on the size of the connector, gripper tool and the force needed for manipulation.
- Interface mechanism is recommended to assist, guide or add force during the operation. Useful when the manipulator is not capable of having enough force to perform the dis/connection of the connector.
- Cable carriers are suggested to allocate the cables. Cable carriers include cable trays, cable trunking/conduits, cable chains, festoons and support springs. These should be integrated with the design of the modules, so it is necessary to consider the space needed. The advantage is that they avoid unexpected obstacles, interference, and accidents.
- The length of the cable must be enough to allow the dis/connection operation, allowing flexion of the cable. Avoid excessive length to tangle the cable with the manipulator or other components.
- The connector and cable material must be compatible with the environmental conditions. Examples: austenitic stainless steels for connector bodies, ceramic inserts, noble metal plating on pins and sockets, hermetically sealed units, gold plated pins for the connectors, etc. It will depend on condition as temperature, radiation, and others, but it is recommended to avoid non-resistant material such as plastic.
- The position and orientation play an important role to achieve simple and easy handling of the connectors, as well as to avoid interferences. It is essential to consider the following recommendations:
 - Place the connector in an accessible location for the RH Equipment.
 - Electrical connectors must be in positions that do not interfere with the removal of the main components.

- The electrical connector could be mounted in a horizontal or vertical axis. The correct axis is related to the movement direction and placement of the robotic arm, besides, the position of the devices to be connected.
- The connector position must avoid the bending of the cable, for example, employing extra support or bending protection. Excessive tension and force should also be averting.

Figure 4.23 - Two different connector's placements in the horizontal and vertical axis. There are in-line connectors in the images above and 90° angled connectors in the pictures below.

Figure 4.23 shows an example of a connector placed in a horizontal axis (on the left) and the vertical axis (on the right) with a robotic arm attached to an overhead crane. In this example, the vertical connector position causes more tension to the cable. Thus, the connector position will also be related to cable routing. As other guidelines mentioned [104], [109], the recommended cable position is in the vertical axis (preferable downwards). However, it is not always possible due to components dimension, accessibility, and other reasons. On the other hand, the 90° angled connectors showed in this example present a better path for the cable, with less tension that the connectors in-line.

4.3.3.1. Electrical service penetration

Cables must pass through the roof, walls or soil. Thereby, the electrical service penetrations should consider the mode of repair, replacement, and upgrading of the cables. There are different proposals:

1. Integrate the cables in a removable shielding plug.
2. Remove the cables from the inside of a conduit located in a fixed non-removable structure.
3. Remove the cable from the inside of a conduit located in a removable shielding plug. The option depends on the cost, maintenance schedule, feasibility, power involved, probability of failure, etc.

In the case of permanent electrical cables that do not require maintenance or upgrading, these might be integrated into a non-replaceable shielding structure. Moreover, extra service penetrations and redundant cables should be provided to avoid added them in the future (see [108] for more detail).

4.3.4. Fluid connectors

Some devices or components require fluids for operation or cooling. Hoses or pipes transport fluids from one point to another. The hoses have a removable part at the end, which is composed by a fluid connector. As the electric connectors, fluid connectors need a quick and easy dis/connection in facilities that need RH operations.

Table 4.4 - Different types of fluid connectors (Photos source: staubli.com and [119]).

Types	Description
<p>Conventional connectors</p>	<p>There is a wide variety of conventional connector types. The inconvenient is that the design is not adequate to be used by RH Equipment, as a servo manipulator. Depending on the shape and material, a particular interface or gripping tool may be required to be RH grasped.</p>
<p>RH connectors</p>	<p>The special commercial connectors for RH have a series of characteristics to be manipulated by a robotic arm. For example, a flat surface to easily grip the connector. Companies like Stäubli offer this type of connectors.</p>

<p>Multi-connection/Multi-coupling</p>	<p>The multi-connectors include several standard fluid couplings in a unique structure. These can be custom made and can also include other types of connectors as the electrical. Typically, they are specifically designed and custom made for each application.</p>
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The advantage of connectors specially designed for RH is that these can be manipulated with a single robotic arm. Concerning the RH connector presented in Table 4.4, the robot only has to push the connector to introduce it and pressing a button. At the same time, the robotic gripper grasps the connector to disconnect it.

Design practices for fluid connectors:

- Commercial RH connectors or appropriately modified are preferable for RH manipulation.
- Try to use connectors with a suitable gripping interface to achieve an easy and fast dis/connection operation. Recommendations are exposed below:
 - Connector bodies with flat and parallel surfaces are easier to grip with manipulator tongs. Cylindrical bodies become more complicated for parallel grippers.
 - Knurling on the gripping surfaces aids operability, especially for rotary motion connectors.
- The preferred nominal diameter for pneumatic connectors is 8 mm. Nevertheless, up to 11 mm are acceptable for RH the connectors. Diameters greater than 11 mm should be consulted with the RH team because the handling could be more complicated.
- It is preferable to position the connectors in the vertical axis (preferably downwards). Avoiding an angle greater than 30 degrees to the vertical [104], [109]. However, it is not always possible or adequate for a robotic arm. The correct axis is highly related to the movement direction and placement of the robotic arm, besides, the position of the devices to be connected.
- The bending of the cable must be avoided. Extra support can be used to prevent the bending of the hose.

- Connectors must be enough space to be grasped by the gripper. The minimum allowed distance recommended between adjacent connectors is 40 mm. However, it depends on the size of the connector and the force needed for manipulation.
- The materials of the connector must be adequate for the environment condition. For radiation environment the material recommended can be stainless steel 360L for the connector structure, o-ring seals of Nitrile (standard STÄUBLI supply) and seals of Fluorocarbon (Viton).
- The quality and design of material must create optimum fluid flow. The material must be efficient and safe for the applications, especially with corrosive gases and liquids.
- The connector or hoses must be compatible with the RH Equipment capabilities.
- Connectors without a specific insert position are preferable for RH. If it not possible, alignment key or guide pins are recommended for a correct connection between male and female connectors. The alignment guides must always be visible.
- Visual marks with labels or colours are recommended to identify how the connectors have to be connected.
- Connectors with locking button system are preferable for a secure disconnection. The button should protrude from the connector for easier iteration with the manipulator.

4.3.5. Pipes and flanges

The function of the pipes is transfer fluids, powders or solids from/to in-cell to/from out-cell and flanges provide breakpoints on the pipes. The design of the pipes should be defined from the beginning of the facility design to avoid interferences with the rest of the facility elements and RHE.

Table 4.5 - Description of the types of mechanisms to dis/connect the pipes (Photos source: littlepeng.com, technetics.com, [109] and staubli.com)

Types	Description
<p>Bolted flanges</p>	<p>The use of bolted flanges may be required. The flanges are connected through bolts and nuts (see the image). An inconvenient is the time needed to dis/connect all the bolts and nuts, in addition to the difficulty of doing so with the RH Equipment. This solution is not suitable for a RH operation.</p>

<p>Quick Disconnect System of flanges</p>	<p>This kind of systems allows an easy and fast dis/connection of the clamps and flanges. The clamp holds the flange, and a screw enables opening and closing the clamp. There are different designs of QDS in the commercial market, wherein the mechanism sometimes is accompanied by a bellows to compress a part of the pipe. This mechanism is recommended for areas where the operator cannot enter if the probability of the failure is high, and maintenance scheduled is constraining.</p>
<p>Multi-connection/Multi-coupling</p>	<p>It is a panel to coupling several flanges for different pipes. Some commercial companies offer commercial quasi-standard couplings (e.g., Multi-Connection System (MCS) from Staübli). However, the multi-coupling has restrictions on the dimensions of the pipes since it depends on the panel sizes and the specific designs.</p>

The flanges allow more easy pipes removal, requiring disconnection and connection operations. As shown in Table 4.5, there are different mechanisms to dis/connect the flange. The selection of adequate flanges highly depends on the RH robotic arm and the failure probability of pipes and flanges.

Figure 4.24 - Example of a modified RH Quick Disconnect System with a bellows system for accelerator DONES component.

Figure 4.24 illustrates an example of a Quick Disconnect System flange for DONES accelerator. As the image details, it incorporates the recommendations mentioned in this subsection. This system makes possible the pipe disconnection with a screw system that releases a collar chain. Then, it has a screw system to compress the bellows to give space

for a movement in the horizontal axis. For the pipe connection, follow the same procedure in a reverse way. The design practices for pipes and flanges are listed below:

- Minimise the number of pipes and flange.
- Try to use commercial RH flanges or appropriately modified for RH manipulation.
- The flanges should be removable to allow refurbishment/replacement of the flange in case of failure.
- Flanges that require precise torque and complex tightening sequences should be avoided.
- Bolted flanges are less suitable than QDS solution for RH. In the case of use bolted flange, the vertical axis is preferable than a horizontal axis for RH operations, as shown in Figure 4.25. Flanges in horizontal axis need to use then appropriate supports, guides and captive bolts or nuts to avoid the dropping. Although, vertical axis can also require captive nuts on the flange.

Figure 4.25 - Bolted flange in the vertical and horizontal axis. The arrows show the elements that can fall due to gravity. Image modified from Trinos Vacuum System Inc

- It is preferable bolts or nuts with a retaining system to avoid dropping during the dis/connection operation.
- The set pipe-flange should remain stable in position during dis/connection operation.
- Spigots and extra positioning aids can be helpful to assist during the RH dis/assembly operations and achieve the correct position (see Figure 4.24 and Figure 4.26).

Figure 4.26 - Spigots to assist during the pipe positioning [109]

- The flange interfaces, like screws or bolts, have to be in a visible and accessible position for the RH Equipment.
- Depending on the flange selection, the set (pipe plus flange) should be provided with a bellows mechanism to allow smooth dis/assembling. It is recommended incorporate a QDS, as it remains fixed in the tube once released, and the bellows compression gives rise to space to remove the pipe (see Figure 4.24).
- The seal rings of flanges have to have mechanical limits to avoid over compression.
- Special features are recommended if seals have to be installed and replaced remotely. For example, Garlock Helicoflex supply RH seals.
- When the gripper of the manipulator cannot grasp the pipe due to the dimensions or shape, it needs a gripping interface to facilitate this operation (see Figure 4.27).

Figure 4.27 - Gripping interfaces in pipes. This interface facilitates grip and transport tasks with a robotic arm [110])

- Enough accessibility has to be considered to reach the flange with the RH Equipment.
- Enough space has to be provided to perform the RH operation avoiding collision or interferences with the rest of accelerator. The space that requires the RH Equipment has to be considered.
- Enough fixation of the seal in the groove of the flange has to be provided. It gives a safe attachment of the seal during manipulation of the flanges.
- The number of pipes should be minimized. (For instance, grouping multiple tubes in a single flange).

Other method is weld and cut the pipes with specific tools, although these operations are not always recommended in radiation environments. For example, the diameter and thickness must be suitable for the tools and the tubing must be accessible and properly oriented to facilitate this operation.

4.3.5.1. Pipes penetration

Pipes must pass through the walls, roof or soil. The probability of failure of the pipes, the repair methods and the tightness should be considered for the design decision and distribution of pipes. The pipes and flanges have less probability of fail than the electrical connectors. Some recommendations are cited below:

- Sometimes, piping service can be integrated into a permanent shielding structure.
- Large pipes can be designed integrated with the shielding structure if the cost is a strong constraint.
- Small pipes should be installed in replaceable shielding plugs. It allows the replacement, maintenance and repair.
- Extra service penetrations and redundant pipes should be provided.

4.3.6. Fasteners

The term “fasteners” in this document is referred to any type of bolt, screw, nut, zip, clamp or pin suited to hold two or more elements together. The fasteners are mechanical elements used for the fixation. Conventional fasteners are challenging to be manipulated remotely. For example, fastening between a conventional bolt and nut requires great skill during insertion and tightening operations. Moreover, when these are loosened, they can easily fall off when not being held, making the remote process extremely difficult. Therefore, this section presents a series of recommendations so that the RH operation with fasteners can be more secure, fast and easy to perform. Table 4.6 shows different types of fasteners recommended for RH manipulation.

Table 4.6 - Description of different types of fasteners for RH (Photos source: [104], [107], [113], savetix.de and boellhoff.com)

Fasteners types	Description
<p>Free captive bolt</p>	<p>The proposal RH bolt has threaded and a waisted part to allow captivation of the bolt [104]. Additionally, it is specially constituted by:</p> <ol style="list-style-type: none"> 1. Tapered and cylindrical ‘lead-in’ for positioning and also to avoid cross-threading during the starting of engagement. 2. A cone head to favour the coupling of the tool with the bolt head. <p>Its use is satisfactory if the bolt does not hinder the RH dis/assembling operations.</p>
<p>Spring-loaded captive Bolts</p> <p>Close Spring-loaded captive bolt</p>	<p>This captive bolt has a spring to remain attached to the structure after unbolting it. Regardless of the position, the spring catches the bolt and allow hold it permanently. The difference between the captive washer bolt and the spring captive bolt, it is that the last one allows hiding the bolt inside of the structure. This option is preferable if there is a tendency to drop during dis/assembling, and when the bolts hinder the reliable installation of the mating components.</p>
<p>Captive washer bolt</p>	<p>This washer retains the bolt on the structure when it is released. Regardless of the position, the washer catches the bolt and allow hold it permanently.</p>

<p style="text-align: center;">Captive nut</p> <p style="text-align: center;">TYPE I - RETAINED NUT</p> <p style="text-align: center;">TYPE II- CAPTURED NUT</p>	<p>A nut is a mechanical part with a central hole for attaching a bolt, fixed or sliding. There are several categories of self-retained/locking nuts: plate or anchor nuts, caged nuts, clinch nuts, etc. The advantage is that the nut remains attached to the component structure after unbolting. Figures show two different modes of nut: I) retained nut and II) captured nut. This option is preferable if there is a tendency to drop during disassembling.</p>
<p style="text-align: center;">Threaded inserts</p>	<p>Threaded inserts allow for the reuse or repair of damaged, broken, or stuck threaded holes. These are inserted into the hole, and once in position, it remains fixed. These also can be fixed with wedges, which prevent wrong turns due to twists or vibrations.</p>

Design practices for the fasteners:

- Use commercial RH fasteners or properly modified non-RH fasteners. It allows major availability and lowest cost. If not, a new fastener has to be created for the specific application.
- The use of the ISO metric (international standard) is recommendable to know and define the dimensions of the bolts.
- Try to include the same type and size of fastener for the components that need RH operations, if possible. This avoids changing the tool during RH operations. If that is not possible, try choosing two or three preferred sizes of the same bolt type for the entire module. For example, use only M6 and M10 bolts if M8 and M12 are not strictly necessary in a module (or vice versa). It allows to simplify

tool selection and minimize the need for changing tools during maintenance operations.

- Avoid the use of small bolts (M5 and smaller). M5 bolts and smaller are delicate for the remote manipulation. It demands a refined servo-manipulators for handling (extra cost).
- The bolt has to be large enough to be loosened and tightened with a tool.
- Magnetic properties of fastener material are preferable. If not, an aid can be used during the manipulation.
- Install the bolts in a vertical or horizontal position, and avoid inclined positions because it demands a more complex trajectory with the robotic arms. The bolt placement depends on factors like the equipment and component location, weight, etc.
- Cross-threading has to be avoided.
- Try to avoid the use of hex socket-head bolts in dirty and power environments to prevent obstruction of the head by dirty and debris.
- Deburr and clean the fasteners elements before their installation.
- The type of head recommended depends on the size of the bolt:
 - Hexagonal head (exterior) is recommended for values greater than 17 mm (M17).
 - Socket head is recommended for values less than 17 mm (M17). Note that the hole can become clogged with dirt and other contamination.
- Use materials to resist environmental conditions. In the case of select metals fastener, these require a minimum hardness of Rockwell C45 to resist damage from tools.
- Use dissimilar materials (or different hardness) and radiation-resistant lubricants if galling might occur.
- Prevent or avoid fracture or seizure of the bolt. The next alternatives should be considered when seizure, galling or rupture of the bolt has a certain probability to occur. For that, use bolts with a mechanised pilot hole to allow a RH drill out operation, use of threaded removable inserts, or install redundant extra threaded holes in the fixed member to decrease the severity of the failure.
- Try to avoid pins and clamps that require precise operations and/or pulling/pressing the fasteners for dis/assembling, such as spring pins (roll pins),

circlips (snap rings, U rings and variations), cotter pins and hairpin cotter pins, etc. These should not be used for RH applications unless necessary.

Reference standard values of the rough maximum tightening torques for RH bolts used in JET and ITER [125], see Table 4.7:

Table 4.7 - (ISO Metric Coarse BS 3643-1:1981) Tightening Torques used in JET, and planned for ITER [125]

Thread	M6	M8	M10	M12	M16	M20
Tightening torque (Nm)	7.5	18	37	60	160	300

Different commercial or modified-commercial bolting tools are used for tightening and release the bolts: hydraulic, pneumatic and electric torque wrench, ring spanner, bolt runner and torque multiplier. In some cases, only slight modifications of the commercial tool are needed to convert it in a RH tool, see for example [126].

4.3.7. Patch panel

There is not a wide variety of commercial patch panel to connect individually electric connectors, internet connection, or others. The problem of commercial panels is that these do not turn out adequate to be manipulated by robotic equipment, and there is not space enough to dis/connect the connectors with the robotic gripper. Therefore, patch panels with special design are required for RH. Figure 4.28 shows an example of a custom patch panel designed by CERN robotic team. This design has enough space to handle connectors and cables with robotic arms.

Figure 4.28 - Non-commercial patch panel used in CERN accelerator

The patch panel manipulated via RH needs several specific requirements: dimensions, position, material and layout. The female connectors will be embedded in the panel. These must be suitable for RH, as explained in the previous section 4.2.

Design practices for patch panels:

- There are no commercial panels to be used by robots. The commercial panels for RH need a custom design.
- The position and orientation depend on each case.
 - The panel must not obstruct the passage or access to other components.
 - Preferably, the panel should not be put on the floor.
 - The female connector position has to attend the recommendations cited on subsection 4.3.3 and 4.3.4.
 - Avoid place the panel upside down.
 - The patch panel must be accessible for the RH Equipment.
- The dimensions of the panel depending on the space available and the number of connectors. Always considering the distance between connectors should be between 40 to 100 mm.
- The material of the connectors and the panel will be different depending on the environment where it is located. The material must withstand extreme conditions. It becomes crucial when the connectors or the panel cannot be easily replaced with new ones. For example, it is recommendable to avoid plastic connectors in a radiation environment.
- The connectors should be labelled to identify each one. Labelling should withstand the extreme conditions where it is located.

4.4. Comparison and evaluation of RH tools and elements

It is necessary to find a reasonable balance to get the correct RH System. A balance between the previous guidelines and other factors (e.g., cost, maintenance schedule, facility availability, expected flexibility, among others) must be made. In this subsection, the tools and elements typically required in RH operations are evaluated following a subjective score analysis. The assessed terms throughout the chapter are the following exposed in Table 4.8.

The measurement is made by scoring with H: high, M: medium and L: low. "High" represents the maximum punctuation and "Low" the lowest. For example, if the flexibility is punctuated as "L", it means that it has almost no flexibility.

Table 4.8 - Legend of the terms used to compare the tools and elements for RH

Title	End/point	Description
Dexterity	Low/High	How is the skill level that the operator has to have?
Effort	Low/High	How hard did the operator have to work/operate remotely (mentally and physically) to accomplish the operation goal?
Flexibility	Low/High	How easy is to adapt the RHS (equipment, tool or interface element) to different accelerator elements or components?
Accurate	Low/High	How accurate is the tool during the RH operation? It considers that the human cannot assist during the process.
Performance	Low/High	How well the equipment or element can do task reliability on the elements without human intervention.
Capability	Low/High	How much can the equipment or tool offer? For example, the maximum load capacity.
Temporal demand	Low/High	How much time is needed to complete the task remotely?
Equipment requirements	Low/High	How much may the item interfaces need for the equipment and tools?
Equipment demand	Low/High	How much may the item/interfaces need for the equipment and tools? (e.g., the interface demands high precision be handled or even a lot of force to grip it)
Cost	Low/High	How much money does the tool or interface cost?
Commercial availability	Low/High	Do these exist commercially? Is there a wide variety of them?

4.4.1. Gripping devices

The selection of a robotic gripper depends mainly on the environment and characteristics of the objects to be manipulated. The gripper can be pneumatic, hydraulic or electric. Electric grippers are quite accurate, but they may have some weaknesses in irradiated environments. Instead, pneumatic ones are simple and have no incompatibilities with irradiated environments, but these are not as accurate. In the case of hydraulic grippers, these have a high load capacity and stability. However, fluids may lose properties at high levels of radiation [127], [128].

Figure 4.29 - Grippers (Source: schunk.com, robotiq.com, [129]).

Table 4.9 - Comparative between different types of robotic grippers

		Accurate	Flexibility	Grasping Performance	Commercial Availability	Cost
A	2 Fingers Parallel	M	L	M	H	L/M
B	2 Fingers Adaptive	M/H	M	H	H	M
C	3 Fingers Parallel	H	L	M	M	M
D	3 Fingers Adaptive	H	M	M	M	H/M
E	Flexible Fingers	H	H	M/H	L/M	H/M
F	Hand (4-5 Fingers)	L/M	H	L	L/M	H

There is a great variety of types of robot grippers. The way to grip the object depends on the number and shape of the gripper fingers. Therefore, an assessment of different grippers must be made based on several factors. Figure 4.29 shows an example of each robotic grippers mentioned in Table 4.9, which evaluates several robotic grippers based on various properties.

Two-finger grippers can grasp a wide range of elements or objects accurately. However, two-finger parallel grippers do not adapt as well to different shapes or geometries of the part. In contrast, flexible finger [129] can be adapted to various forms, as Figure 4.29 e) shows. The three-finger grippers are more precise and can handle more diverse element sizes and shapes. For this reason, they are usually more expensive. The

grippers with more than four fingers are complicated to use and cannot carry a large load capacity. The robotic hands of five-finger can mostly grip anything that fits in hand, but these are often not accurate enough. For these reasons, they are not very popular and are not yet used in the industry.

4.4.2. Lifting devices

In accelerator facilities, one of the most demanded tasks is the transport of critical components. The equipment and tools to carry out the transport operation are very important to ensure the safety and success of the task. The drawbacks of some accelerator areas are the high radiation levels and harmful elements. In these cases, the RH operations are mandatory, but sometimes it supposes a challenge. It is crucial to select an adequate lifting system to perform the task without human assistance. The following Table 4.10 cites and compares different tools of Figure 4.30. Most of them are capable of actuating by it-self (option B, C and D), so these do not need in-situ human assistance.

Figure 4.30 - Lifting tools (Source: elebia.com, schunk.com, DONES)

Table 4.10 - Comparative between different types of lifting tools. The operation is performed without human intervention

		Effort	Accurate	Flexibility	Performance	Capability (Payload)	Commercial Availability	Equipment requirements	Equipment demand	Temporal demand
A	Conventional hook	H	L	H	L	H	H	M/H	H	M/H
B	Automatic hook (Elebia)	M	M/H	H	M/H	M/H	M/H	L	L/M	L
C	Twistlock with motor	L/M	M/H	L	M/H	M/H	L	L/M	L/M	L
D	Vero-S	L/M	M/H	M	M/H	L/M	M/H	L/M	L/M	L

Conventional hooks are typically used to transport components due to their simplicity, performance, and availability on the market. The drawback is that these can hardly be

remotely controlled. It is almost impossible to insert the hook without the help of a human or robot. In contrast, Elebia's automatic hooks allow it to engage automatically. Its operation is based on positioning the eye lifting bolts with a magnet so that the hook is inserted automatically. Figure 4.30 b) shows the Elebias hook, and Figure 4.18 explained the process to engage the automatic hook. The other systems c) and d) are the Vero-S from Shunk company and twistlocks systems, the last one is a custom interface for IFMIF-DONES. These systems facilitate the task because they only need to be positioned and inserted in a pocket-hole. The disadvantage of these systems, unlike hook systems, is that hook systems are more flexible. It means that accelerator components can more easily aggregate lifting systems with hooks than others such as twistlocks.

4.4.3. Electrical connectors

The selection of the connectors depends on several factors: the capacity and strength of the manipulator to handle and dis/connect and the connector, the number of connections, the maintenance program, environment, reliability, availability, among other. Table 4.11 studies several factors comparing the different types of commercial connectors shown in Figure 4.31.

Figure 4.31 - Commercial electric connectors (Source: lemo.com, staubli.com and [105])

Despite the wide variety of conventional connectors, the connector a) of Figure 4.31 should be avoided for robotic arms. These cannot guarantee a secure grasping due to the connector shape. If they are used, it is recommended to add an adapter to facilitate grasping and handling operation. The operation time increase because these are not friendly to be manipulated with a robotic arm. Experimental tests have been done telemanipulating this type of connectors [11]. It shows the times that users have taken to insert the male connector into the female connector. It uses a particular framework to facilitate this type of RH operations.

It is preferable to use connectors that are specially designed for RH use, such as b) and c). Among the variety of connectors for RH, push-pull connectors are recommended, avoiding those that require rotary motion. The connection of connector type c) is secure. However, it requires a robotic arm with enough force to operate the lever. Concerning the multiconnectors, these must be designed for each application, see example in Figure 4.31 d). Therefore, multi-connector availability is lower, and their cost is higher. The advantage is that multiple power lines are grouped in one connector, so it

can reduce the operation time since the manipulator cannot have to handle multiple lines. Multiple connectors could require high equipment requirements because the size and weight of this type of connector can increase. Nevertheless, a personalised design can reduce the RH Equipment requirements, for examples adding robotic systems assistance (guides, gripper interfaces, etc.), or even an automatic system to connect them.

Table 4.11 - Comparative between different types of electrical connectors

		Dexterity	Effort	Flexibility	Performance	Commercial Availability	Equipment requirements	Equipment demand	Temporal demand
A	Conventional connector	H	M	M	L	H	H	L/M	M
B	RH connectors (Type 1)	L	L	M	H	M	L	L	L
C	RH connectors (Type 2)	L	L/M	M	H	M	M	L	M
D	Multi-connectors ¹	L/H*	L/H*	M/H*	M	L	L/H*	L/M	L/M*

On the other hand, the connectors that must be connected in a single position are more tedious for RH. Some electrical connectors need it due to the number of contacts. The contacts of the male connector must match the holes of the female connector. In these cases, it is suggested to use guides (pin, key) to find out the correct position remotely.

4.4.4. Fluid connections

Figure 4.32 - Commercial fluid connectors (Source: staubli.com)

¹ (*) It depends on the design features of the multi-connector (e.g.: weight, dimensions, etc.).

Fluid connectors are similar to electrical connectors. The evaluation made in subsection 4.4.3 is the same for fluid connection. Table 4.12 shows the assessment for each connector of Figure 4.32.

Table 4.12 - Comparative between different types of fluid connectors

		Dexterity	Effort	Flexibility	Performance	Commercial Availability	Equipment requirements	Equipment demand	Temporal demand
A	Conventional connector	H	M	M	L	H	H	L/M	M
B	RH connectors	L	L	M	H	M	L	L	L
C	Multi-coupling ²	L/H*	L/H*	M/H*	M	L	L/H*	L/M	L/M*

4.4.5. Flanges

The selection of the type of flange depends on the several factors such as the capabilities of RH Equipment, maintenance scheduled, the failure probability of the pipe and flange, cost, etc. The capability of the RH manipulator is a determining factor to select the adequate flange. Table 4.13 shows the evaluation of the various elements and mechanism to disconnect the pipes (see Figure 4.33).

Figure 4.33 - Commercial connectors (Sources: littlepeng.com, technetics.com and totaltools.ro)

Table 4.13 - Comparative between different types of pipe connections

		Dexterity	Effort	Flexibility	Performance	Commercial Availability	Equipment requirements	Equipment demand	Temporal demand
A	Bolted flanges	H	H	M/H	H	H	M	L/M	H
B	QDS of flanges (Type 1)	M	M	H	L/M	L/M	L/M	M	M
C	QDS of flanges (type 2)	L	L	M	M/H	L/M	L	L	L
D	Cut and Weld flanges ²	L/H*	L/H*	M/H*	M	L	M/H	L/M*	H

Bolted flanges are the most common and economical. See the design in Figure 4.33 a). The problem is that these are complicated to be remotely disconnected due to the number of bolts. The time used for tightening the bolting sequence can exceed the time required to perform the maintenance operation. Thus, these should be avoided. Otherwise, it is recommended to use captive bolts to prevent them from falling off.

Quick Disconnect Systems flange is a recommended system due to its easy and fast remote disconnection, see Figure 4.33 b) and c). There are few types of mechanisms on the market, so depending on the pipeline and needs, a custom design may be required. In Figure 4.33, two kinds of QDS are shown, the disconnection system is the same, but the difference is that mechanism b) is completely released and c) is not. Therefore, system c) is more recommendable for totally remote operations.

On the other hand, tools for cutting and welding pipes demands skill and precision. These tools become more delicate and dangerous because they can leave contaminated dust on the elements and environment. Therefore, cutting and welding operations must be avoided whenever possible. Although sometimes these are required if there is not any flange to remove the pipes. The selection could be difficult, although two situations can determine the decision:

1. If the probability of failure is high and the maintenance program is limited, then the QDS flange should be considered (see b) or c) of Figure 4.33).
2. If the probability of failure is low and/or the maintenance program is lax. A balance of various factors must be carried out, considering the cost of remote

² (*) It depends on the type of the equipment, tool, pipe, etc.

operations for a specific operation, the time expected, radiation levels, etc. In this case, bolted flanges or cutting/welded procedures could be preferred.

It also important consider the replacement of the seal flange. It must be replaced out-cell hands-on or by RH, depending on radiation and contamination levels

4.4.6. Fasteners

Fasteners are very important elements. These allow to fix and hold components. In particular, various components and mechanisms use fasteners, an example is shown in Figure 4.33 b) and c). The evaluation of Table 4.14 shows the differences between sundry types of bolts and configurations (see Figure 4.34). It is focused on how they are handled and operate with remote equipment.

Figure 4.34 - Different bolts configurations

Table 4.14 - Comparative between different types of fasteners

		Dexterity	Effort	Flexibility	Performance	Commercial Availability	Equipment requirements	Equipment demand	Temporal demand
A	Conventional bolt + nut	H	H	H	L	H	M	H	H
B	Free captive bolt + nut	M/H	M/H	H	M	L	L/M	H	M
C	Captive bolt with washer	L	L	H	H	L	L	L	L
D	Spring-loaded captive bolt	L	L	L	H	L	L	L	L

The conventional bolt with nut is preferable to be avoided for RH operations, see Figure 4.34 a). It involves delicate activities such as inserting the bolt and nut, tightening the nut, and so on. It usually requires a two-arm manipulator robot, one arm for hold the bolt and another one to tighten the nut. The bolt illustrated in Figure 4.34 b) has been modified to be favourable for RH. However, it has the same problem as type a); this can

be dropped. The design b) is recommended to be used as a captive bolt with spring, retaining washer or self-locking nuts, as c) and d). The inconvenience of that is the custom design since the availability could be low.

The retaining systems of c) and d) are a solution to minimise the difficulty of the disassembly operations. System c) has a retained washer and d) has a spring, these are needed to avoid bolt drops down. These systems keep the bolt or nut in the component, avoiding its extraction and insertion in each operation. The inconvenience of d) and sometimes the c) is that they require unique designs (less availability). From RH point of view, captive bolts or nuts are preferable, considering the design showed in the option b). This design also can be extrapolated for screws.

Chapter 5

Gamma radiation effects on the robots and electronic devices

This chapter provides a study of the impact of gamma radiation on electronic devices and robotic systems. This section shows various experiments performed with a neutron accelerator and the results obtained after each test. The results have been analysed to draw conclusions that contribute to the knowledge of the remote operations with robots in places with ionising radiation.

5.1. Introduction

The use of robots becomes primordial when the interaction between the user and the environment turns out to be risky and dangerous [130], [131]. Likewise, sometimes the environment is not safe for the robot either. Harsh conditions can compromise the well-functioning of the robotic systems by affecting its electronics, hardware or communications. In this regard, harsh radiation environments (e.g., particles' accelerators, fusion and fission plants) are challenging places for robots. Radiation particles can produce an alteration of the robot's behaviour, causing temporal or permanent failures in the electronics, especially in semiconductor devices such as the Integrated Circuits (ICs) [132]. It originates long terms effects due to Total Ionising Dose (TID) and Displacement Damages (DD) [121], and short-term effects expressed as Single Event Effects (SEEs) [133]. However, Total Ionising Dose effects [121], [134] and Single Event Effects [121], [135] are the two major affections to electronics devices when radiated with ionizing particles [134], [136]–[138]. The ionising dose effect is defined as the gradual effect occurring in electronics components during its exposition to radiation. It can cause physical damages in the device or component, inducing to a failure when the accumulated TID reaches its tolerance limit [139]. For example, it can create a degradation of microelectronics, leakage currents, changing transistor parameters, and so on [10], [140], [141]. The Total Ionising Dose is the total sum of the accumulating effect, of the dose rate and the total time that a circuit is exposed to radiation [137]. Contrarily, SEEs are caused by the action of a single ionising particle, which can penetrate sensitive parts within electronic devices [142]. SEE can lead to randomly appearing glitches in electronic systems at any moment during the exposition time, causing observable changes in the status or performance of the devices. It can be originated due to the corruption of the information, short-circuits, high current state in power transistors, among other effects [135]. It is possible to differentiate two broad categories of SEEs errors: soft (non-destructive) or hard (destructive) errors. Soft errors may cause anything annoying system response or loss of functionalities, wherein the events can change the state of a semiconductor device, or circuit but do not lead to a functional failure [135]. Single Event Upset (SEU) [143], Single Event Transient (SET) [144], Single Event Functional Interrupt (SEFI) [145], [146] are common examples of soft SEEs [143]. In the worst case, hard errors can cause catastrophic system failures. These destructive errors can change the state of a semiconductor device, circuit or system and does lead to a functional failure [135]. Single Event Latchup (SEL) [132], Single Event Burnout (SEB) and Single Event Gate Rupture (SEGR) and Single Event Snapback (SES) are classified as hard errors. Detailed information about the different types of SEE error can be founded in the bibliography [121], [135], [147], [148].

The effect of the ionising radiation on the electronics device depends on multiples factors: energetic particles, time of exposure, radiation levels, material, electronic components (e.g., semiconductors), electronic technology (e.g., Complementary Metal-

Oxide-Semiconductor (CMOS)), the architecture of microcontroller, dimensions (e.g., Surface Mounting Device (SMD) components), etc. Several tests and research have been carried out over recent decades (see subsection 5.1.1). The aim has been to understand and improve the electronics operation and its durability in ionising environments, in addition to investigating techniques for alleviating or mitigating the SEE produced in an irradiated environment [10], [149]–[151]. The success of the robotic operation in this kind of environment is highly conditioned by the adequate analysis, selection and placement of the robot’s components [152]. Sometimes to avoid the radiation effects on robot’s components, there is a tendency to relocate or move the robot’s vulnerable parts to a safe zone, with less or any radiation. However, sometimes this approach is not compatible with the environment’s conditions or the robot operation. If it is not possible, other options have to be considered. For example, shielding sensitive electronic systems [153] or select adequate robot elements (servo motors, sensors, etc.) to guarantee correct functionality during the operating time.

The components selection depends on several factors such as the environment, purpose and budget. Commercial-Off-The-Shelf components are the most commonly used for normal applications. The inconvenience of radiation applications is that most of the time, special designs or components modifications are required to bear certain ionising radiation doses and/or mitigate SEE errors [10], [154], [155], for example using Rad-Hard components. However, it is unusual to find COTS with specific radiation tolerant or resistance properties, and the inconvenience of non-COTS components is that they have a high cost and low availability, in addition to complex political and commercial treaties in some cases [156]. Sometimes this specific Rad-Hard technology can be limited and backward compared to COTS technology [146]; due to the constantly changing and evolving of COTS. However, some advances in smart logics and compact dimensions as SMD are causing new vulnerabilities and threats since charged particles that were once insignificant are now much more prone to disruption [142], [146], [157]. In turn, recent characterisations of advance commercial foundries are showing that TID and SEL tolerance of commercial processes have favourable trends [146]. Therefore, there must be a trade-off when choosing the type of electronics and components for the robots.

5.1.1. Related work

The radiation effects on materials and electronic devices have been investigated for decades to create resistant and robust devices for radiation [158]. The performance and behaviour of COTS have also attracted the attention of researchers, due to the great advantages that these provide [10], [159], [160]. In other specific lines of research, multiple investigations also have been conducted on the effects of microcontrollers under radiation [141], [159], [161]–[165]. Other devices have been tested, such as cameras [166], different sensors [167], [168], servo-drives [169], and other components that robots usually use [170]. There are also experiments and studies about robots in radiation environments

[167], [169]–[173]. Each contribution is important to understand the effects better and know which features or devices are best suited for each hostile environment.

A recent piece of work [174] presents the response of a commercial robot under radiation ($2 \cdot 10^{-3}$ Gy/s), a similar study also has been conducted in this thesis. The response and trajectory of a robot have been evaluated. Unlike the cited work, radiation doses were higher ($0.09 < x < 0.18$) Gy/s since relevant effects were not observed with low radiation. The response of the Control Boards (CBs) has been additionally assessed jointly with the behaviour of the robotic arm. It allows us to observe the effect produced by the degradation of the microcontroller or errors in the joints of the robotic arm. Moreover, the experiments carried out also compare the impact of radiation applying different protection techniques at the same time (hardening, protection and relocation). These tests have been not found in the literature, and this is quite crucial to science [130].

This work continues investigating and delving into the COTS components for robotic applications, in addition to experimenting with the behaviour and response of the robot in radiation areas (without going into deep detail of the IC's internal effects). For this purpose, different tests have been carried out. Firstly, distinct Control Boards with COTS Atmel microcontroller have been tested. The novelty has been designed a Control Board with some radiation resistance. The objective was to compare the effects of radiation on each Control Board (especially the microcontroller's response) to know which is more resistant and robust, as well as comparing SMD microcontrollers and traditional technology. Subsequently, different methods proposed in the literature [10] have been put into practice to reduce or mitigate the effects of radiation. These have been compared to evaluate which ones give better results (response and durability) for the control of servo motors and sensors in robots, in addition to individually observing the effects produced by each of them on temperature sensors and servo motors. Finally, a low-cost robotic arm has been irradiated until the microcontroller failed. This experiment looked to find how long a robotic arm can work adequately with non-radiation resistant devices, and observe the degradation in the programmed path of the robotic arm.

5.1.2. Goals and hypothesis of the experiment

The objective of this study is to perform various experimental tests under gamma radiation to achieve multiple goals:

- To know the overall robot behaviour and response until the collapse of the system under ionising radiation. Collapse is as the moment in which the robot cannot perform the operation for which it is programmed. It can be due to total system failure or a random response. Moreover, this study also seeks to ascertain:

- The evolution and degradation response of the robot components (servo motors, sensors and Control Board), as the accumulated radiation and time increases, in addition to knowing the TID of these electronic components.
 - The robot performance quality when the accumulated radiation and time are increasing, and also analysis of the quality of the trajectory made by the robotic arm.
 - Time and radiation accumulated until the robot can no longer function properly.
- Test different types of Atmel microcontrollers under radiation, comparing the performance and operation of Rad-Hard and non-Rad-Hard microcontroller. The aim was to find out the durability and the effects of radiation, such as the Total Ionising Dose, electronic fails as SEE, and other vulnerabilities.
 - Compare three methods commonly used to reduce the effects of radiation on electronic components (hardening, protection and relocation). The aim is to determine which one may be the best for irradiated environments and know how these influence the robot components behaviour.

The established hypotheses have been the following:

- **H₁:** Radiation resistant microcontrollers are more resistant in environments with gamma radiation.
- **H₂:** Robot performance is affected when there is gamma radiation.
- **H₃:** Placing sensitive electronic devices outside of an irradiation area is the best solution for robot performance and durability.

5.1.2.1. Facility and accelerator

The tests have been carried out in a special room for ionising radiation test at CIEMAT. The gamma irradiation has achieved thanks to an electron accelerator, Van de Graaff type. It produces braking radiation (Bremsstrahlung) by means an electron beam with currents up to 150 μ A and energies up to 2 MeV. Therefore, CIEMAT can replicate the harsh conditions of facilities using Co-60 sources [175]. The samples to irradiate were located on the accelerator target location (an aluminium sheet of 127 x 200 mm) to achieve homogeneous radiation and receive the direct impact of the ionising beam. This plate was as close as possible to the emission point of the Gaussian-distribution of electrons.

5.2. Radiation effects

Radiation causes different effects on the materials, which mainly depends on the type of radiation. This chapter focuses its attention to the effects produced by the gamma radiation. This type of neutral charge radiation is photons with energy (on the order of MeV), which is capable of ionising and penetrating deeply into the matter. Photons can create known types of interaction with matter: photoelectric effect, the Compton effect, and pair production [10], [121], [147]. Each one has a different interaction with matter and also depends on the energy levels of the photon [121]. The general effects of ionising radiation on materials are impurity production, atom displacement, ionisation, and large energy release in a small volume. These are related to the type of radiation, wherein gamma rays can cause heating over long distances, indirect ionisation and displacements via the Compton effect [176]. However, radiation can cause more specific changes in matter, which can vary material properties such as chemical, magnetic, mechanical, electrical, and so on. More detailed information on these material effects can be found in different books and documents [10], [139], [176], [177]. In particular, this chapter goes deep on the radiation influence on electronic and electrical devices, although a small review of electro-mechanical systems such as motors will also be made.

Concerning the electronic and electrical devices, the passive electrical elements (glass, resistors, capacitors, inductors, cables, etc.) have some natural resistance to radiation due to the type of material, which can vary greatly from one to another [10]. For example, there are many capacitor technologies commonly used. The radiation tolerance differs greatly depending on the type. Electrolyte capacitors are the most radiation-sensitive capacitors and can fail as soon as 100 Gy. Instead, the glass capacitor can bear high levels from 10^5 to 10^8 Gy.

Nonetheless, active devices like the semiconductors, are notably affected by the gamma radiation [10], [147]. Ionisation can produce a charge in sensitive areas of the devices, modify the electrical parameters of the device, deteriorate its characteristics, leading to functional failures of electronic systems or even create irreversible destructive effects [147]. As mentioned before (subsection 5.1), ionisation particles can lead to producing so-called SEEs [134]. A single particle can produce malfunctioning in the semiconductors, producing Single Event Effects. SEE is prompt, having a certain probability (cross-section) of occurring with every particle interaction. It is manifested in several ways, but the root cause is generally the same. For example, the sequence in a semiconductor is the following: a charged particle passes through a semiconductor and interacts generating electrons, which are highly mobile and migrate to the drain, and then the electrons create a pulse of current shortly after the particle's interaction. In almost all cases, the root cause of the SEE is the current pulse [134]. There are a variety of impacts and outcomes on the circuit, giving place to a non-destructive (recoverable failures) or destructive (permanent failure) errors [135].

On the other hand, the active components are also potentially susceptible to fail or stop working due to the Total Ionising Dose, wherein the cumulative radiation over the time can cause a gradual degradation of the device performance. Direct ionisation can be produced when the charged particles pass through a semiconductor material, and it interacts with it [141]. Due to this interaction, electron-holes are generating along the path, and the holes created remain trapped in the Integrated Circuit oxides. This holes created within the oxides cause changes on the device characteristics, leading to adverse effects on the electronic component, such as Integrated Circuits. The “radiation risks and mitigation in electronic systems” document [134] specifies examples of these effects on Metal Oxide Semiconductor (MOS):

- N-MOS (Negative-MOS) has a decrease in switch-on voltage, as the gate is progressively activated by the slow build-up of trapped positive charges. It will provoke a change in timing margins and increases in leakage current, and also the board-level power consumption can increase.
- P-MOS (Positive-MOS) exhibits an increase in switch-on voltage, as the positive charges progressively inhibit the switch-on of the gate. N-MOS devices will fail eventually, and they are permanently activated, and P-MOS devices are permanently de-activated.

Regarding the Displacement Damage, this occurs when particles interact with the silicon lattice. However, DD mainly affects bipolar technologies. CMOS technologies generally do not suffer from DD effects [134].

There are different methods to try to mitigate or minimise radiation effects during the use of electronic devices [150]. For example: avoiding sensitive elements in the irradiated area (split technique), maintenance and repair, shielding or cover the sensitive elements (depending on radiation type), modification of the design (adding hardened or tolerant radiation components) [10], [111], [134], [178], or other specific methods for particular SEEs such as creating a redundant system to detect if a binary digit (bit) has changed [149], among others [148], [150], [151].

5.3. Experiment 1: COTS Control Boards with non-Rad-Hard devices under high radiation doses

The first experiment conducted in the Van de Graaff electron accelerator aims at evaluating the effects of high doses of ionising radiation in non-Rad-Hard COTS electronics. To carry out the study and observe the effects of ionising radiation, four commercial boards were irradiated until they failed and stopped giving a signal (collapse).

Figure 5.1 - Control Boards located at the target of the accelerator

In this experiment, the CBs were tested in the accelerator target, as shown in Figure 5.1. During the irradiation period, the CBs performed a simulation of a 1-DoF robotic controller. Each internally calculates and runs a DC motor controller, where the position of the motor was estimated based on the given speed (see Appendix B). Throughout the test, the test was monitored in real-time by the operators.

5.3.1. Structure layout and operation

The commercial CB tested is the Arduino Uno [179] with ATmega328P [180] microcontroller. Four Arduino Uno were located in the target accelerator, specifically in a suspend aluminium plate, as Figure 5.1 represents. The operators were controlling the test in real-time from a safe area (~ 25 m far and protected by concrete). Figure 5.2 describes in detail the location and layout described, where the components on the right side were irradiated (except the power supply that was in a shielded place). In contrast, the ones on the left side stayed at a safe place during the experiment.

Figure 5.2 - Set-up of the system to test the ionising radiation effect in electronic devices. The safe area is on the left, whereas the radiated environment is represented on the right side of the picture. The power supply on the right is confined in a leaded cabinet

The functioning of the configuration provided in Figure 5.2, starts on the PC located in the control room. The PC uses the Matlab Simulink program to generate the motor speed reference signals that the CBs have to simulate. Also, it creates a protocol for sending and receiving data with a frame. It sends a data frame periodically with different speed signals to the Arduino Mega [181] via Transistor-Transistor Logic (TTL) serial [182]. The Arduino Mega manages and distributes this information to each Arduino Uno. However, before the four Arduino received it, the data frame is sent by Recommended Standard-485 (RS-485) [183] due to the long-distance until the irradiation area. For that, one MAX485 module [184] connected to the Arduino Mega establish a RS-485 cable communication with the other four MAX485 modules located in a protective shield zone of the accelerator (25 meters far). It is done because the RS-485 achieves better communications than TTL and RS-232 over long distances and more immune to electrical noise [182]. Thus, the four MAX485 modules receive the signal via RS-485 and send the data via TTL serial to each corresponding Arduino.

Finally, when each Arduino receive the data (speed of the motor), the microcontroller executes a simulate control loop of a Direct Current (DC) motor considering a Proportional Integrated (PI) controller to get the angle position of the motor (Appendix B). For this experiment, it is possible to consider that all the Arduino boards received the same reference and had identical tuning parameters in their control loops. After the operation, each Arduino sends back the information (speed and position of the motor calculated and control error signal) to the Arduino Mega with the same conversion (TTL-RS485-TTL), and it packages the information to send the data frame to the PC.

The PC compares the values received of each Arduino Control Board with those calculated by Matlab (ground truth), with the same speed references. It allows comparing the errors and detects inconsistencies. The functioning and response of all Arduino Uno were real-time monitored by the operators located in the control room. Additionally, the system program was configured to have a recovering mechanism against some soft SEEs, that is, a software reset signal.

5.3.2. Description of the experiments

The experiment consisted of three consecutive irradiation periods with different ionising gamma radiation dose, at 1 Gy/s, 1.5 Gy/s and 5 Gy/s, respectively. The radiation dose was increased until appreciated an effect on electronics. A thirty seconds stop was done between each irradiation period to configure and prepare the accelerator to increase the radiation level. Each irradiation period had five minutes of duration, except for the third period, where irreversible fails were produced in the electronic devices. There was no manipulation nor substitution of any components that occurred during the experiment. Thereby, the same boards were radiated during the three tests. It permitted evaluating the maximum TID of each device.

The data sent from the boards was monitored to detect any bad-functioning or communication failure during the experiments. In case of loss of communication, a reset signal was sent from the main PC to attempt to recover the system.

5.3.2.1. Results of the experiments

The structure under radiation bore the exposition periods described without faults whatsoever until the 5 Gy/s exposition started. From that moment, the four boards in the system almost simultaneously collapsed, just as the third test began (see Figure 5.3 and Figure 5.4). In contrast, the error and communication channel evidenced no bad-functioning prior to this exposition.

Figure 5.3 - Speed error. The signal starts to fail sequentially at 10 minutes and 12 seconds of total irradiation (right graph, period 3)

Figure 5.4 - Speed signal. The signal starts to fail sequentially at 10 minutes and 12 seconds of total irradiation. The speed is considered 0 when the communication begins to fall at 10-11 seconds after starting the third irradiation period

Table 5.1 shows the duration time, the dose rate and total cumulative dose for each test performed. The TID (or total cumulative dose) reached after three tests were 800 Gy for each Control Board.

Table 5.1 - Radiation experiments results

Test	Time	Dose rate (Gy/s)	Cumulative dose (Gy)
1	5 minutes	1	300
2	5 minutes	1.5	450
3	~10 seconds	5	~50
TID	10 minutes ~10 seconds		~ 800

1. First radiation test at 1 Gy/s

Regarding the 1 Gy/s radiation, no failures or bad functioning occurred during the irradiation. Figure 5.3 a) displays a slight error of the controller's signal. However, this error is presented equally in all the boards. During the irradiation period, no communication channel disturbance or failure was produced.

2. Second radiation test at 1.5 Gy/s

After the first test, the accelerator emission was deactivated for 30 seconds. Then, the emission was reactivated to start the second test, increasing the dose rate to 1.5 Gy/s. The behaviour of the electronic boards irradiated during a five-minute lapse at this dose is shown in Figure 5.3 b) and Figure 5.4 b). These graphs reveal that no significant bad-functioning took place during the test. There is the same error oscillation than the previous irradiation period.

3. Third radiation test at 5 Gy/s

Before starting the third test, the emission was stopped again for 30 seconds. Afterwards, the Arduinos were irradiated with a dose rate of 5 Gy/s. However, the operation only kept normal for the first ten seconds after starting the third test. Immediately after that, systematic failure of the four Arduino boards occurred, as shown in Figure 5.3 c) and Figure 5.4 c). The reset signal was sent several times, both during and after the experiment. However, the controllers never recovered or functioned again.

5.3.3. Discussion

The four microcontrollers reached their TID at 800 Gy with high dose rates (up 5 Gy/s). The results have been studied and compared with those previously performed by other institutions and researchers. The Goddard Space Flight Centre of National Aeronautics and Space Administration (NASA) and the University of Connecticut performed an experiment irradiating Arduinos Uno boards. This experiment was conducted to a lower radiation dose rate (0.33 Gy/s) and longer duration (33.3 minutes). As a result, there is a difference in the TID between experiments: ~ 800 Gy in our test and ~ 600 Gy for the NASA test. However, this result is justified since it has been found in insulators that different dose rates change the total damage observed at the same final dose [185]: the damage, in general, is related to $\frac{1}{\sqrt{\text{Dose rate}}}$. Therefore, it is expected that a lower dose

rate, the cumulative dose until the total failure is also lower, such as the results of the NASA experiment [173].

High dose rates can create photocurrent due to electron-hole pair generation. This photocurrent modifies the characteristics of a semiconductor device and can lead to misunderstandings of the total dose effects and total failures [10]. As the literature mentioned, photocurrent can cause transistors to randomly open, changing logical states of flip-flops and memory cells. In addition to this, high dose rates generate permanent effects that influence fatefully to the systems' response [186]. Consequently, the major disturbance conducted in the experiment appeared during the increase of dose rate until 5 Gy/s. No sooner had this irradiation started (approx. ten seconds after), all the boards completely collapsed in an irrecoverable manner. These were exhibiting the same behaviour response. However, before this failure, there were no significant alterations nor damages that compromise the well-functioning of the system neither communications.

5.3.3.1. Electronic analysis

After the experiment, all the boards and components were checked to determine where the failure was produced. The Arduino boards have various sensitive electronic elements to ionising radiation, such as electrolytic capacitors and microcontrollers (ATMega328 and ATMega16U2 [187]). These non-Rad-Hard components must be seen as vulnerabilities of the system when even are exposed to low doses of radiation [10].

The first electrical inspection suggested that the microcontrollers and power regulators were damaged. However, the microcontrollers ATMega328P were replaced by new ones on the irradiated Arduino boards. After that, the Arduino boards recovered their function. Although two irradiated Arduino UNO showed problems with the port. It indicates that ATMega8U2 microcontroller was also damaged. It acts as a bridge between the computer's USB port and the main processor's serial port. In turn, the irradiated ATMega328P microcontrollers were placed in a new Arduino Uno, but restore its functions was not possible. Neither irradiated ATMega328P microcontrollers could upload a program after the test.

Electronic evaluation indicates that the input current of ATMega328P microcontroller increased after the irradiation experiment, see Table 5.2. This effect has happened differently for each microcontroller, denoting an increase in power consumption. Additionally, the leakage current was tested in the microcontrollers. The pins were tested in high and low modes, as indicating the following references [188], [189]. The values obtained have been compared with a non-irradiated microcontroller, and additionally, it was observed if the current of the pins exceeds the leakage current threshold of the datasheet (1mA). Some pins exceeded the current leakage threshold in high mode, but they were arbitrary pins. Therefore, no relevant patterns or results have been observed in relation to leakage current.

Table 5.2 - Electronic evaluation before and after the irradiation test

CB with microcontroller	Status	μC Input current (mA)	μC Input voltage (V)	Observations
Arduino UNO reference	Before irradiating	5.5	4.9	-
Arduino 1	After irradiating	12.7	4.9	It detects port but does not load the program.
Arduino 2	After irradiating	8.4	4.9	It does not detect port, nor does it load the program.
Arduino 3	After irradiating	20.0	4.9	It detects port but does not load the program.
Arduino 4	After irradiating	7.9	4.9	It does not detect port, nor does it load the program.

The other Arduino's electronic components were also checked without finding any damage to their functions. Therefore, the major vulnerability of Arduino Uno is the microcontrollers: ATmega328P and ATmega8U2 with CMOS technology. CMOS technology improves noise avoidance and performance in a cost-effective manner. Nevertheless, it impoverishes radiation resistance against TID and SEEs [138], [186].

5.3.4. Result conclusions

According to the results under high doses rates, it can be concluded that:

- The ionising gamma radiation has not caused sudden disturbances in the normal operation of the microcontroller ATmega328P, nor affected the communication channel before the total fail system.
- The only remarkable effect noticed during the operation is a slight increase on the signal chattering as the dose increased. It can be corrected by robust software and adequate control design of the control signals.
- The effects of radiation and perturbations of the signal have only been more prominent just moments before totally failing, as shown in the oscillations of Figure 5.3.
- The microcontroller is one of the most susceptible and sensitive electronic elements of the robots. Some options to prolong its duration and operation, and also minimise or avoid the radiation effect can be considered. For example:
 - Replacing the microcontroller by other more radiation-resistant or tolerant [134].
 - Protecting the microcontroller or Control Board with special shielding depending on the type and level of radiation [190].

- Placing the microcontroller in areas with less or no radiation [10].

This could be done with a commercial board although sometimes the requirements demand modifications or a custom board.

- High dose rates can lead to misunderstandings of the total dose effects and failures. Some errors that happen with a low dose rate do not appear at a high dose rate. For example, the damages that result from a high dose rate exposure of a bipolar transistor are smaller to the ones that can be found with a low dose rate [10]. Furthermore, the TID usually becomes greater at high dose rates but the functioning time decrease.
- The electronic analysis of irradiated microcontrollers indicates an increase in energy consumption at the input of some ATMEGA328P. The internal affection has been different for each microcontroller.

5.4. Experiment 2: Behaviour and response of 3-DoF robotic arm

The second experiment conducted aims at evaluating the response and behaviour of a robotic arm under lower radiation doses than the previous experiment. This robotic arm was designed and manufactured in our laboratory CAR (UPM-CSIC). Figure 5.5 shows the design and configuration of the robotic arm. It is composed of 3 rotational DoF, wherein each micro servo motors actuate a joint. This experiment monitored the response of a) one microcontroller (ATmega64M1 [191]), b) the internal sensor of the microcontroller, and c) three micro servo motors (SG90) [192]. It was supervised until the experiment had irreversible failures in its functioning.

Figure 5.5 - Design and configuration of a 3-DoF robotic arm

5.4.1. Structure layout and operation

During the second experiment, the robotic arm with the Control Board was also located at the target of the Van de Graff accelerator. It was coupled to the aluminium plate with a personalized design, as shown in Figure 5.6. The robotic arm of 3-DoF has non-Rad-Hard micro servo motors (SG90) in the joints to move each link. The robot CB has a specific microcontroller, the ATmega64M1. It has been selected because it is SMD and is the non-Rad-Hard version of the Rad-Hard microcontroller that is used for the next experiment (subsection 5.5). Besides, this Control Board has been designed with other COTS components able to bear certain radiation dose naturally. This Control Board has been designed and constructed in our laboratory. Appendix B explains and shows the CB layout, schematics and components selected.

Figure 5.6 – Robotic arm and Control Board located at the aluminium target. The robotic arm performs the trajectory commanded by the CB

Figure 5.7 - Structure layout of experiment 2. The safe zone is on the right side of the image, where there is the control room to command and monitored the robotic arm located in the accelerator area. The right side of the image shows the robot system at the irradiated zone, and the communication module and buck converter in the lead box.

Figure 5.7 illustrates the main structure layout of experiment 2. Robot CB has been controlled by a Raspberry Pi [193], which is in a safe area and supervised by the operators. The bidirectional communication is similar to the mentioned in the previous experiment (subsection 5.3). It is done through TTL serial and RS-485 to cover the long-distance until the accelerator area. This conversion has been possible by means of two MAX485 modules.

The Raspberry Pi (used as PC) controls the robotic trajectory, communication and response signal by means Qt program. It creates a protocol for sending and receiving data with a specific frame. Also, an error checking function has been added for this frame, the Cyclic Redundancy Check (CRC) [194]. This function sums up all the characters and adds the result to the end of the frame. The Raspberry PI has stored angles for the servo motors to realise a specific trajectory with the robot. These angles were previously calculated with the inverse kinematic in Matlab. Thereby, the Raspberry PI sends the respective angles to a frequency of 200 ms. Arduino MEGA processes the data frame to send it to the MAX485 modules, and later to be received by the robot CB.

Once the Control Board has checked and stored the data received, it sends specific Pulse Width Modulation (PWM) signals to each servo motor. PWM depends on the data provided by the Raspberry. This signal moves the servos to a specific position to perform the desired trajectory. After that movement, the Control Board gets the real signal position of the motors with the internal servo potentiometer. Parallel, the Control Board obtains the analogue signal of the temperature sensors and the microcontroller memories values (Electrically Erasable Programmable Read-Only Memory (EEPROM), Static Random Access Memory (SRAM) and flash) [161]. These values obtained are sent back to the Raspberry Pi to supervised the robot and microcontroller status.

The memories of the microcontroller are monitored to check if any bite has changed, and so identified soft SEE (if it is possible). In the case of appearing SEE errors or catastrophic failures, software and hardware reset have been implemented. The software was programmed with a reset signal to restart the board and mitigate possible soft errors. Alternatively, the power can be turned off to avoid possible malfunctioning of the board and motors. The Control Board and servo motors have a different power supply so that the power restart can be done separately.

5.4.1.1. Memory error detection

Dedicated application program was developed to detect and mitigate soft SEEs as SEU and SET. It is based on an Error Detection and Correction (EDAC) program [195], which read and write the content of EEPROM, SRAM and flash microcontroller memories. The purpose is detecting if some single-particle changes a binary digit of the memory [159].

The flowchart of Figure 5.8 shows the program implemented. Initially, the registers and memories are initialised, and the memories arrays are filled with pre-established values (i.e., 0x00H,0xFFH...) before starting the irradiation test. During the

experiment, the program checks the memories values in every communication, observing if some change has been produced. If so, this error is reported and analysed. Depending on the error, the microcontroller can be reset via hardware or software to reconfigure the SRAM and EEPROM. These memories have variables of the program, as opposed to the Flash memory, which can only be rewritten by uploading the program to the microcontroller. For that, it is necessary to enter the accelerator area, and it is not possible during its functioning.

Figure 5.8 - Flowchart of the SEE checking software

5.4.2. Description of the experiments

This second experiment consisted of a single gamma irradiation period until detecting an irreversible error in the functioning of the robotic arm. During this period, the Control Board and the servomotor 1 received 0.09 Gy/s, and the servo motors 2 and 3 received a radiation dose ranging from 0.09 to 0.18 Gy/s. This non-uniformity in radiation doses was a cause of the distance from the target to the accelerator output (0.26 m). Radiation varies for servo motors 2 and 3 because they were moving within the accelerator target. On the other hand, the response of microcontroller memories, temperature sensor and motors were continuously monitored during the test.

5.4.2.1. Results of the experiments

The planned robotic arm movement was executed until concluded the experiment. However, a deterioration of robotic trajectory was appreciated during the irradiation period. The irradiation was stopped after an error detection at 52 minutes 26 seconds. As Figure 5.9 shows, the error experimented provides a strange signal to the micro servo motors and the temperature sensor. This abrupt signal is produced by an internal

microcontroller reset error signal. It appears more frequently as time passes, as happens with the deterioration of the micro servo motor position signal.

This trouble was tried to solve applying the resets mechanisms and waiting several minutes. However, this error did not allow the correct operation and movement of the robotic arm to continue working. In this way, the experiment concluded at this point. After the experiment, the program was uploaded to the microcontroller via In-Circuit Serial Programming (ICSP). Surprisingly, the program could be uploaded, but the robotic arm no longer worked properly anymore.

The cumulative dose of the microcontroller ATmega64M1 has been 283 Gy. In the case of servo motors, calculate the cumulative dose is not trivial due to the non-radiation uniformity of this experiment and the different motor positions during the trajectory. The radiation received must be greater than 0.09 Gy/s, so the minimum total dose is 283 Gy. Moreover, the positions and cover of the servo motor 1 and 2 differ from the motor 3. The last one is located in a position that the electron impact directly to that. Because of that, this had a hard radiation effect that the other ones.

Concerning the electrical analysis, it was performed on the microcontroller before and after the experiment. The results conducted that the voltage of microcontroller remains the same (3.29 v), and the current had increased a little from 5.20 mA to 8.49 mA.

Figure 5.9 - The signal response gave by servo motor 3. The reset signal starts in minute 52, where the signal begins to be zero every so often. It also happened in the other servo motors and internal temperature sensor

The response and behaviour of the robotic arm elements have been assessed in detail in the next paragraphs. The following evaluation has been made assuming that the obtained values do not follow a normal or gauss distribution. It has been verified by Shapiro – Wilk test and graphically. Then, non-parametric analysis of the values has been carried out. In this case, by means Wilcoxon signed-rank test. The null hypothesis established has been the following:

H₀: There are no differences between the samples.

The H_0 hypothesis is used throughout this chapter, and it is rejected with a p-value less than 0.05.

- **Micro servo motor response:**

The motors follow a pre-established trajectory to cover the aluminium plate. For that, the servo motors angles were previously calculated. Thus the microcontroller receives the angles and gives the order to move the motors, wherein servo motor 1 and 3 follow the same trajectory, and servo motor 2 has an independent one. The response of the servo motors is atypical for this test due to the position of the motors and the uniformity of the radiation on the plate. The Wilcoxon test was performed to find out if there are differences between the position values obtained after and during the irradiation period. The p-values obtained are shown in Table 5.3. This test indicates that there is a notable difference in the position values for the servo motor 3, and a slight difference for the servo motor 2.

Table 5.3 - Test Wilcoxon results comparing the positioning of motors before irradiating and the positioning of the servo motors during the 52 minutes of irradiation (until the microcontroller failed)

Motor	P-value	Conclusion
1	$6 \cdot 10^{-1}$	Same distribution (fail to reject H_0)
2	$3 \cdot 10^{-2}$	Different distribution (reject H_0)
3	$1 \cdot 10^{-9}$	Different distribution (reject H_0)

Figure 5.10 represents the response of each servo motor. The servo motor 2 has little signal degradation during the irradiation period. In the case of the servo motor 3, it has position misadjustment that appears 30-35 minutes after the irradiation period begins. This error in position remains until the microcontroller failed. Possibly, it was more affected by the radiation due to its location on the accelerator target, wherein the electron could have directly impacted the motor system.

Table 5.4 - Test Wilcoxon results comparing the positioning of motors before irradiating and the positioning of the servo motors during the first 35 minutes of irradiation

Motor	P-value	Conclusion
1	$6 \cdot 10^{-1}$	Same distribution (fail to reject H_0)
2	$7 \cdot 10^{-2}$	Same distribution (fail to reject H_0)
3	$3 \cdot 10^{-1}$	Same distribution (fail to reject H_0)

To investigate further, Table 5.4 present the results of the Wilcoxon Test comparing the results obtained before irradiate and during the irradiation period from 0 to 35 minutes, that is, before the position error appeared in the servo motor 3. The results show how the servo motors did not have malfunction during this initial period.

a) The response of servo motor 1

b) The response of servo motor 2

a) The response of servo motor 3

Figure 5.10 – Servo motor response. Left: values obtained before being irradiated. Right: values obtained during the irradiation period (52 minutes)

- Robotic arm trajectory

Joints 1 and 2 of the robotic arm define the trajectory to be followed inside the aluminium plate. This trajectory for 2-DoF has been calculated by direct kinematics (see mathematic deduction [196], [197]). For that, the angle position of the servo motors is necessary. The positions on the x-and y-axes are obtained using Equations 1 and 2:

$$x = l_1 \cos q_1 + l_2 \cos(q_1 + q_2) \quad (1)$$

$$y = l_1 \sin q_1 + l_2 \sin(q_1 + q_2) \quad (2)$$

Wherein, l is the length of the joints and q the position angles of each servo motor. Figure 5.11 shows the robotic arm trajectory obtained with the servo motors 1 and 2. The left image compares the initial trajectory with the reference path to follow. The trajectory has a lag due to the adjustment calibration of the servo motor potentiometers. The right image shows the trajectory degradation; orange dots represent the initial trajectory, and the blue ones just before the microcontroller failed. Small variations can be appreciated on the laterals of the trajectories (-7.5 and 7.5 in x-axis).

Figure 5.11 – Robotic arm trajectory with the values of servo motors 1 and 2. Left: the blue dots represent the trajectory at the beginning of irradiation, and the orange line is the reference path. Right: the orange dots are the trajectory at the beginning of the irradiation period, and the blue dots just before the microcontroller failed.

The trajectories are more or less the same before and after the irradiation period with servo motors 1 and 2. These were not radiation affected as happens with servo motor 3. For this reason, to visualize its trajectory deterioration, a hypothetical trajectory has been created with the position angles of the servo motors 2 and 3. It has been graphed as shown in Figure 5.12. These graphs show the degradation evolution of the trajectory. In this case, the positioning error becomes more noticeable from minute 30 to 35, and the robotic trajectory starts to be different after 40 minutes of irradiation.

Figure 5.12 - Hypothetical evolution of the trajectory deterioration obtained by the position of servo motors 2 and 3. The blue dots show the robotic arm trajectory and the orange dots the reference path

The data obtained of the joint 3 (servo motor 3) has been represented as a circumference in Figure 5.13. The movements of robotic end-effector have been plotted as a circumference, following Equations 3 and 4. (θ is the angle position and r is the radius).

$$x = r \cdot \cos(\theta) \quad (3)$$

$$y = r \cdot \sin(\theta) \quad (4)$$

Figure 5.13 shows the trajectory degradation, wherein it is possible to observe how it differs from the original one. The blue is the reference path, and the orange is the path done after 35 minutes of cumulated radiation.

Figure 5.13 - The trajectory of the robot end-effector. It represents the position values of the servo motor 3) in a circumference. The blue lines are the reference path and the orange ones the trajectory obtained after 35 minutes of irradiation

- Temperature sensor response:

The microcontroller has an internal sensor. It has been irradiated until a total cumulated dose of 283 Gy. The Wilcoxon test has been applied to know if there are differences between the temperature sensor values obtained before and during the irradiation period. The Wilcoxon test determined that the null hypothesis is violated with a p-value notably less than 0.05. The box plot of Figure 5.14 makes these differences evident.

Figure 5.14 - Box plot representing the values of the internal microcontroller temperature sensor. The blue box represents the values obtained before irradiate, and the orange box the values obtained during 52 minutes of irradiation

Figure 5.15 shows the temperature values evolution in detail. The graph on the left shows the values after the irradiation test, and on the right, the values registered during the irradiation period. The curiosity of these values is a slight increase in the values. As is possible appreciate, it happens 2 minutes after the microcontroller reset error.

Figure 5.15 - Internal microcontroller temperature sensor response. Left: before being irradiated. Right: during and after the irradiation period. The red line marks when the microcontroller starts to fail

The sensor presents some noise, as Figure 5.15 represent on the graphs. It is because the control program has not implemented a sensor noise filtering algorithm.

5.4.3. Discussion

Microcontroller ATmega64M1, internal microcontroller temperature sensor and micro servo motor (SG90) responses have been analysed to know the radiation effects during the gamma irradiation period of 52 minutes.

- **Microcontroller analysis**

Microcontroller ATmega64M1 started to fail after 283 Gy of accumulate radiation dose. The fail was a reset signal every so often, which increases over time, as shown in the graph of Figure 5.9. This reset signal stopped the correct functioning of the robot system. Datasheet of Atmega64M1 specified that this microcontroller has three reset signals [198]: Power-on Reset (POR), Brown-out Reset (BOR) and Watchdog Timer (WDT). After the reset occurred, access to the microcontroller to determine the type of reset was not possible via software. Therefore, an evaluation of the electronic analysis and the causes of the reset has been set out below.

BOR could be produced since the electronic testing done after stopping the accelerator indicates an anomaly with the microcontroller current, which rose from 5.20 mA to 8.49 mA. It suggests a possible impedance reduction or leakage of current, which could cause an internal voltage problem, giving a Brown-out Reset when the voltage was under the limit established. It could instigate internal microcontroller damage, creating a malfunctioning of the system. Moreover, the internal microcontroller temperature sensor experimented a temperature rise two minutes before the reset failed. It is known that a leakage current produces an increase in temperature. Therefore, this information can give us an idea that when started the internal deterioration.

In this way, the leakage currents of the microcontroller pins were checked in the laboratory. The analysis was carried out by comparing the values (high and low) of a non-irradiated microcontroller with the same program as the irradiated microcontroller. The results point out that the irradiated microcontroller has different current values in various pins, and the leakage current threshold proposed by the manufacturer is also exceeded (50nA). The discovery was an increase in current at the crystal pins, which are connected to the external clock. This component determines the speed with which the microcontroller operates. A problem in the functioning of this component can cause a violation time on the instruction, where the WDT would be triggered.

A single particle could also provoke a SEEs on the microcontroller CB. Soft SEEs were monitored on the microcontroller memories (EEPROM, SRAM and flash), such as SEU, Multiple Bit Upset (MBU) or SED. However, no memory status changes or register bits were detected. Other different SEEs have been evaluated finding similitudes with microcontroller behaviour. SEFI has similitudes with the microcontroller response. Its error causes a component to restart, crash or malfunction in a detectable way [145]–[148]. Nonetheless, the temperature rise could be a key to ruling it out, or there was another phenomenon that caused the damage to the microcontroller.

Sometimes a power cycle of the device on time can restore normal operation [121]. However, the software and hardware reset didn't solve the problem in this experiment. Another method is to reload the microcontroller program. This was done after finishing the test, but it still never worked properly again. Therefore, the damage created by the accumulated ionising dose was already remarkable and irreversible.

After making the analysis and research other results, the predominant effect of the gamma radiation in CMOS devices is the ionising dose effect. It produces a degradation of the components due to the cumulated radiation. As the literature mentioned [141], TID generates trapped charge in oxides and at interfaces [199], potentially changing the threshold voltage and increasing leakage currents that can result in various circuit-level impacts including increases in propagation delays [200]. These can modify the electrical parameter of the device, and deteriorate its characteristics [121], leading to the malfunctioning of the microcontroller. The effects experimented coincide with those described in the literature. Moreover, the reference [141] cites that the TID effect can be observed before appearing the failure, as happens in our experiment.

- **Micro servo motor analysis**

The ionising radiation effect on the microcontroller apparently did not disturb the servo motors operation. Only the response was perturbed once the internal reset error appears. Instead, the radiation unevenly affected each motor, as it happens in a real environment. The servo motor 3 turned out to be the most affected. The servo motors are formed by organic compounds like lubricants, seals elastomers, and other sensitive components to the radiation as the potentiometer (position sensor) or Integrated Circuit, see Figure 5.16 a). The radiation tolerance of them depends on the type of material and components [10].

Figure 5.16 – Main parts of a servo motor and the position control loop implemented

The weak points of the servo motor have been listed below:

- 1) The potentiometer has integrated a resistive material, which can be either different types as carbon composition, wire conductive plastic, cermet [201].

Depending on the radiation resistance of the material [10], [111], it could produce an error in the potentiometer position.

- 2) The Integrated Circuit to control the servo motor motion can bring about problems with radiation. It usually integrates a signal amplifier and controller (e.g., kc9102).

The most affected servo motor was checked in the laboratory. The potentiometer and DC motors gave correct values when analysed. Therefore, the deterioration of the signal has occurred due to the Integrated Circuit for controlling the position of the servomotor, which is a radiation-sensitive component.

5.4.4. Result conclusions

According to the results of the experiment, it is possible to conclude that:

- The microcontroller starts to fail with lower radiation levels (0.09 Gy/s). The ATmega64M1 failed with a 283 Gy of accumulated dose. However, it did not have bad behaviour before starting to send the reset signal.
- The degradation of the microcontroller begins to be noticed in the internal temperature sensors 2 minutes before the first internal reset appears. There was a temperature rise due to the microcontroller deterioration. However, this was not perceptible by the servo motors data.
- The performance of the servo motor was “apparently” unaffected when the microcontroller was irradiated. It was only noticeable when the microcontroller started sending a reset signal.
- The radiation has degraded the response of some servo motors. It was not the same for all the servo motors, and the positioning error did not happen immediately after starting to irradiate.
- Robot trajectory can deteriorate when it is operating under gamma radiation. It can appear progressively or ipso facto. It is related to the radiation effect or degradation of the robot actuators or electronic device. The dose rate is a relevant factor; another experiment with a low dose of radiation ($2 \cdot 10^{-3}$ Gy/s) have not seen noticeable changes in the robot trajectory [174].

5.5. Experiment 3: Comparative between microcontrollers and methods to minimise the radiation effects

This third experiment tests different types of electronic devices for three purposes. The first is to compare several options to alleviate or avoid the radiation effects on electronics. The methods proposed in this test are:

1. Radiation hardener: components with radiation resistance.
2. Shielding: electronics are shielded with a protective material (e.g., lead) [10], [121].
3. Relocation: sensitive electronics are placed in a safe area with less or no radiation.

The second objective aims to analyse the behaviour and effect of radiation on different types of microcontrollers. The microcontrollers used for this irradiation test have been: 1) ATmegaS64M1 [202] and 2) ATmega328P. The novelty of ATmegaS64M is that it has some radiation resistance (up to 300Gy of TID), and the other one no. The microcontroller dimensions and technology are also different. The ATmegaS64M1 is small encapsulated since it is SMD (TQFP), and the ATmega328P is bigger because it is a DIP package. The third purpose has the goal of evaluating the sensors and actuators response under radiation, particularly the servo motors and temperature sensors.

Figure 5.17 - Control Boards, servo motors and sensors on the aluminium plate to be irradiated at the target of the Van de Graff accelerator

In this way, to carry out comparisons between microcontrollers and the methods to minimise the effects of radiation, different CBs have been evaluated individually. Each Control Board has associated various servo motors and temperature sensors, as Figure 5.17 shows. During the experiment, the response of the microcontrollers, servo motors and temperature sensors was monitored and supervised in real-time by the operators. The test was performed until irreversible failures in the operation of the mainboards were detected.

5.5.1. Structure layout and operation

This irradiation test has been conducted to get more relevant information about the radiation effects. In this case, different mitigation methods are compared. Some components have been exposed directly to the radiation, and others have been located outside the radiation area. The four Control Boards tested have been the following:

1. (Rad-Hard) Control Board with special Rad-Hard microcontroller (ATmegaS64SM1). It controlled: a) One Parallax Standard servo motor and b) One LM35 temperature sensor [203] and one internal temperature sensor of the ATmegaS64M1 microcontroller. The Rad-Hard board has been designed with components able to resist certain radiation doses. The microcontroller was specially selected to be Rad-Hard since it is one of the most sensitive devices [10]. Appendix C shows the Printed Circuit Board (PCB) layout and principal components of that.
2. (Shield) An Arduino Uno board (conventional ATmega328P microcontroller) protected in a 2 mm lead box. It controlled: a) two Parallax Standard servo motors (one servo motor shielded with 2 mm lead and the other unshielded), and b) two LM35 temperature sensors.
3. An Arduino Uno board (conventional ATmega328P microcontroller). It controlled: a) two Parallax Standard servo motors (one servo motor shielded with 2 mm lead and the other one not), and b) two LM35 temperature sensors.

Outside the irradiated area, in a place with lead protection, was located:

4. (Relocate) An Arduino Uno board. It controlled three Parallax Standard Servo motors: one of them located in the protected area and the other two were in the irradiation target (one servo motor shielded with 2 mm lead and the other one not).

Figure 5.18 describes the distribution and elements mentioned. They are connected to the control room and are monitored by the operators in a safe radiation place. The software functioning is similar to the described in experiment 2 (subsection 5.4). The communication also is the same as experiment 1 (subsection 5.3). It is done via TTL serial and RS-485 due to the distance, making the conversion by means the MAX485 modules. The discrepancy in this third experiment is the different microcontroller used at the same time and conditions.

As the experiment 2, the Raspberry Pi send different position references for the servo motors. Each Control Board executes the position value it has received. Then, each one obtains the data of its temperature sensors, potentiometer of the servos (position sensor) and status of the microcontroller memories. As the other experiments, these values are visualized in a display to be supervised by the operators in the control room.

Figure 5.18 - Structure layout of experiment 3. The control room (left side of the image) is located in a safe place to command and monitor the components located on the accelerator area (right side of the image)

Concerning the control system implemented, it also has software and hardware reset to restart the system in case of malfunction. The software restores the program on the Control Board, and the hardware reset consists of turning the power supply off and on. The advantage is that the architecture implemented allow reset each Control Board and servo motors individually, without the need to reset other elements that were working correctly.

5.5.2. Description of the experiments

The samples were irradiated for 38 minutes. The radiation dose was 0.18 Gy/s during the first 29 minutes. After that, the radiation was multiplied per ten to reach 1.5 Gy/s. This dose was maintained until concluding the test 9 minutes later. This increase was made to see if the radiation affected the protected Arduino, sensors or motors.

During the irradiation test, the accelerator was stopped when the Control Boards failed. During this period, several attempts were made to try to recover the CBs that were failing. It was done viewing the errors, and subsequently, sending software reset signals and turning off the power to reset the system.

5.5.2.1. Results of the experiments

The main information about the experiment is summarised in Table 5.5, wherein it details the irradiation periods, the dose rate and the cumulative dose for each case. The first irradiation was stopped after the Rad-Hard Control Board began to fail (195 Gy of cumulative radiation dose). The second irradiation period stopped when Arduino Uno had a hard fail (221 Gy of cumulative radiation dose). The third irradiation was finalised

to increase the radiation dose, and the last period concluded 9 minutes later when the system reached a total cumulative dose of 1128 Gy. The accelerator operators decided to stop the experiment at this moment.

Table 5.5 - Description of the irradiation periods

Periods	Irradiation time	Radiation (dose rate) (Gy/s)	Radiation (cumulative dose) (Gy)	Observations
First	18 minutes 06 seconds	0.18	195.48	Fail RadHard Control Board
Second	2 minutes 26 seconds	0.18	26.28	Fail Arduino Uno
Third	9 minutes	0.18	97.2	-
Four	9 minutes	1.5	810	-
Total	38 minutes 32 seconds		1128.94	

Arduino Uno inside of 2 mm lead box didn't cause any trouble or incidence since the lead brake the electron penetration and the radiation gamma that reached the Arduino Uno Control Board was lower. The same happened with the Arduino Uno relocated outside of the accelerator target area. However, the servo motors and the temperature sensor response were affected under radiation. Their response has been assessed in detail in the next subsections.

The obtained values do not follow a normal or gauss distribution; this has been verified by Shapiro – Wilk test and graphically. Then a non-parametric analysis of the values was carried out.

5.5.2.1.1. Results and analysis of the Rad-hard Control Board (ATMegaS64M1)

The Rad-Hard board did not show abnormal behaviour until 18 minutes and 6 seconds after being irradiated, 195 Gy of cumulative dose. The microcontroller began to send a constant reset signal that did not allow continue with the experiment. Software and hardware reset was done, but the Control Board did not work correctly any more. Therefore, the board could no longer be used.

- Servo motors:

The motor response usually has more outliers and dispersion values when it is being irradiated than when it has not been irradiated, see the box plots in Figure 5.19. The Wilcoxon test confirms it, the null hypothesis that establishes similitude between samples are violated in some references (p-value of the order of 0.01), specifically for motor angles from 60° and 160°.

Figure 5.19 - Box plot that represents the servo motors response for each angle reference, from 0 to 160. The blue boxes represent the servo motor response without radiation. The orange boxes indicate the servo motor response for each position reference during the irradiation period

Figure 5.20 - Evolution of servo motor response during 18 minutes of irradiation

Figure 5.20 shows the servo motor response evolution in detail during the irradiation period of two angle references (60° and 80°). It shows an upward in the last few minutes before the microcontroller gave fault signals.

- Temperature sensor:

Two temperature sensors were irradiated: the internal temperature sensor of the microcontroller and the external sensor (LM35). The values obtained have been (Internal sensor: $\text{mean}_{\text{initial}}:40.22$, $\text{std}_{\text{initial}}:2.39$, $\text{mean}_{\text{end}}:39.07$, $\text{std}_{\text{end}}:2.69$), (External sensor: $\text{mean}_{\text{initial}}:23.39$, $\text{std}_{\text{initial}}:0.64$, $\text{mean}_{\text{end}}:25.27$, $\text{std}_{\text{end}}:1.85$).

Figure 5.21 - Box plot representing the temperature sensors values. Left boxes show the internal microcontroller sensor values, and the right ones the values provided by the LM35 temperature sensor. The blue boxes are the data obtained before irradiate and the orange ones during the irradiation period

In both cases, the Wilcoxon test was applied, and the null hypothesis was rejected. The p-value in both cases is much less than 0.05. It concludes that the radiation affected the sensor values. Figure 5.21 shows these effects, as it represents the differences between the sensor after and before being irradiated. However, as shown in Figure 5.22 and Figure 5.23, this affectation becomes noticeable after 10 minutes of irradiating. From that moment, the LM35 sensor begins to record higher temperature values. The internal sensor of the microcontroller has more outliers below the mean value, and a temperature rise occurs 2-3 minutes before the failure of the CB.

Figure 5.22 - LM35 response. The graph on the left represents the values of the sensor before the irradiation and the graph on the right during the irradiation period

Figure 5.23 - Internal temperature sensor ATmegaS64M1 response. The graph on the left represents the values of the sensor before the irradiation and the graph on the right during the irradiation

As Figure 5.20, Figure 5.22 and Figure 5.23 represent, the value of temperature sensors and motors have noise before and after being irradiated. It is due to several factors such as the non-linearity of the potentiometers and the digital analogue converter, where each sensor has a different uncertainty, so a calculation of said uncertainty must be made to filter the noise. In this case, the control program did not have any filtering algorithm to reduce noise. Instead, the Arduino boards have the Arduino Integrated Development Environment (IDE). It performs the transformation from bits to a numerical value. It only takes integer values, so it has less precision in the final measurement value [204].

5.5.2.1.2. Results and analysis of the Control Board Arduino Uno (unshielded lead)

The ATmega329 microcontroller of the Arduino Uno did not show considerable abnormal behaviour during the irradiation period. The total duration of the microcontroller was 20 minutes and 26 seconds, with a cumulative dose of 221 Gy. The microcontroller had a hard error that disabled the Arduino Uno board functioning. The most likely cause of failure is that microcontroller reached the maximum TID for this time and radiation dose, leading to a catastrophic failure.

- Servo motors:

Figure 5.24 shown a prominent error in the position of the motors, which evolves equally. These values started to increase after 16 minutes of irradiation at 0.18 Gy/s, and 4 minutes after appeared the irreversible microcontroller reset error. It indicates a problem with the microcontroller.

a) Values of servo motor without lead shield

b) Values of servo motor with a lead shield

Figure 5.24 - Servo motor response before and during the irradiation period (with shielding and without). The examples show the angle references for 40° and 80°

The shielded and unshielded motors show greater differences in positioning before and after being irradiated. It can be observed in the box plot of Figure 5.25 and Figure 5.26, where notable differences are observed. Wilcoxon's test clearly rejects the null hypothesis of similarity, granting a p-value less to 0.001. This value decreases as the system accumulates radiation, wherein the system also is being more affected. Furthermore, the Wilcoxon test indicates that there are more differences between the values obtained with the unleaded motor. However, this is verified with the results obtained from the Arduino placed outside the irradiated area.

Figure 5.25 - Box plot representing the position of the servo motors with shielding. The blue boxes (left side) are the data without radiation and the orange boxes (right side) during the irradiation period. It shows the data for each angle position

Figure 5.26 - Box plot representing the position of the servo motors without shielding. The blue boxes (left side) are the data without radiation and the orange boxes (right side) during the irradiation period. It shows the data for each angle position

- **Temperature sensor:**

Two temperature sensors LM35 have been monitored. The influence of radiation has been clearly noticed, (Sensor 1: $\text{mean}_{\text{initial}}:23.0$, $\text{std}_{\text{initial}}:0.0$, $\text{mean}_{\text{end}}:25.83$, $\text{std}_{\text{end}}:6.36$), (Sensor 2: $\text{mean}_{\text{initial}}:24.0$, $\text{std}_{\text{initial}}:0.0$, $\text{mean}_{\text{end}}:28.42$, $\text{std}_{\text{end}}:6.80$).

Figure 5.27 - Evolution of the values provided by two LM35 temperature sensors. These graphs represent the first and second irradiation period (represented in blue). The values obtained in the irradiation pause are in yellow, wherein the values are constant

Figure 5.27 illustrates as the temperature values increment considerably after 13 and 7 minutes of start to irradiate the samples. Interestingly, the temperature values are approximately constant when the accelerator is stopped. However, once the accelerator is reactivated, the values continue to rise until the ATmega328P microcontroller fails. It evidences the radiation effect on the temperature sensor. The box plots of Figure 5.28 clarifies this radiation affectation.

Figure 5.28 - Box plot representing the temperature values of two LM35 sensors. It compares the values before and during the irradiation period. The line represents constant values, which is reasonable if there is no radiation

5.5.3.1.3. Results and analysis of the Control Board Arduino Uno (with lead)

Unlike previous tests, the Arduino Uno was inserted in a lead box. Braking radiation or Bremsstrahlung generates ionising radiation when it hits a charged particle in a material. The penetration of this particle depends on the type of material. In this case, the impact is made against a lead box and not directly on the electronics devices. In this way, less amount of radiation produced after the impact reaches the electronic board located inside the box. It was not possible to know the accumulated dose received by the microcontroller, but it could be experienced that this received less radiation and its consequences. It did not fail during the irradiation period of 38 minutes (29 minutes at 0.18 Gy/s and 9 minutes at 1.5 Gy/s). For more information, some tables indicate the level of gamma radiation absorption in function on the material and thickness [10], [121].

- Servo motors:

a) Values of servo motor without lead shield

a) Values of servo motor with a lead shield

Figure 5.29 - The behaviour of servo motors (with lead and without) during different periods. The examples show the angle references for 20° and 40°

The servo motors comply with the Wilcoxon null hypothesis during the 29 min irradiation period at a dose of 0.18 Gy/s; relevant differences cannot appreciate. Nevertheless, during the last irradiating period at 1.5 Gy/s, this hypothesis starts to be violated ($p\text{-value} = 1 \cdot 10^{-4}$). Certain outliers are observed for both servo motors (with lead and without), this detail can be appreciated in Figure 5.29. Thereby, the radiation dose at this period is “high enough” to affect the operation of the microcontroller or servo motors. According to the Wilcoxon test, the positioning degradation of both motors is more or less similar. However, when the accelerator stopped emission, the outliers disappeared, as shown in Figure 5.29.

- Temperature sensor:

The Arduino with a lead shielding has two LM35 sensors, one located outside the lead box, and the other inside (Sensor 1 interior: $\text{mean}_{\text{initial}}: 21.0$, $\text{std}_{\text{initial}}: 0.0$, $\text{mean}_{\text{end}}: 21.130976$, $\text{std}_{\text{end}}: 0.52$), (Sensor 2 exterior: $\text{mean}_{\text{initial}}: 27.69$, $\text{std}_{\text{initial}}: 0.45$, $\text{mean}_{\text{end}}: 27.15$, $\text{std}_{\text{end}}: 0.49$). The mean value of both sensors is very small before and after irradiation. In contrast, the sensor outside of the lead box presents a greater dispersion of values as the box plot of Figure 5.30 represents, and Wilcoxon test verifies. Figure 5.31 presents an increment of the temperatures values minutes after of stop the irradiation test. The curiosity is that the values of the LM35 sensor (outside the lead box) increase linearly after stopping the accelerator. It is unusual because the ambient temperature does not rise after the accelerator is turned off, and in this case, the microcontroller was not damaged. Thus, it denotes that the temperature sensor is broken. It was verified in the laboratory, where the irradiated sensor gave a value of 1.40 v under temperature ambient. In contrast, the shielded sensor provided 0.26 v. (LM35 voltage is directly proportional (linear) to temperature, where there is a rise of 10 mV for every 1 °C in temperature).

Figure 5.30 - Box plot representing two LM35 temperature sensors values (one outside of the lead box and the other one inside). The lines mean that the values obtained are the same or similar

Figure 5.31 - Evolution of the temperature sensor data in the last irradiation periods and after concluding the experiment

5.5.3.1.4. Results and analysis of the Control Board Arduino Uno (outside accelerator target)

Figure 5.32 - Response and evolution of the data between the different servo motors for a reference of 80°. a) servo motor outside the irradiation area, b) servo motor with lead and c) servo motor without lead

Figure 5.33 - Response and evolution of the data between the different servo motors for a reference of 140°. a) servo motor outside the irradiation area, b) servo motor with lead and c) servo motor without lead

The most delicate robot piece, the electronic Control Board (Arduino Uno), was located outside the irradiated area. This board controlled three motors: one located outside the

irradiated zone as the Control Board, and the other two were in the accelerator target. These motors were irradiated until the test was stopped, after 38 minutes with a cumulative dose of 1228 Gy/s. Considering that the servo motor with 2 mm lead protection did not receive the same amount of radiation as the motor without protection.

The responses between the three servo motors have been compared, the motor located outside the irradiation zone presented a correct response throughout operation (see Figure 5.32 and Figure 5.33). Contrarily, motors situated in the irradiated area show a more significant number of outliers during the irradiation period, becoming more noticeable with the accumulation of radiation. Wilcoxon's p-value violates the null hypothesis for the irradiation period of 1.5 Gy/s. The shielded and unshielded motors showed differences in the position references response. However, the servo motor without any protection has been the most affected. Subsequently, those outliers remain when the radiation stop after 38 minutes, as seen in the graphs c) of Figure 5.32 and Figure 5.33. Thus, the radiation has been able to cause permanent damage to them. The bottom line is that radiation also affects the positioning of the servo motors, regardless of whether the Control Board is being irradiated or not.

5.5.3.1.5. Radiation effect on the nylon material

The system had nylon nuts to tighten some components at the accelerator target. Figure 5.34 exhibits a visual degradation, the nut on the left had a direct impact of the electrons and radiation. The others were at the rear of the target.

Figure 5.34 - Visual degradation of nylon nuts

The nylon is a polymer of the polyamide family. As the literature mentioned, it has low radiation resistance [111]. Although, other deterioration properties such as tensile was not observed after 1 MGy.

5.5.3. Discussion

This subsection makes a review of the third experiment, and analyse the result obtained of the microcontrollers, servo motors and temperature sensor.

- **Microcontroller analysis:**

Rad-hard Control Board with ATmegaS61M1: Rad-Hard microcontroller originated a constant reset when it failed, and this became an unserviceable device. The response of all servo motors and temperature sensors makes evidence a progressive increment of the values obtained (position angles and temperature degrees) minutes before appearing the first microcontroller reset signal. It could be due to an Analog to Digital Converter (ADC) problem on the voltage of reference, where the comparators were incorrectly converting the sensor values. The damage increased over time until the microcontroller detected prominent damage. At this moment, the microcontroller activated a protective reset (Brown-out Reset), and it entered in a reset loop to protect it of bad functioning, such as an internal voltage problem on the internal microcontroller components. It is important to remember that long-term cumulative ionising damage could degrade the microcontroller [205]. It may induce threshold voltage shifts, leakage increase, and deteriorate its functionality [206], [207]. However, the curiosity is that the microcontroller started to fail under a TID below the value recommended by the manufacturer (300Gy) [202]. Alternatively, SEEs also could happen: SEFI can cause have continuous exceptions, run standby, or enter an unknown and unrecognisable state. SEB can provoke the destruction of the device due to a high current state in a small area of an Integrated Circuit. And also a SEGR, which is associated with a gate dielectric rupture causing increased leakage current, causing overheating and destruction.

The progressive increase of the temperature sensor data and the positioning error in the servo motors evidence an internal degradation of the microcontroller. The electronic analysis was not done after the fails because the radiation testing continued with the other CBs. Nonetheless, the Arduino inside of the lead box and the other one outside the irradiated area didn't suffer any alteration or fail. The electronic analysis was done after the accelerator shut down. This analysis presented more low current on the microcontroller after an accumulated dose of 1 MGy.

Arduino Uno (ATmega328P): Arduino Control Board suffer an immediate hard fail after 221Gy of accumulate dose. The degradation of the microcontroller was perceptible on the LM35 temperature sensor and servo motor signal, which presents a progressive increment of the data obtained after being irradiated for 7 minutes. Therefore, a catastrophic failure due to ionising damage could happen.

- **Servo motor analysis:**

The servo motors have shown differences between positioning before and during the irradiation period. It has been seen in an increase in outliers, especially for motors that were irradiated at 1.5 Gy/s. In the case of the microcontroller that was directly exposed to the radiation, the actuators showed how the positioning values increased minutes before the microcontroller failed. Moreover, small differences have been noted between partially shielding and non-shielding servo motors.

As was mentioned in subsection 5.4.3, servo motors could be affected by several internal elements such as the potentiometer, control circuit and DC motor. The

potentiometer and control circuit are the most susceptible. Nevertheless, it depends on the position, type of potentiometer resistor material and the devices of the motor controller circuit.

- Temperature sensor analysis:

Table 5.6 exposes the temperature sensor mean values obtained before and after the irradiation period.

Table 5.6 – Temperature sensor data obtained without radiation and during the third irradiation experiment. It shows the mean values, standard deviation and de cumulative dose for each sensor

Micro-controllers	Type of temperature sensor	(No) radiation		(Yes) radiation		Cumulative dose (Gy)	Status after 1 MGy
		Mean	Std	Mean	Std		
Control RH board (ATmegaS64M1)	Internal μc sensor	40.22	2.39	39.07	2.69	195	-
	LM35	23.39	0.64	25.27	1.85	195	Broken (1.40 v – 26 °C)
Arduino Uno (ATmega328P)	LM35 (1)	23.0	0.0	26.06	6.36	195	Broken (1.37 v – 26 °C)
				25.83	6.80	221	
	LM35 (2)	24.0	0.0	28.48	7.48	195	Broken (1.35 v – 26 °C)
				28.42	6.80	221	
Arduino Uno inside a lead box (ATmega328P)	LM35 (1)	21.0	0.0	21.13	0.33	194	Broken (1.41 v – 26 °C)
				21.11	0.32	221	
				21.08	0.28	319	
				21.29	0.52	1128	
	LM35 (2) inside of lead box	27.69	0.45	27.47	0.49	Not defined	No broken (0.26 v – 26 °C)
				27.31	0.66	Not defined	
				27.22	0.57	Not defined	
				27.15	0.49	Not defined	

During the third experiment, it was possible experimented on the sensors the following behaviour:

1. Temperature sensors had affected minutes before the microcontroller failed.
2. The degradation signal appears early in the LM35 sensors than the internal microcontroller temperature sensors.
3. The LM35 sensor, during a radiation dose of 0.18 Gy/s, has less deterioration when the CB is shielded or dislocated.
4. All LM35 directly exposed to radiation show an irreversible deterioration in the signal after accumulating 1 MGy and being irradiated at a high dose (1.5 Gy/s) for 9 minutes. They provided greater voltage values than a no irradiated LM35.

Table 5.6 shows the values for each sensor after the irradiation test.

5.5.4. Result conclusions

According to the results experienced during the experiment 3, it can be concluded that:

- Rad-Hard microcontroller failed before a non-Rad-Hard microcontroller.
- ATmegaS64M1 failed with a TID lower than what the manufacturer provides.
- ATmegaS64M1 could be not recovered applying software reset and restoring the power supply when the reset signal appeared.
- Microcontrollers ATmega328P and ATmegaS64M1 evidenced the deterioration incrementing the values obtained by the temperature sensors and servo motors connected.
- Lead with a thickness of 2 mm stopped the radiation gamma penetration.
- The irradiation altered the values of the servo motors located in the irradiation area. It has been more noticeable for the unshielded servo motor (see Figure 5.32 and Figure 5.33).
- The irradiation altered the values of the temperature sensor located in the irradiation area (see Figure 5.28). The deterioration is more evident with high levels of radiation (1.5 Gy/s).
- After finalising the irradiation test, the LM35 sensors exposed directly to the irradiation did not return to give correct temperature values.

Chapter 6

Remote Handling in IFMIF-DONES

There is a growing demand for RH in some accelerator facilities due to the harsh environmental conditions. IFMIF-DONES is following the recommendation to detail the RH activities in the design phase. It is defining, designing and developing the RH operations and equipment required during the facility lifetime. This chapter shows some RH operations needed to maintain critical components of the accelerator and irradiation cell of IFMIF-DONES.

6.1. Introduction

Energy is essential and fundamental to our society. It allows us to light our houses, heat buildings, drive cars, operate machines, and more. The way of obtaining electricity has been changing and evolving over the years, although the leading energy providers have been fossil fuels. However, there are two significant issues with fossil fuels: they pollute the atmosphere and they are running out. Hence, the humanity is looking for alternatives as our main source of energy, especially a safe, abundant and less harmful energy source to the environment. Examples of this type of energy sources are wind, solar, solar photovoltaic, solar thermal, biomass, geothermal, nuclear fusion, tidal, and biofuels.

In nature, nuclear fusion occurs in stars, including the Sun. For that reason, it is said to be the “energy of the stars”. Nuclear fusion promises to be the energy of the future. Nevertheless, this source is one of the more enormous challenges that humanity has ahead since recreating the sun's energy source requires demanding conditions. The fusion is based on a nuclear reaction that releases energy stored in the nucleus of an atom. It also happens in nuclear fission, but there are important differences between both. In the main, a nuclear fusion reactor is intrinsically safe. The reaction stops when the fuel supply is cut off, so there would be no risk of explosions or nuclear accidents. Furthermore, energy fusion is clean energy. It does not produce harmful gases and nuclear waste that it generates has low activity.

To understand it in more detail, nuclear fusion basically consists of the union of two light nuclei to form a heavier one. The easiest reaction to get is one that fuses a nucleus of deuterium and tritium. However, to join two positively charged nuclei it's necessary to have very high temperatures (close to 200M °C). It is the way to confer nuclei, increasing kinetic energy to overcome their natural repulsion, and so the nuclei can fuse. The result of the fusion of these elements generates 17.6 MeV of energy, helium (a completely harmless gas) and a neutron surplus, as shown in Figure 6.1.

Figure 6.1 - Nuclear fusion with deuterium and tritium reaction. This reaction produces energy, helium and a neutron. (Source: chemwiki.ucdavis.edu).

Nuclear fuel is converted to plasma at a very high temperature, which makes it complicated to handle the substance. For this reason, scientists have developed and used different strategies to maintain plasma and fuse nuclei: magnetic confinement and inertial confinement. Magnetic confinement is the best known. It has led to notable developments in recent decades. For example, it is the one used in Tokamak and Stellarator reactors such as JET, ITER and Wendelstein 7-X in Germany [208]. Nevertheless, the scientific challenges of using magnetic confinement in reactors are critical and numerous. To summarise, these can be condensed into two:

1. Materials capable of withstanding the demanding working conditions of a nuclear fusion reactor, specifically inside the reactor.
2. The magnetic field has to be controlled with the necessary precision for an extended period. It is relevant because if not, the plasma can touch the contained walls, and it can melt the walls due to the high temperature of the ionized gas (plasma). Also, if this happens, the plasma can be cooled, and the fusion will stop.

The goal is to make nuclear fusion profitable. For that, it is necessary to recreate appropriate conditions, achieving a high probability that the deuterium and tritium nuclei will fuse. It is vital to ensure that the energy needed to be invested in the system is less than the energy obtained as a result of these mergers. For this objective, the experimental fusion reactor ITER is being built [209]. ITER aims to demonstrate the feasibility and profitability of fusion energy. It is of great importance for the future commercial fusion reactor as the DEMOnstration Power Station (DEMO) reactor [210], which is planned to start operating in 2040-2050. However, DEMO not only needs to know the viability of ITER, but also depends on the results obtained by the installation of IFMIF-DONES. It is a crucial piece in the field of materials engineering since it pretends to solve one of the great problems of materials in the fusion reactor.

6.2. Background and objectives

The irradiation environment in future fusion power plants is characterised by the presence of 14 MeV fusion neutrons in the first wall area [211], [212]. It produces a degradation of the materials and properties of the components, which is a problem for the safety and operational life of fusion reactors. For a deep understanding of the radiation effects on materials, it's necessary to have a fusion neutron facility. According to the scientific community, the best option for a materials irradiation facility is an accelerator-based source that uses lithium-deuterium nuclear reaction. It produces a wide spectrum of energy that completely covers the spectrum of the fusion reactor in the region of the first wall, and it also is capable of reproducing the nuclear responses responsible for material damage under irradiation [212].

To achieve these objectives, an international scientific research program was proposed in the 1990s, a project called IFMIF. Since 2006, it was agreed to address the

so-called IFMIF/ Engineering Validation and Engineering Design Activity (EVEDA). In this framework, IFMIF/EVEDA produced in 2013 the “IFMIF Intermediate Engineering Design Report” (IIEDR). It is an intermediate IFMIF engineering design for a generic site [213]. The IIED Report assumes that IFMIF's mission is to produce the materials irradiation test data required for the design, licensing, construction and safe operation of DEMO. Since 2015, EUROfusion and Fusion for Energy (F4E) started a process to develop the engineering design of DONES (DEMO Oriented Neutron Source) and to identify possible European Union (EU) sites to host the facility. The objective to develop the design of DEMO oriented irradiation facility up to such level that it is ready for the start of the DONES construction as early as 2020 [76]. Finally, the country candidate to host the DONES facility has been Spain.

IFMIF-DONES facility aims to be a novel research infrastructure to test, validate and qualify the materials to be used, especially for design and construction the future fusion reactors as DEMO. The materials must be tested under similar conditions to those produced inside the reactor, where these must be able to resist high-energy neutrons and high heat flux from fusion systems.

6.2.1. Mission of DONES

The goal of DONES is to create a neutron source that produces high-energy neutrons with sufficient intensity and irradiance volume to achieve various purposes [76], [212]:

- Generate material irradiation test data, relevant to anticipated needs in radiation resistance for structural materials in DEMO. This information will be handy for the design, licensing, construction and safe operation of the Fusion Demonstration Power Reactor.
- Generate a database for the comparative evaluation of the responses to radiation of materials from materials computational science.

As reference [212] mentioned, various technical objectives must be met in the DONES facility to achieve the cited purposes. These are related to the neutron spectrum, neutron fluence, temperature range, dpa and temperature in high flux region.

As it has been appreciated, this facility is relevant to the scientific world as it will provide relevant knowledge for future nuclear fusion facilities and, in turn, a database on the behaviour of certain materials, which could be very useful in other areas. Additionally, DONES is expected to be available during ITER operation. In this way, DONES could help ITER in some aspects of its operation phase.

6.3. IFMIF-DONES Performance

IFMIF-DONES consists of a 40 MeV, 125 mA deuteron linear accelerator in continuous wave mode [212]. The deuterium beam strikes on a rectangular target of liquid Li curtain

of 25 mm thick located at the Test Cell. The Lithium flows at 15 m/s, to dissipate the beam power, and generate a neutron flux of $\sim 10^{14} \text{ cm}^{-2} \text{ s}^{-1}$ with neutron spectrum up to 50 MeV energy [214]. It reproduces the expected condition of fusion power plants [212]. The specimens to be tested are in the High Flux Test Module (HFTM) component. It is also located in the Test Cell, behind the lithium target (i.e., Target Assembly). So that the neutron beam irradiates the materials and damage rates can be obtained under controlled temperature conditions. To simulate the behaviour suffered inside a reactor, the material samples will be kept for a long irradiation period (up to two years). Subsequently, these are partially dismantled, and the irradiated samples will be characterized. The process described can be visualized in Figure 6.2. This image shows the main components and systems involved in the IFMIF-DONES reaction. In turn, Figure 6.3 illustrates the IFMIF-DONES plant. It details the dimensions and the location of some relevant areas, such as the Test Cell and the accelerator.

Figure 6.2 - Summary of IFMIF-DONES performance. Deuterium beam impact on the Liquid target and irradiate the specimens. Image modified from [214]

Figure 6.3 - DONES accelerator plant

The Test Cell is a blind cell of IFMIF-DONES, wherein the test irradiation will be produced. This cell has to withstand radiation, tritium production, vacuum, the running Li loop and the intense deuterium beam. The surrounding shielding walls of the TC are the primary biological shielding to protect the surrounding rooms and cells against neutron and gamma radiation. Heavy concrete (3.4 g/cm^3) is selected as the primary material of the surrounding shielding walls. The thickness of the TC walls is designed to assure the dose outside the biological shielding below $7.5 \text{ } \mu\text{Sv/h}$ during the irradiation experiments [215]. The access to this area is done removing the shielding plugs at the top. It is mandatory to carry out RH activities inside of Test Cell.

6.4. RH in IFMIF-DONES

IFMIF-DONES is a demanding facility in terms of plant availability and systems reliability. Each system of IFMIF-DONES is designed to guarantee the availability of more than 90% to achieve the goal of availability of 70% of the plant [J2]. According to this, several systems require inspections, monitoring and maintenance tasks over many years in a hostile environment. The primordial requirement is that these activities are carried out in an efficient, safe and reliable way.

Figure 6.4 - DONES schematic Plant Configuration. Image modified from [212]

The maintenance of some components is vital since these can compromise the regular functioning of the plant. The critical maintenance will be carried out through Remote Handling procedures employing the RHS implemented for IFMIF-DONES. The RH

maintenance of IFMIF-DONES will be done in the Test Systems (TS), Lithium Systems (LS) and Accelerator Systems (AS) [J2], [212]. Figure 6.4 represents an overview of the DONES' systems, where it is prominent to visualize the structure and distribution. The critical components of AS, TS and LS are classified depending on the type of maintenance that needs. This classification follows the same criteria adopted in ITER, see Appendix D.1. It takes into account several factors, like zoning, dose rates maps, decay heat of components and so on.

This chapter focuses on the RH maintenance of some component of TS and AS. The following subsections include relevant information about the RHS, design requirements, functions, process and maintenance tasks to be done in DONES facility.

6.4.1. RH Systems

The IFMIF-DONES RHS is a man-in-the-loop system for performing remote tasks. As Figure 6.5 displays, the RH Systems are controlled and operated from a common place, that is, the RH control room using specialized operator interfaces.

Figure 6.5 - The basic configuration of the RHS of IFMIF-DONES [J2]. The three red boxes refer to the leading IFMIF-DONES Systems

It manages a total of five sub-systems on the plant, where each one has a different purpose as explained below (see Figure 6.4 and Figure 6.6 to better understanding).

- RHS of the TS: this system performs remote maintenance on the components housed on the Test Cell. Components such as the High Flux Test Module, the plugs to open and close the TC (Upper Shielding Plug (USP) and Lower Shielding Plug (LSP)), the Piping Cable Plugs (PCPs), etc.
- RHS of the LS: it is devoted to the maintenance of the Li loop and Li purification system. Part of the RHS of the LS is common to the RHS for the Test Systems, mainly for the maintenance of the Target Assembly and the Quench Tank (QT).
- RHS for the AS: this system is required for the maintenance of accelerator components. The components are distributed in different areas like the Target Interface Room (TIR) and the Radiation Interface Room (RIR) and Beam Transport Room (BTR).

- Viewing System: is dedicated to visually supporting RH operators during maintenance operations.
- RH control system: the RHS of IFMIF-DONES is provided of its control system.

Part of the RH Systems are physically located in different maintenance areas of DONES: Access Cell (AC), Lithium Loop, Purification System, BTR and RIR. The RH Equipment in these areas is mainly composed of overhead cranes and robotic arms to perform the RH operations. Most of the RH Equipment is in the Access Cell maintenance area (see Figure 6.3 and Figure 6.6). This area covers all the RH operations demanded from TC and TIR (last part of the accelerator). The top view of this area can be visualized in Figure 4.13.

Figure 6.6 - 3D model of the Access Cell maintenance area and the RH equipment (layout of 2019). The AC covers the Test Cell and TIR. Currently, this area is rectangular as best depicted in Figure 4.13

Figure 6.7 - IFMIF-DONES maintenance areas and activities

To clarify, the schema of Figure 6.7 details a complete overview of all the systems, maintenance areas and principal components to RH maintain.

6.4.2. RH maintenance sequence

DONES follows a succession of steps to prepare, perform and complete the maintenance tasks, see the sequence in Figure 6.8. This chapter is only focused on the activities highlighted in the yellow box: configuration of the maintenance areas and execution of the maintenance task. The actions of these steps are as follow:

1. The configuration of the maintenance areas. It starts configuring the maintenance area and components before carrying out the RH operations. For example, get all the necessary equipment, transport the new component until the room, disconnect connectors or pipes *hands-on*, etc.
2. The execution of the maintenance task. After concluding the previous steps, RH activities are performed until achieving successful results. The maintenance procedure has to follow a list of RH tasks pre-established.

The other steps are also relevant to conclude a RH operation. For example, the acceptance test of the components is a decisive activity since it confirms the success of the maintenance activity and the correct functioning of the component.

Figure 6.8 - Steps to complete a maintenance task via RH in DONES

6.4.3. Occupational Radiation Exposure (ORE)

The International Commission establishes recommendations for radiation exposure of personnel. The ICRP provides recommendations and guidance on all aspects of protection against ionising radiation. The main ICRP60 recommendations for any individual radiation workers are:

- The annual dose rate should not exceed 20 mSv per year, averaged over five consecutive years.
- The dose rate in a single year should not exceed 50 mSv.
- The dose rate for non-radiation workers should be kept below 1 mSv/year.

ITER and IFMIF-DONES show that there is a will to keep the limits of these projects well under the recommendations of the ICRP60. For example, ITER is considering that

the dose rate for any individual radiation-worker should be kept below 5 mSv/year and should not exceed 0.5 mSv in any working in shift. In DONES, the project criteria for limits doses and Occupational Radiation Exposure are taken from International Atomic Energy Agency (IAEA) [216].

Test Cell and the last part of the accelerator (TIR) need a strict RH maintenance due to the high dose rates, greater than 100 mSv/h. These areas are classified as “forbidden areas” since the radiation is so elevated for humans. Concerning the accelerator, specifically for the regions of the Accelerator Vault (AV), BTR and RIR, the irradiation could be higher than 100 Sv/h due to the neutrons and secondary photons. However, after a cooling time (1 day-week), the dose rate becomes less than 1 mSv/h. Thus, this zone is classified as “limited permanence area” when the accelerator is shut down. Therefore, the operator can enter to do hands-on operations with certain restrictions [J4].

6.5. Test System RH

Test Systems has the means to accommodate the High Flux Test Module under a controlled environment and conditions for the irradiation (nuclear D⁺ and Li reaction). The Test Systems are located on the first floor of DONES building, in the Test Cell as shown in Figure 6.3 and Figure 6.9 [76], [215], [217]. Appendix D.2 collects the Test Cell dimension. Some Lithium components also are located in, as the Target Assembly and Quench tank, which are part of the Lithium loop.

Figure 6.9 - Test Cell components. HFTM allocates the specimens to test under a neutron environment. The image on the right shows the TC open, without TC Cover Plate (TCCP), USP and LSP shields [76], [215].

Most of the systems and components housed in the TC have intrinsic radiological hazard due to their operation so that they will be subjected to regular and planned maintenance.

The dose rate maps around TC indicates that there are 1 Sv/h after 28 days after shut down (see the biological dose maps in Appendix D.3). The dose rate is several order of magnitude over the limit for the hands-on maintenance. Then, all the TC components demand RH maintenance.

Figure 6.10 - Plate and plugs that isolate the Test Cell

The critical TS components are the TCCP, USP, LSP, PCPs and HFTM (see Figure 6.9 and Figure 6.10) [76]. The High Flux Test Module is the core of the DONES facility. This component has to be replaced periodically to extract the samples tested. The TCCP, USP and LSP need to be removed whenever access to the Test Cell is necessary (see Figure 6.10). These are transported with an overhead crane and stored in the Access Cell. This operation becomes critical since the plugs are heavy concrete blocks to isolate the TC (up 120 tons). In the case of the six PCPs, these also need periodic RH maintenance. These concrete blocks provide shielding and pipe/cable accommodations to TC components. For example, the PCPs house the pipes to transport the helium for cooling the HFTM.

6.5.1. RH Equipment in TS

The equipment of Test System is located in the Access Cell, as Figure 6.6 displays. The Access Cell contains two overhead cranes [J2]. The first crane is the Heavy Rope Overhead Crane (HROC), see Figure 6.11. It can transport heavy loads (up 140 tons), as the bulky TC and RIR shielding plugs that cover these areas. The second overhead crane is the Access Cell Mast Crane (ACMC), see Figure 6.12. This crane has a lower load capability (up 2 tons). Instead, it has a telescopic mast to attach tools as a Parallel Kinematic Manipulator (PKM) or robotic arm at the extreme of the mast. The linking is possible with a fast change interface at the end of the mast, named Gripper Change System (GCS). Figure 6.13 details an example of a male and female GCS.

Figure 6.11 - HROC overview design [J2],[218]

Figure 6.12 - ACMC overview design [J2],[219]

Figure 6.13 - QC-1210 Base Tool Changer from ATI INDUSTRIAL AUTOMATION

Besides, there is also a Robotic Arm on Rails (RAR) in the Access Cell floor. This robot will be used to assist with the TC tasks and possible recovery and rescue operations. The

other robotic arm of 6-DoF will be attached at APMC mast. This robot is needed to perform dexterity activities in TC. These robots are under design since it has to meet with the facility requirements and bear the extreme conditions of the TC.

6.5.2. High Flux Test Module

One of the most critical components is the High Flux Test Module [76], [220], [221]. It contains the specimens that are stacked hermetically enclosed in a capsule (irradiation, monitoring or reflector capsule type). Figure 6.14 indicates as the capsules are together in an HFTM container.

Figure 6.14 - The basic configuration of the DONES's High Flux Test Module [220]

The HFTM container will be separated and extracted remotely of HFTM component in DONES' hot cell, called the Irradiated Materials Treatment Room (IMTS). After that, it will be transported outside DONES, to the Post Irradiation Examination (PIE). HFTM also contains other important elements, as the cooling He pipes and one connector plate with 688 pins on the top to supply energy and signals for Type-K thermocouples, heater-wire circuits and fission chamber. The helium pipes and electrical connector are connected to the PCPs.

The inconvenience of this component is that it continues being a highly activated component after the irradiation period. RHE has to replace it every two years, although each year is necessary to extract the HFTM to perform other RH maintenance inside of TC. The RH replacement of HFTM demands highly requirement due to the particular importance of the specimens that it contains.

6.5.2.1. RH maintenance procedure

The HFTM is one of the most delicate components, so the RH needs to be painstakingly accurate. The complete replacement consists on to remove the HFTM from the TC, and

transport it until the IMTC to extract the samples tested during two years. Subsequently, another HFTM with new specimens have to be installed in the TC to start the late irradiation period.

HFTM RH maintenance requires preparatory activities (for example, inserting the new HFTM with the specimens to test in the next irradiation period, set-up or preparing the tools and equipment needed for this operation). The RH maintenance starts when the Test Cell is accessible. It happens when the TCCP, shielding plugs (USP and LSP) and USP cooling pipes connectors are removed from TC. After this moment, HFTM is accessible for the RH Equipment, and then HFTM replacement is possible.

Figure 6.15 - Maintenance process to replace the HFTM component

The current sequence to replace the HFTM are listed in Figure 6.15. The main activities have been detailed to understand each step. However, the reader must know that the procedures and designs can change because DONES is in a dynamic stage, which aims to find the best results considering the rest of the installation requirements.

• Remove and install pipes and connector between PCP and HFTM

The PCPs houses pipes and cables that need to be connected with the TC components. HFTM has helium pipes to be cooled, and also power and electrical connexion. Figure 6.14 and Figure 6.16 show the connections on the top of the HFTM. In this way, HFTM and PCPs have to be connected with a bridge system, as shown in Figure 6.16 and Figure 6.17. This system has the requirement to provide a secure and straightforward method to be connected and disconnected via RH (e.g., the robotic arm of APMC).

To date, this system is under development. The challenge is the type of cables that this system will house. This cable has to resist gamma and neutron radiation, wherein the neutron dose will be so high concerning other applications. The most related cables to withstand this type of extreme conditions have the inconvenience that they are almost rigid. It is down to the kind of material since it has to be particular to endure the neutron flux. Cable stiffness becomes a challenge to design the bridge system to connect the HFTM and PCP.

Figure 6.16 - HFTM and PCP connections

Figure 6.17 - Conceptual design of the bridge connections between PCPs and HFTM

- **Attach and transport the HFTM**

The tool to transport the HFTM safely with the APMC is under development. The principal idea is to have interfaces to grasp and release the component quickly. The proposal is to incorporate various pneumatic pin actuators. These allow RH manipulation and does not have interference with the radiation. Figure 6.18 exemplifies the sequence of gripping and transporting the HFTM until its TC position. Image 1) shows the conceptual design of this transport tool (the yellow one), and image 2) the HFTM storage structure with the HFTM. It is also used to transport the HFTM until AC with a mobile

pallet. The RH group from Karlsruhe Institute of Technology (KIT) has designed this storage structure. It has to meet with specific requirements to avoid vibrations or alterations of the HFTM specimens during the transportation.

Figure 6.18 - Sequence to transport the HFTM component

On the other hand, the transport tool has a female GCS on the top. It is used to be attached by the PKM tool. The PKM is used to get angular inclination since the mast crane only has movement in x, y and z. This function is relevant for the positioning of the HFTM.

- **Position the HFTM on TC**

HFTM positioning is a crucial operation. It has to place the HFTM in the correct TC location. This task is done with the ACMC, PKM and the HFTM transport tool. The equipment and tool help to precise position the component. Final positioning takes place when two locations are reached: 1) the contact base of TC and 2) the TA component. Figure 6.19 and Figure 6.20 display how the HFTM is positioned on the TC contact base with the help of locating pins. Figure 6.20 also details the positioning system between HFTM and TC. In both places, the positioning systems have pins to assist in the final positioning of the HFTM.

Figure 6.19 - RH System positioning the HFTM on the TC base

The TA positioning system follows the recommendation to separate 2mm both components. For that, the group from WIGNER company has developed an interface to achieve this requirement. As Figure 6.20 represents, the HFTM-TA interface system is a structure to limit the distance and reach the TA guide pins. It is possible due to the two holes that the HFTM structure has in the limiter arms.

Figure 6.20 - 3D design of HFTM Positioning system

- **Release and fix the HFTM on TC**

During the irradiation period, the HFTM must be behind the TA and remain fixed within the Test Cell. For that, it is necessary a system to keep HFTM fixed on Test Cell, and release it when the HFTM need to be removed or replaced. The current proposal is based on eight captive bolts on the base plate of HFTM, as Figure 6.21 shows. This image also includes the robotic arm and bolting tool to complete the RH operation, indicating the different points to operate.

Figure 6.21 - Robotic arm with bolting tool to fix the eight captive bolts

This system has to meet some RH requirements. The interfaces have to be “friendly” and secure to be managed by a robotic arm and tool. Captive spring bolts are a proposal for these to remain on the base plate since this system prevents the bolts from falling out, making it easier to tighten and loosen the bolts with the robot. The possible disadvantage of the spring bolts is that the spring properties could be altered depending on the extreme conditions of TC, so it has to be evaluated carefully. Figure 6.21 shows a generic example of what the captive spring bolts look like and their position when it is unreleased and released. Nonetheless, the design guidelines suggest that it is preferable to use a captive bolt with a conical head for being RH manipulated.

- **Adjust HFTM positioning**

The HFTM position has to be adjusted once it is placed and fixed on the contact base of TC. This component has an adjustment system on the HFTM sides to achieve the correct angle. The adjusting process is done with the robotic arm and tool, see Figure 6.22. The robotic arm must be able to accurately adjust the central support joints of the HFTM positioning system.

Figure 6.22 - Adjusting system of HFTM. It is on both sides of HFTM

Laser beam or cameras will be used to ensure that the components are correctly positioned. In the case of the cameras, specific visual markers will be added.

6.6. Accelerator System RH

DONES will be equipped with a continuous-wave 175 MHz linear accelerator, providing a 125 mA, 40 MeV deuteron beam [76]. DONES accelerator consists on the following systems: ion source, Low Energy Beam Transport (LEBT), Radio Frequency Quadrupoles (RFQs), Medium Energy Beam Transport (MEBT), Super Conducting Cavities (SCC), High Energy Beam Transport (HEBT) [J3], and Beam Dump (BD) [J5]. These can be identified in the conceptual schema of Figure 6.23 [J4], [76], [212]. Article [222] illustrate the LIPAc components and layout.

Figure 6.23 - Conceptual design of DONES Accelerator Systems

The accelerator has a few components that need to be maintained via RH [J4]. Hands-on maintenance is allowed for most of the accelerator component after a few days of cooling. This assumption is based on the possibility to keep the beam losses below 1 W/m in the region. Nevertheless, some components will remain highly active after the accelerator is shut down, so they will need RH maintenance. Beam Dump, lead shutter, scraper, collimator, RIR modules and TIR modules are examples of components that need RH [J4]. These are located from the HEBT section 2 until the HEBT section 3. For more clear idea, Figure 6.24 shows the critical areas where these components are.

Figure 6.24 - Areas of the Accelerator Systems (AV, BTR, RIR and TIR). It includes the Test Cell but is belongs to Test Systems [J3]

Accelerator Vault, Beam Transport Room and Radiation Isolation Room share the same area. Instead, Target Interface Room is isolated due to the hazardous environmental

conditions. The access to this area is done through the Access cell, which houses the RHS to perform RH maintenance in Test Cell. TIR has a hatch on the top, which has to be removed to access inside, as it happened with the Test Cell.

6.6.1. Beam Transport Room

Beam Transport Room houses part of the HEBT line (section 2) and the Beam Dump [J3]. BTR is classified as “limited permanence area” during the accelerator shut down and cooling period (see radiation dose in Appendix D.4). The radiation levels greater of 1 mSv/h allow limited access to the operator, who can perform some hands-on operations. Nevertheless, the access becomes prohibited when the shielding of some critical components are removed (i.e., the Beam Dump and scraper shieldings). These highly radioactive components are contained in a heavy shielding to reduce the radiation levels, and it requires RH operations when these need to be replaced.

Figure 6.25 indicates the most critical components to maintain via RH in the BTR [J4]. These components are the BD cartridge, scraper and lead shutter. Cartridge and lead shutter have a corrective maintenance type with a 3rd classification (see the component classification in Appendix D.1). Thus, the RH maintenance only is required in case of fail or malfunctioning during the DONES lifetime. However, the scraper has been classifying as 1st class, so periodic RH maintenance will be required. In this way, the BTR needs specific RH Equipment to satisfy the requirements of the components, building and environmental conditions.

Figure 6.25 – Top view of BTR components

This thesis is focused on two critical components of the accelerator: Beam Dump (cartridge) and scraper. The RH maintenance is specified in the next subsections 6.6.3 and 6.6.4.

6.6.2. RH Equipment in AS

BTR needs special equipment to carry out the RH maintenance of the HEBT line. Due to the current building layout, two overhead cranes with the telescopic mast are needed

for the BTR area. The design of these cranes is the same as that of the ACMC shown in Figure 6.12. The location of the cranes can be visualised in Figure 6.26. The south crane covers the lead shutter and Beam Dump components, and the other crane the north part of BTR, AV and RIR. The advantage of this type of crane is that it is possible to attach the components directly with the GCS interface or with a personalised tool. Moreover, the telescopic mast can couple a robotic arm of 6-DoF to perform dexterous operations such as tightening bolts, grasp elements, and so on. Figure 6.27 shows the robotic arm coupled to the telescopic mast of the overhead crane. It has a bolting tool to loosen bolts.

Figure 6.26 - RH Equipment of BTR. It is formed by two overhead cranes with a telescopic mast to cover the AS

Figure 6.27 - Robotic arm coupled at the telescopic mast of the south overhead crane

6.6.3. Beam Dump (cartridge)

The Beam Dump objective is stopping the pulsed beam (40 MeV at 125 mA deuteron beams) at low duty cycle during the DONES accelerator commissioning, operation and start-up phases after shut down, allowing its tuning and characterization [J5]. The component that stops the beam is the cartridge, which is a copper cone of 2.5 m long and 0.3 m inner diameter aperture (see Figure 6.28) [J4].

Figure 6.28 - 3D design of Beam Dump. It shows when the BD shield is open

It will be cooled by water flowing at high velocity along its outer surface. As Figure 6.29 details, the cartridge is surrounded by a shielding made of iron and low Z material for attenuating the neutron and gamma radiation originated by the interaction of the deuterons with the copper [223]. Figure 6.28 clarifies the BD shielding and how it is divided into two parts. The shielding is opened and closed horizontally for easy access to the cartridge [J5]. The BD design is based on LIPAc, but some modifications are being made to be adapted to DONES.

Figure 6.29 - Section view of the BD when the shielding is closed

Cartridge is classified as 3rd class, so it could require to be replaced during the operation of the plant. This activated component needs to be removed via RH, but some hands-on activities can be done when the shielding is closed or when the activated components (without shield) are not in the BTR. The following subsection presents the procedures to replace the cartridge.

6.6.3.1.1. RH maintenance procedures

Figure 6.30 - Maintenance process to replace the Beam Dump component

The objective of the Beam Dump maintenance is to replace the cartridge with a new one. It requires preparatory activities to configure the area and elements for the replacement. After concluding the initial operations, the RH maintenance is carried out when the BD shield is open. From this moment, the RH Equipment is in charge of removing the cartridge and install a new one. The installation ends when component test acceptance gives successful results. The list of Figure 6.30 shows the process developed to replace the cartridge considering the facility requirements (i.e., building team, accelerator designers, etc.). Table 6.1 displays the activities sequence after opening the BD shielding.

Table 6.1 - Sequence of the activities to replace the BD cartridge when the BD shield is open

7) Open the Beam Dump shield	8) Remove the cartridge	9) Place a new cartridge

10) Take the old cartridge out	11) Fix the cartridge	12) Align the cartridge

13) Connect the cooling pipes	14) Connect the cooling pipes	15) Close the BD shielding

The following paragraphs describe more deeply the main activities to perform the cartridge replacement.

- **Lead shutter de/activation (remote)**

The lead shutter is in a multipurpose vacuum chamber just before the Beam Dump (see Figure 6.28 and Figure 6.31). The shutter is used to protect the last part of the beam tube in case of abnormal beams, actuating as a plug. It shields the accelerator against the gamma radiation coming from the cartridge copper cone through the beam tube when the beam is off. Additionally, it reduces the dose rates in the part of the accelerator vault, enabling hands-on maintenance [224].

Figure 6.31 - Lead shutter and actuator elements. It was designed for IFMIF/EVEDA LIPAc [224]

Figure 6.32 - Sequence to close the beam tube with the lead shutter actuator.

For the described purpose, the lead shutter closes the beam tube when the accelerator has to be switched off. It is later removed when the RH maintenance finalises. The lead shutter is composed of a moving and a fixed part, as Figure 6.31 details. The non-fixed part of the shutter is moved remotely by an actuator. It positions the lead shutter in open (beam on) or closed (beam off) positions, see the sequence of Figure 6.32. The linear pneumatic actuator is connected to an extended rod that links with the moving part of the shutter by a captive bolt system that can be operated from the shutter attachment port [224].

- **New and old cartridge transport (RH)**

During the preparatory phase, the new cartridge has to be introduced before open the BD shield. The cartridge will be transported remotely with a mobile omnidirectional platform. After introducing the cartridge in the room, the new component is attached with the overhead crane, and it is transported to the storage area. The mobile platform will remain on-site, expecting to the removal of the old cartridge. Finally, the old component will be transported through the plant until reaching the IMTC area, that is a room for a components treatment. The flow material team is in charge of the cartridge extraction and transport. This task is still under development to ensure that the cartridge can be transported to the IMTC area securely, avoiding contaminating the facility and exposing humans to danger.

- **Drain valve de/activation (remote)**

The cartridge has a cooling water system, as Figure 6.33 details. The system has two pipes welded to the stainless steel 304L rear flange, the coolant supply inlet tube is located at the centre and the outlet tube is on the upper part to the extraction of the cooling water. The water coolant enters through the inner cone and returns through the space between the shroud and the cartridge stainless steel external cylinder. The passage from the inner cone to the cylinder space takes place through the three rows of holes on the shroud near the front aperture (see Figure 6.33). The water flows depending on the region; the velocity can vary between 4 m/s and 10 m/s. [223].

Figure 6.33 - Interior of cartridge and cooling system

When the cartridge needs to be replaced, the water inside of the cartridge has to be removed. The water is drained by an automatic valve located on the outlet pipe (see Figure 6.34). The system opens the valve remotely to remove the cooling water, and finally, the drain valve is closed when the process is complete.

Figure 6.34 - Cooling system path and water directions. The blue arrow represents the input water, and the red one the output water

- **Electrical connectors dis/connection (remote)**

The cartridge has various signals and thermocouples. These have to be disconnected when the cartridge is replaced and then connected when the new cartridge is installed. As chapter 4 mentioned, there are several connectors. For this application, a personalised Multi-Connection System is being designed. It has to be disconnected when the cartridge is removed with the crane, and connected when the new cartridge is placed on the floor platform. This simple concept saves time and avoids radiation exposure of robots and humans.

- **Cartridge release and installation (hands-on)**

Figure 6.35 - 3D Cartridge design and location. The support legs to fix the cartridge on the platform

The cartridge has four legs in the support structure. These are used to be fixed on the alignment platform. The support legs are composed of positioning guides and holes, as shown in Figure 6.35. The holes are used to insert bolts, which allow the cartridge to be held and attached to the alignment platform. The cartridge maintenance demands release it from the alignment platform. This operation is done hands-on when the cartridge shielding is close. Figure 6.36 depicts the sequence for loosening and removing the bolts and nuts on each cartridge leg.

Figure 6.36 - Disconnection sequence. The bolt and nut are removed from the support leg and alignment platform. This operation has to be done for the four cartridge legs

On the other hand, Figure 6.37 shows how to fix and install the new cartridge once it is positioned on the alignment platform. This operation is done with the BD shielding open.

Figure 6.37 - Connection sequence. The bolt and nut are joining the support leg and alignment platform. This operation has to be done for the four cartridge legs

A human will perform these actions. It is not suitable to be manipulated with RH Equipment. Nonetheless, if the environmental conditions become more severe or other complications appear, the current interfaces (bolts and nuts) have to be reconsidered and adapted to be feasible to be RH manipulated. For example, using captive spring bolts and nuts, as chapter 4 recommends.

- **Vacuum dis/connection (hands-on/remote)**

The cartridge has to be disconnected and connected from the beam line. It requires a mechanical system capable of easily completing these operations. Based on this requirement, the Remote Disconnection System (RDS) implemented for the LIPAc of IFMIF has been incorporated in DONES [225].

Figure 6.38 - RDS system on the Beam Dump. The RDS disconnection follows the steps represented

Figure 6.39 - RDS elements. Part A has the function of opening and closing the collar chain with a mechanical system. Part B has the bellows to separate the cartridge. The complete description is in the article [225]

Figure 6.38 shows the RDS design and its position in the Beam Dump. Figure 6.39 details the parts of the RDS. The RDS has an articulated collar and two adjacent bellows in each side of the collar. The bellows allows the cartridge to be easily removed and besides compensates for manufacturing and assembly deviations. It also has mechanisms to align

and operate the disconnection system. Similar systems have been used for remote disconnection in other accelerators as J-PARC and SNS.

An operator performs hands-on the RDS disconnection when the BD shielding is closed [J4]. Figure 6.38 shows the actions to disconnect the RDS. First, the rod has to be rotated for opening the articulated collar. It is possible with a road torque of 2.8 Nm at the horizontal end. Secondly, the human has to operate the pulling equipment (tractel) to compress the hydroformed bellow (up to 47 mm). The compression is done through a stainless steel cable guided by pulleys. For that, the operator has to apply 121 N on the tractel, whereas the force reaching the bellows is 2520 N. Additionally, this system has three guiding rods to provide a smooth compression motion, and also a locking system to retains the bellows in that position when it achieves 30 mm of compression [225].

The reverse procedure is to connect the vacuum when the new cartridge has been placed. This operation is done when the shielding is open since the radiation levels are appropriate for humans. Nevertheless, if future radiological studies determine that the operator entrance will be not allowed or is not feasible, this system could be operated remotely with a robotic arm or motors.

- **Pipe flange dis/connection (hands-on)**

The cooling pipes need to be disconnected to replace the old cartridge, and then, connected them to install the new one. There are two cooling pipes (water inlet and outlet). The current radiological studies determine that it is possible to disconnect and connect the pipes hands-on. Still, only it can be done when: 1) the shielding is closed, and 2) there are no activated components in the room without a shield.

Chapter 4 presents different union devices to disconnect the pipes. In this case, the mechanism selected to streamline and facilitate the hands-on operation is a commercial Quick Disconnect System from Technetics company. As shown in Figure 6.40 and Figure 6.41, this mechanism releases and opens the clamp section completely by operating a screw. It allows removing the mechanical system from the pipes, so it avoids to have compress bellows as other complexes QDS for RH.

Figure 6.40 - Concept and design of QDS from Technetics (Source: technetics.com)

Figure 6.41 - QDS mechanism. The yellow arrows indicate the screws to turn for opening the clamp section, and thus be able to release the QDS

Advantageously this system could be disconnected easily with a robotic arm and a specific tool (nutrunner), so it can be useful if the radiological studies become more critical. However, it is recommended that the skill and dexterity of a human are utilised to connect the QDS. The connection task requires placing the QDSs in the pipes and then turn the screw to close the clamp section. This operation could be awkward and tricky for a robotic arm.

On the other hand, an additional problem has been detected recently. The pipes could release water droplets during transportation, so a solution is being sought to avoid this potential trouble.

- **Opening and closing of the BD shielding (remote)**

The primary function of the Beam Dump shielding is limiting the radiation generated by the beam particles interaction with the copper inner cone and by the induced activation. It attenuates the gamma and neutron fluxes produced inside it. In order to reduce the level of radiation, a multi-layer shielding design has been defined based on LIPAc proven design [J5]. It will be made of lead, steel and polyethylene (three-layer shield, with a combination of heavy material + light material + heavy material). The last layer of heavy material aims to attenuate the photons produced in the light one by neutron captures in hydrogen. It has been designed to comply with the legal limits during DONES operation and to allow human presence in the area during the accelerator shut down.

Figure 6.42 - Beam Dump opening sequence

The Beam Dump's shielding is divided into two halves, each weighing 24000 kg. The opening and closing of the shielding will be done remotely through various electrical motors coupled with gearbox and wheels [J4]. These move the two halves of the shield in the horizontal axis. It will be opened up 1250 mm to give access to the cartridge. Figure 6.42 shows the sequence to open the BD shielding, although to close it, it is the reverse process.

Once the BD shielding is open, the humans cannot enter to the room. From that moment, RH tasks will be performed until the activated cartridge is removed. However, the BD shielding will be not close until completed the cartridge replacement and installation tasks.

- **Cartridge removal, transport and placement (RH)**

The cartridge can be removed from the Beam Dump once the cartridge is released of the beam tube, cooling pipes and alignment platform. The sequence to remove and transport the cartridge is in Table 6.2. The installation procedures follow the reverse actions.

Table 6.2 - Sequence to remove the cartridge from the BD position with the overhead crane

Operation	Draw description
1) Position the tool to grasp the cartridge
2) Attach the cartridge
3) Lift and transport the cartridge

The overhead crane of BTR transports the cartridge. It is possible by means the GCS interface (see Figure 6.13). The male GCS is at the mast of the crane and the female GCS on the cartridge. One difficulty of these tasks is to place the support cartridge on the alignment platform correctly. However, there are cameras and positioning guides to assist in this RH operation. The guide pins are located on the alignment platform, as Figure 6.35 shows.

- **Cartridge alignment on the floor platform (hands-on)**

The floor platform, where the cartridge legs are positioned, has four mechanical systems to enable a general alignment (see Figure 6.43). This system helps to place the cartridge correctly. It allows aligning in three spatial directions (x, y and z). The process is to turn the screws to move the cartridge base, wherein a laser tracker will check the position of the component.

Figure 6.43 - Mechanical supports to align the cartridge

This operation will be carried out hands-on when the new cartridge is on the platform and the activated cartridge is not in the room.

6.6.4. Scraper

In DONES plant, the scraper is needed to remove stray particles excessively separated from the beam centre. The scraper has been integrated within the main line half-way through between the dodecapoles. The design of this scraper is based on LIPAc but with a much higher power deposition on it, see the scraper design in Figure 6.44. It will have four independent, refrigerated and moveable blades along x-and y-axes, perpendicular to the beam. Due to power depositions on each blade of around 1250 W, the scraper will have a great activation. Thereby, the scraper is enclosed inside a radiation protection shielding whose thickness is 500 mm. The shielding dimensions are highly dependent on the activation level reached by the scraper due to power deposition, which is assumed to be no more than 2.5 kW. Figure 6.45 details the scraper and shielding that are being designed for DONES. It includes particular elements for RH operations since it requires periodic maintenance due to the high activation and deterioration. The following subsection presents the activities to replace the scraper.

Figure 6.44 - 3D scraper design

Figure 6.45 - 3D scraper design with shielding

6.6.4.1. RH maintenance procedures

Scraper replacement is delicate due to the radiation and activation levels after shut down the accelerator (see radiological maps in Appendix D.4). This component demands RH activities to carry out the replacement, overall when the scraper shielding is open. Exceptionally, the operators can perform some tasks when the activated scraper is out the BTR. However, this assumption is currently under evaluation. Figure 6.46 presents the updated operations to replace the scraper periodically. The actions specified are described more precisely in the following paragraphs.

Figure 6.46 - Maintenance process to replace the scraper component

- **New scraper transport (remote)**

The new scraper has to be introduced in the BTR after opening the scraper shielding, during the preparatory phase of maintenance. The scraper will be introduced remotely in a movable platform. After that, it will be stored in the room until its installation. The mobile platform also remains in the place waiting to transport the activated scraper.

- **Draining and filling of cooling water (remote)**

A water-cooling system is used to extract heat generated by the ohmic losses. This water has to be drained of the cooling channel when the scraper has to be replaced. The opening of the drain valve is done remotely. Subsequently, the drain valve turns close after installing the new scraper since the cooling system must be water filled to a proper scraper function.

- **Opening and closing the scraper shielding (remote)**

The scraper has a shielding of 16000 kg, which has to be opened and closed to give access to the component. The best proposal based on the requirements of the area has been to open and close the shielding with a rotary movement, see Figure 6.47. The upper half part of the shielding is being moved by the action of a pneumatic system, which must be able to move 8 tons.

Figure 6.47 - Conceptual proposal for opening and closing the scraper shielding

- **Scraper dis/connection from beamline (RH)**

The scraper is connected to the beam line. The disconnection and connection will be done by means a Quick Disconnect Systems and bellows. Figure 6.48 shows the specific design for RH dis/connecting the scraper in both sides of the line. To replace the activated scraper, the robotic arm connected to the mast of the overhead crane and a specific tool must to rotate the bolts of the collar chain to release the scraper of the beam line (Action 1 of Figure 6.48), and then the bolts of the bellows to compress them (Action 2 of Figure 6.48). The process is similar when the new scraper has to be connected.

Figure 6.48 - QDS to RH dis/connect the scraper to the beam line. The image also shows the sequence to disconnect the QDS

The scraper line has several guide pins to facilitate the placement and attachment with the beam line, as Figure 6.49 illustrates. These pins are introduced in the line when both bellows are decompressed and the collar chains are tightened.

Figure 6.49 - Guide pins to place and connect the scraper with the beam line

- **Connectors dis/connection (RH)**

Power, data signal and fluid have to be supplied to the scraper. The cable or pipe has to be disconnected and connected to allow the RH replacement. For that, a personalized Multi-Connection System is being designed. It is located on the bottom part of the component. The concept is based on automatically release the MCS when the overhead crane lifts the scraper, and then, connect it when the scraper is placed on-site. The MCS will be designed with guide pins to achieving a correct position, similar to those presented in the commercial example in Figure 6.50.

Figure 6.50 – Multi-coupling system. These include fluids and electricity. (Source: Staübli)

- **Scraper dis/connection (RH)**

Figure 6.51 - 3D Scraper design. There are two bolts to guide and fix the scraper on the support structure

The scraper is fixed to the support with two guides and bolts. The system is detailed in Figure 6.51. During the scraper installation, these are used as aids systems when the scraper is placed on-site, and subsequently, the bolts are tightened to keep the component immovable. For removing the scraper, the two bolts have to be loosened. This operation is performed with a nutrunner tool and a robotic arm.

- Scraper removal, transport and placement (RH)**

Once the scraper has been released, the scraper will be replaced. The method will be the same used for replacing the Beam Dump cartridge. The ACMC attaches and transports the scraper with the GCS. This system allows to carry the activated scraper until the movable platform, and then, grasp the new one. The new scraper will be transported and place with the overhead crane in its corresponding location inside the shielding. Table 6.3 shows the steps to remove and carry the activated component until being positioned on the movable platform.

Table 6.3 - Sequence and steps to remove the scraper from the shielding with the overhead crane

1) Position the tool to grasp the scraper	2) Attach the scraper
3) Transport the scraper	4) Release the scraper in a mobile pallet

The correct insertion and position are possible through guide pins on the scraper support, see Figure 6.52. The support with pin allows held and maintain the scraper on the place.

Figure 6.52 - Guides and support elements to hold the scraper on position

- **Cartridge extraction (flow material team)**

The flow material team is in charge of the scraper extraction and transport. It will be done with a mobile platform, which has to transport the scraper safely until the IMTC.

- **Scraper alignment (hands-on)**

The scraper has a system to achieve proper positioning of the scraper. Figure 6.53 shows the alignment system implemented, which is on the scraper alignment platform. The aim is operating the screws to adjust the scraper position at x, y and z axes. Laser trackers check the scraper position during the alignment activity.

Figure 6.53 - Alignment system of the scraper

Chapter 7

Robot teleoperation in biohazard environments

In the last decades, highly infectious diseases as Ebolavirus have been a hazard to humanity, to such an extent that it changes people's lives. These continue being a problem for health personnel since they have to be in frequent contact with sick people. For these reasons, this chapter implements a telerobotic system capable of performing basic health care. The iteration human-HMI-robot has been also studied and analysed to determine the effective hardware and software combination for remote accuracy tasks.

7.1. Introduction

During the past few centuries, there have been critical situations due to contagious and propagation of highly infectious diseases. For example, the influenza A virus (H1N1), tuberculosis, Ebolavirus and currently the coronavirus (COVID-19). These need to be treated to reduce the malignant effects and/or to avoid death. Ebola was a big challenge for humanity during outbreaks in 2014 and 2016. It has a high case fatality rate (greater than 50%). Similarly, COVID-19 has become a pandemic during 2020, which has a high transmission level and is causing many deaths worldwide. In both cases, the sick people have to be treated in medical centres to try to overcome the virus, wherein the health personnel have to attend and assist the patients following strict security protocols. Nevertheless, direct contact health care is high risk due to its easy transmission. Even European hospitals have been threatened by the contagion of these highly infectious diseases.

Over time, robotic technology has been applied in multiple medicine fields [226], [227]. However, this technology has not been widely developed for patients with highly infectious diseases, which must be kept isolated and require special care. The nurse robots have to meet a series of technical requirements to be able to actuate with humans. These must provide high reliability with patient's iteration, and high adaptability to different tasks and manoeuvrability. It presents different considerations from those often discussed in the robot literature for other medical applications. For these reasons, telehealth care tasks are preferable in real-time and the robotic system has to be suitable for each situation. For example, it has to be composed of adequate actuation elements, feedback devices and other requirements about the communication and delays. The high requirements are similar to those demanded in radiation environments, such as when the robot is manipulating radioactive component and the margin of error should be minimal.

The implementation of robots for this purpose is a great benefit to humans since they are immune to infectious diseases and can avoid face-to-face human contact. It prevents the probability of contagion and malady spread among humans, where health personnel are highly affected in these cases. Moreover, the nurse robots also can help when the sanitary personal are saturated, alleviating the workload.

7.1.1. Background and related work

Nowadays, a wide variety of sanitary robots exist for medical applications. In the field of telesurgery, the well-known da Vinci Surgical System has been operating patients for decades [228]. In the field of health care, interesting applications have emerged in the recent years: robots are able to lift and transport patients [13], [229], [230], transport and deliver meals and items to hospitals [231], [232], sample patients' blood [233], wash limbs [234], monitor vital signs [13]. In addition to remote assistance and communication between patients and health personnel [235], [236], guided in the hospital [13], assistance

in the diagnosis and supply of medicines [13], among other applications included in the article: “A review on humanoid robotics in health care” [233].

For biohazard environments caused by infectious diseases, there are robots to clean infectious pathogens using ultraviolet light, like those used by the Little Moe robot. Another system can track down contamination in real-time to warn people (verified for Ebola) [237]. Other robots have been designed to help sanitary personnel to remove the Personal Protective Equipment used as Ebola shield [43] since this routine task requires more than 1 hour. Additionally, during the COVID-19 pandemic, some robots have been used to take vital signs like temperature, and provide remote communication with sick patients. Example of this is the InTouch Health Vici robot. In China, an intelligent robot has been used to conduct throat swab sampling for the diagnosis of the coronavirus or to take the temperature of incoming patients [238]–[240].

However, there is not much information about robots performing telehealth care in an infectious environment [241], [242]. The study [241], specifically analyses the patient confidence when a robot interacts with it. The humanoid PR2 robot was used for this test. This robot performs certain basic tasks such as delivering gauze, removing a cloth or providing a thermometer. It shows a robotic system capable of basic health care patient tasks. In contrast to the work done, the robotic system presented in this thesis performs a set of the more complex routine task such as taking temperature, pulse and blood pressure, patient mobilisation, and others. The humanoid also could actuate without the patient assistance, that is, if the patient is unconscious or asleep. Additionally, this implementation has been conducted to study the operator-robot precision and iteration with the human.

7.1.2. Goals and hypothesis

Robotic systems able to perform safe and accuracy telehealth care activities provide great benefits. It avoids direct contact between sick patients and sanitary personnel in critical biohazard circumstances. The system implemented in this chapter was motivated to perform telehealth care with Ebola patients in hospitals. The goal has been created a versatile telepresence system to execute remotely several medical activities. It is made up of slave elements (humanoid robot) and masters devices (haptic devices, VR glasses, etc.). These were selected with the aim to provide the best possible virtual immersion on the remote area. The health care that patients need in this situation were defined with the help of medical experts in the area of infectious diseases at the Carlos III Hospital (February 2016, Madrid). The tasks defined were taking temperatures, blood pressure, pulsations, patient mobilisation, supply of medications and ultrasound.

Additionally, other studies have been done to evaluate the performance of the operator while the robot carries out remotely the tasks. This evaluation compares the teleoperation results by changing the number of architecture channels, scaling and haptic control modes. The experiments want to answer certain doubts in the teleoperation field. It attempts to know:

- What type of remote task produces more contact and workload realism with a humanoid robot.
- The best control mode with a haptic device for telehealth care tasks. Analysing if a combined control mode (rate and position) lead good results.
- VR glasses are suitable for performing telehealth care.
- Operator feel and performance when remotely operating a humanoid robot (comparing 2 and 3 channels). Giving answers to the following questions:
 - Which is better for telehealth care?
 - Which complete faster the remote task?
 - Which is more accuracy during fast movements?
 - Which has lower contact forces during robot environment iterations?
- Which scale factor is preferable during the remote operations with a humanoid robot (1:1 vs. 1:2).

The established hypotheses have been the following:

- H₄: 3-channel is better than 2-channel for teleoperation tasks with a humanoid robot.
- H₅: Humanoid robot can perform telehealth care with a certain precision.

7.2. Operator feedback in medical application

Subsection 2.1.2 introduces the importance of operator feedback during the execution of remote operations. This subsection evaluates the operator feedback in the medical sector. In medical applications, the visual feedback is usually combined with haptic feedback. The combination is better than using only visual or force feedback [243]. An example is founded in Vascular Interventional Surgery (VIS), where a catheter is inserted [244]. The lack of haptic feedback in high precision tasks (such as force-sensitive tasks in cardiac operations) could cause long operation times and difficulty in execution. Sometimes the lack of haptic feedback is supplemented by visual indicators, but this scenario is only applicable when the surgeon has a good internal understanding of the tissue [228]. The study [243] mentioned that haptic feedback improves performance, precision and speed of the task to be executed. In this way, force feedback is advantageous in the field of telesurgery [229]. Furthermore, during complex and delicate electrosurgical tasks, force feedback is crucial to adjust input forces and to preclude exaggerated forces, which can cause damaging tissue and breaking threads. In this context, another study [245] suggest that the use of 6-DoF control devices improves user perception and performance feedback than 3-DoF devices.

This project wanted to merge the advantages of visual and haptic feedback for carrying out health care tasks with a remotely controlled humanoid robot. This time, the

feedback has been implemented with Virtual Reality glasses and a haptic device, which provide greater immersion to control a teleoperated robot in a hostile environment [246].

7.3. Set-up description and implementation of the robotic system

The development and implementation of the project were carried out at the DLR Institute of Robotics and Mechatronics in 2015-2016 (during the first PhD internship). To develop this system and meet the defined objectives, various activities were carried out as 1) software programming, 2) software and hardware integration, and 3) validation and tests with the humanoid robot and the Human Machine Interface devices. The following subsection describes in detail the system implemented in DLR.

7.3.1. Tele-robotic system description

The system implemented follows the bilateral master-slave scheme showed in Figure 7.1. The slave robot is located in the “dangerous area” to interact with the patients. The operator is in the remote safe area to control the master devices and feel the robot feedback with the HMI. This system allows control of the robot without peril that the operators have direct contact with sick patients.

Figure 7.1 - Bilateral teleoperation system. Left: DLR Justin Robot Space operating (Slave). Right: Human operator controlling the robot with the Phantom, Xsens Unit and Oculus devices

The teleoperation system was tested at the German Aerospace Center, DLR. The tests were not performed with real Ebola patients, but the robot has been prepared to act under this specification and execute the remote tasks with humans.

7.3.1.1. Robot description

The robot used has been the Justin humanoid robot from DLR [247], [248], see Figure 7.2. Justin brings great dexterity thanks to the two KUKA-DLR Light Weight Robots (LWR) arms [247], [249]. This type of arm has 7-DoF with impedance control and a

load capacity of 14 kg, wherein each Justin's arm has a hand (DLR HitHand II) [250]. The humanoid is also equipped with a 2-DoF head with two Prosilica cameras.

Figure 7.2 - Upper body humanoid Justin Robot configuration

The humanoid robot has been controlled remotely. It follows the orders commanded by the operator. At the same time, the robot transmits the environment information through its two cameras (visual information) and arm force sensors (haptic information). It is necessary to clarify that there are two Justin robots in DLR: Rollin' Justin and Space Justin [251]. The main difference is that the first one is mobile and the second one is fixed. During the development of the project, both robots have been used. However, only space Justin robot was used during the tests of subsection 7.6 due to availability and accessibility reasons.

7.3.1.2. Human Machine Interface description

The operator's master console is made up of different devices with the aim to provide a suitable control robot: 1) Phantom Omni to control the robotic arm position and receive the force feedback, 2) Oculus Rift DK2 to visualize the environment in 3D, 3) Xsens Unit to control the Justin robot head, and 4) foot pedals to assist with the software control of the Phantom Omni device and the robotic hands.

Figure 7.3 - Physical control and reception devices for telemanipulating Justin Robot

Figure 7.3 has each device linked with the corresponding part of the humanoid robot. The following paragraphs explain in detail each one:

- Phantom Omni. This device is a serially configured joystick-type haptic interface. It uses a serial kinematic structure to provide 3-DOF force feedback (3.3 N) as well as a 6-DOF positional measurement [252]. The phantom device has a stylus to be held by the user with the aim of control the device links, the single HIP (Haptic Interaction Point). The HIP, also known as the end effector of the haptic device, is shown in Figure 7.4. More details on the kinematic Phantom Omni characteristics can be found in the bibliography [252], [253].

Figure 7.4 - Joints of Phantom Omni: motorized joints (J_1 , J_2 , J_3) and non-motorized joints (J_4 , J_5 , J_6). It provides a stylus that the operator must hold to interact with the device [252]

This haptic device has the function of controlling the Justin robotic arms and feels their iteration with the environment. The Phantom buttons located in the stylus control the opening and closing of the robot's hands. The advantage of this haptic device compared to others is that it is quite intuitive, requiring less learning and adaptation time than other systems such as the Omega haptic device (also used in this project). Moreover, the joints of the Phantom device have some similarity with the position of the robotic arm joints.

- Oculus Rift DK2. The VR glasses provide visual feedback. It shows in 3D the video stream of the place where is the robot. For that, the video is captured by Justin's prosilica cameras. The benefit is that it helps to increase the operator environment immersion.
- Xsens Unit. It is an inertial measurement device. It is located in the operator's head (specifically on the VR glasses) to measure its acceleration and angular velocity. This information is provided to Justin's robot to move the robot's head in the same way that the operator's head is moved in real-time.
- Pedals. These have been controlled with the human's feet. The pedal pressing has been used as "a deadman switch" to control the coupling of the robotic slave system, change of control mode (position to rate, and vice versa) and increase the robotic

arm workspace. The specific use depends on the type of algorithm applied (subsection 7.4).

The haptic device aims to control the robot in position and rate, in addition to providing haptic feedback. This feedback, together with the Virtual Reality glasses, are intended to make the operator feel immersed in the remote environment. These devices have also been used for other types of medical scenarios [254]–[259].

7.3.2. System software and communication

Each device has its software and implementation. The following Table 7.1 shows the software and communication mode used in the master devices and slave robot:

Table 7.1 - Telerobotics system software for telehealth care. It has been implemented in the DLR

Master devices	
Phantom Omni	It has been run on a Linux operating system, and its operation has been implemented in Robot Operating System (ROS), under C++ and Python programming languages. The data has been transmitted and received to the robot via Ethernet through the User Datagram Protocol (UDP) protocol.
Oculus Rift	DLR software ‘Sensornet’ has been used to grab video from cameras over Ethernet (via UDP). The video is received by means GStreamer, where additionally, the video data is written into shared memory on the receive side. The video is visualized via Instant Reality from Fraunhofer [260].
Xsens Unit	The IMU data has been read with DLR software. A separate robotkernel is built up, and the data is published in DLR’s ‘Links and Nodes’ Middleware.
Foot pedals	The pedal activation has been read with DLR software from a parallel port. The communication has been done via UDP and published in ‘Links and Nodes’ Middleware.
Slave (robot)	
Justin Robot	The Justin humanoid robot and the hand controller have been programmed in Matlab Simulink and have been executed in an RT Linux system. The data was communicated via UDP on a local network.

The DLR team measured the communication delay and it has a negligible delay ($\sim 1\text{ms}$).

7.3.2.1. System architecture

The slave and master devices have bidirectional communication in order to implement a teleoperation system with proper robotic control and feedback. Figure 7.5 describes the telerobotics configuration between the master and the slave. Each system sends information to each device so that the set works in a coordinated way.

Firstly, the two Phantom Omni managed by the operator’s hands capture and calculate the relative pose of their respective haptic device (in reference to the initial state) [261]. The relative pose (state) contains the position and unit quaternions (orientation and velocity) of the Phantom. At the same time, the button state of Phantom is detected, that is if the button has been pushed or not. All this information is transmitted

via UDP in vector data to the slave robot. This information is processed on the Justin controller to move the robotic arms and close or open the DLR HitHand II hands. On the other hand, the Space Justin robot sends the measured force experimented in the work environment, which is obtained through the force-torque sensor of the end-effector robotic arm. This information is sending to the haptic device, so it can simulate this force in the form of limitation of movement in the device, giving a real haptic feeling of the interaction of the robot with the environment. Parallel, the VR glasses stream the video captured by Space Justin's head cameras. In turn, the inertial motion sensor (Xsens) sends the acceleration and angular velocity information to position Justin's robot head (2-DoF) in the same operator's head position.

Figure 7.5 - Software intercommunication between the telerobotics master and slave system

The master foot pedals also play an important role during the robot operation. The workspace of the haptic device is less than the range of the robotic arm. Therefore, the Phantom cannot reach the entire robot workspace. One of the proposed solutions was to implement an indexing method to expand the workspace iteratively after pressing a pedal. So when the Phantom reaches its mechanical limit, the operator pushes the master pedal with the feet. At that moment, the freeze signal is sent, which performs two functions: it keeps the robotic arm position frozen, and in turn, positioned the Phantom single HIP in an initial state/position. When the Phantom single HIP is in the initial state, the position of the robotic arm is thawed. From this moment, the master device returns to normal operation and has more working space to move the robotic arm again. This pedal method was used in two algorithms described in subsection 7.4 and during the tests that are presented in subsection 7.6.

The software architecture implemented for use Phantom Omni in ROS is showed in Appendix E. It explains the software structure to implement a telerobotics haptic control with the Justin robot.

7.3.2.2. Safety

The Justin robot is configured to be completely stopped in case of improper operation, emergency or other circumstances. The telerobotic system can be stopped by software or pressing an emergency stop button (deadman) in a more critical case. During the experiments, the operator assistants supervised the operation and made sure everything was working properly. The operators and test participants were instructed how to stop it in case the experiment fails, or the operation went wrong or became risky.

7.4. Haptic device: Phantom Omni device configuration in ROS

Subsections 2.1.2 and 7.2 shows the importance of feedback during remote robot tasks. The type of control devices, their configuration and implementation mode have an important role in the operation results. The master control device selected for this project is the Phantom Omni, as was previously mentioned. This device has been mainly selected for its haptic feedback and its intuitive handling. The problem is that it cannot cover the entire working area of Justin's robotic arms. In these cases, a workspace indexing is usually implemented, which is applied when the master device reaches its mechanical limit. For that, different configurations can be used, such as combine position and rate control modes, or expand the workspace [262][263]. This section analyses and compares different ways to indexing the workspace when the Phantom reaches its limit (e.g., pedal, button and position algorithm), and also other "control modes" for controlling the robotic arm (i.e., rate and position). The comparison is made to determine which is better to telemanipulate a humanoid robot during telehealth case tasks. It has been done implementing a bilateral position-force control architecture with 3-channel, which transmit the master position and also the calculated and measured forces of the slave and environment. The three control methods implemented have been the following:

1. The rate-position controller: it automatically swaps the control mode when the device reaches the workspace limit (defined by a sphere). The control mode changes from being controlled in position to being controlled in rate, and vice versa. This change depends on the master device position.
2. Rate-position controller with indexing method: it changes the control mode through an external interface (button or pedal). When the external interface is activated, the control mode changes. The position control mode becomes to be in speed, and vice versa.
3. Position controller with indexing method: it expands the workspace using an external interface (button or pedal). In this case, when the operator wants to expand the master device workspace, the button or pedal is pushed/pressed to

freeze the position of the robot. After that, the Phantom Omni reaches the initial position, and the workspace has increased again.

The first control method has to take as reference the algorithm “rate position-controller” implemented in the UPM [262]–[264]. The other methods are a modification of the first one. The three methods have been implemented using the Phantom Omni device and the ROS framework.

7.4.1 Method 1: Rate-Position controller with internal indexing

The UPM telerobotics team developed an algorithm under the patent “Method of guiding teleoperated robotic devices to alternate control mode in position and control mode in speed” (ES patent 201132146). This method, “rate-position controller”, has been adapted for this project.

Figure 7.6 - Status of “Rate-Position controller with an internal indexing” method

The advantage of this method is that it enables to control the Phantom Omni device in position and rate mode without the use of external interfaces. It automatically changes the control modes depending on the HIP location. The workspace is contained in an ellipsoidal volume, which is divided into different states (see Figure 7.6). The state 0 is the initial position, the state 1 is the position controller, the state 2 is a vibratory transition phase, the state 3 is the rate controller, and the state 4 is the rate collision. The schema of Figure 7.6 represents the transitions between the states.

- State 0 “go to the centre”: it positions the single HIP of Phantom Omni in the starting centre of the ellipsoid workspace through a spring-damper force [263]. At this point, the master device is synchronising with the slave's current position and keeps its position frozen. State 0 is defined in the work centre as a small “hysteresis circle”. The HIP leaves this state when it exceeds the small hysteresis circle. As Figure 7.6 displays, the device is in the state 0 when: 1) it initializes, 2) it changes the control mode to position, or 3) a collision have been produced.
- State 1 “control in position”: this state allows control of the robot in position mode as long as it does not exceed the limit volume of state 1. The slave imitates the movements executed by the master, and at the same time, the master device

receives the robot contact forces occurred in the remote environment. For that, a bilateral position-force architecture has been implemented.

- State 2 “vibratory phase”: when the HIP exceeds the limits of the state 1 (position controller), a vibrating force is generated to inform the operator of the transition to speed control mode. The vibratory stimulus is a damped oscillatory signal of 250-500 ms with a frequency of 30 Hz.
- State 3 “rate control”: this state controls the robot in rate mode. For safety, the speed of the robot is reflected in the operator by means a spring-damper. Therefore, if the master device moves away from the sphere, the speed command will be greater but a safety force exerted by a spring will also be greater for the operator. To return to position mode, the operator must go out of the rate volume. When it happens, the master device automatically brought the HIP to the work centre, where the master and slave are synchronized.
- State 4 “rate collision”: it checks the collisions. If a collision happens during rate control, the speed commands sent to the robot a stop command. At this moment, an opposition force is applied to move the master device (single HIP) to the centre of the workspace, returning the algorithm to the state 0.

7.4.2. Method 2: Rate-Position controller with external indexing

The second method was implemented based on the Rate-Position controller method. The new control algorithm includes some states specified in section 7.4.1. These are the state 0 “go to centre”, the state 1 “control in position”, the state 3 “speed control” and state 4 “rate collision”. State 2 has not been implemented because the transition between control modes (position to rate and vice versa) is done with an external interface. Two types of external interfaces have been tested for this method: Phantom button and foot pedal. In both cases, the transition is executed when is pressed one of these interfaces.

Figure 7.7 - States and workspace of “Rate-Position controller with external indexing” method.
This method has two control modes in the same area.

Method 2 starts at the centre of the working ellipsoid (state 0), as Figure 7.7 and Figure 7.8 represent. Once the HIP exceeds the small hysteresis circle (orange circle in Figure 7.7), the slave becomes controlled in position mode. In case of pressing an external

interface, the master is brought to the workspace centre, and the rate control mode is activated. For safety reasons, the rate control has a spring-damper proportional to the Phantom single HIP position (and also the robot speed), the force of the spring is greater the farther it is from the centre. It prevents the operator from applying high speeds unconsciously.

Figure 7.8 – States transitions of “Rate-Position controller with external indexing” method

This method also has implemented the “rate collision” status, which is checking if an undesired collision is produced. In case of detecting a collision, the HIP is moved with a repulsive force to the centre (state 0).

7.4.3. Method 3: Position controller with external indexing

This algorithm only implements one control mode, the control in position. This method only has two states: the “go to centre” and the “position controller”, see Figure 7.9.

Figure 7.9 - States and workspace of the “Position controller with external indexing” method. It only has one control mode, when the Phantom joint reach to the ellipsoid limit is possible to press an external interface to relocate the joint in the centre (state 0). This process is done freezing the robot position

As in the previous algorithms, this starts in the work centre. The control in position is executed when the HIP device comes out of this small volume. The difference with the

other methods is that when the master HIP device reaches the mechanical limits of the ellipsoid. To restore the position workspace, the external interface is actioned by the operator, and subsequently, the workspace indexation is produced. At this moment, the slave position is frozen, and the master device is brought back to the central point to make the entire workspace available again. The complete state sequence can be visualised in Figure 7.10, wherein it is much simpler than the previous ones.

Figure 7.10 – States transitions of the “Rate-Position controller with external indexing” method

7.4.4. Evaluation of control master architectures

The three control methods presented have been evaluated using the Phantom Omni, VR glasses, the Xsens and external interface (button and pedal). Thus, the operator can control the robot position. Moreover, he/she receives the force and visual feedback from the environment. The advantage of using the VR glasses together with the Xsens is that they isolate the operator from the real environment. It generates an immersive sensation as if the operator were the own robot and had a proprioceptive sensation of the head. The proprioceptive sensation does not happen using certain devices, such as joystick or control panels. In this case, the control of the robotic arms movement differs from how the operator usually moves his/her arm since the control is done through the operator's hands. It produces changes in the operator's perception, and the brain must be adapted. It could be a drawback when the operator has to execute dexterity and agility operations, such as grasping and inserting a pulse oximeter to the finger of an unconscious patient. Therefore, the control algorithm and the HMI devices selection are important for brain perception. It can influence learning and training time, adaptation, task execution, and robot handling.

- **Method 1. Rate-position controller with internal indexing:**

- Better control of the robot's movement in large workspaces, where it is not required movements with great precision or delicacy.
- A vibration feeling differentiates the control mode change (position to rate control). This stimulus creates confusion and sense overload when the operator

is performing an operation that requires concentration, dexterity, and precision with visual isolation.

- Rate control is not secure nor precise during the performance of operations that demands precision.
- This algorithm avoids the use of additional external elements to carry out the control mode change.
- Collisions during the rate control have more probability of being occurred than with the position control.

- ***Method 2. Rate-position controller with external indexing device:***

- Better control of the robot's movement in large workspaces, where it is not required movements with great precision or delicacy (as method 1).
- The indexation method by pressing a button need the operator's fingers. It can cause involuntary movements since the hand is being used to control the position of the master device (Phantom Omni). Moreover, pressing a button with visual isolation can be tricky (due to the use of VR glasses). Therefore, this is discouraged.
- The indexing method by a pedal needs the use of the operator's feet. It is recommended since the foot would only be used for this task. These act together with the hands, like when driving a car. It would not be advisable to have many pedals because this would create confusion.
- There is a force that positions the master device in the centre of the workspace. It happens during the initial state and when the control mode is switched. It is recommended especially if the operator is visually isolated with the VR glasses.
- Rate control is not secure nor precise during the performance of operations that demands precision (as method 1).
- Collisions during the rate control have more probability of being occurred than with the position control (as method 1).

- ***Method 3. Position controller with external indexing device:***

- Better control of the robot's movements in not very large places.
- The indexation method by pressing a button need the operator's fingers. It can cause involuntary movements since the hand is being used to control the position of the master device (Phantom Omni). Moreover, pressing a button with visual

isolation can be tricky (due to the use of VR glasses). Therefore, this is discouraged (as method 2).

- The indexing method by a pedal needs the use of the operator's feet. It is recommended since the foot would only be used for this task. The foot works together with the hands, as when driving a car. It would not be advisable to have many pedals because this would create confusion (as method 2).
- A single control mode does not create operator's confusion or mental fatigue.
- The force towards the centre of the ellipsoid is practical and intuitive to position the master device when the indexing method has executed to extend the workspace.

This automatic position is useful when the operator is isolated with the VR glasses.

Table 7.2 shows the subjective parameters related to the workload of each implemented algorithm. This evaluation has been based on the subjective test provided by NASA TLX [265]. It has served to evaluate the most appropriate algorithm to be implemented in the master devices for executing telehealth care tasks. It has helped carry out real and objective tests with different subjects.

Table 7.2 - Subjective workload evaluation performing delicate remote tasks in small spaces (using haptic devices and VR glasses). Three control methods have been evaluated in this test.

	Method 1. Rate-position controller with internal indexing	Method 2. Rate-position controller with external indexing	Method 3. Position controller with external indexing
Mental demand	High	Medium	Low
Physical demand	Medium	Medium	Low
Temporal demand	Medium	Medium	Low
Effort	Medium	Medium	Low
Performance (small workspaces)	Medium	Medium	High
Performance (large spaces)	High	High	Low
Frustration level	Medium	Medium	Low

7.4.5. Discussion

Dexterity and precise tasks in small spaces require more mental and physical demands. Control mode changes (position-rate or rate-position) can create confusion and a lack of precision when performing precise tasks in small spaces. Control a robot in position and rate mode is more suitable and practical for large workspaces. Even though Method 1 allows controlling the positioning of the arm without using any additional device or

interface. This method meant an extra mental load when having to remember the different states and automatic changes depending on the Phantom single HIP position. Moreover, the vibrational transition mode of method 1 can cause disorientation when the operator is isolated with VR glasses. The extra stimulus can put on scaring or alerting the operator when he/she is concentrated.

In the case of method 1 and 2, the physical exigency is greater during the rate control mode since spring had been implemented to limit excess speed, increasing the operator's fatigue in this mode. Moreover, these methods need more execution time if the workspace expansion is required, as it is necessary to change the control mode to place the Single HIP Phantom in the workspace centre. Thus, frustration on delicate tasks (i.e. take a patient's blood pressure, push a button) was higher using two control modes. It can produce insecurity and stress and also involuntary movements.

In turn, method 3 gives better results with a single position control mode. It is more precise and less confusing for accuracy tasks as the telehealth care. Moreover, method 3 has an external indexing method so as not to overload the operator and avoid unwanted movements with the hands.

These results are relevant to know what type of control mode is suitable for telemanipulating humanoids. These indicate that a single control mode in position is better for telehealth care tasks. In turn, two control modes are necessary when the humanoid has to be manipulated in large areas. In this case, two control modes to manage the robotic arms are not needed, but it could be a good option if the robot has to be moved until another area. As Figure 7.11 illustrates, the suggestion is to implement method 3 to control the robotic arms, and then has an extra pedal to change the method. A rate-position control is better to move the base of the humanoid.

Figure 7.11 - Control mode to telemanipulate a humanoid

The following subsection 7.6 shows several experiments with subjects, wherein method 3 has been implemented.

7.5. Telehealth care execution tasks

This section shows pictures of how Justin robot executes telehealth care tasks with humans. Figure 7.12 shows the medical tasks that were specified by medical experts (subsection 7.1.2). The activity of “delivering medical supplies” could not be done because the Rollin ‘Justin (mobile robot) was not available during the test dates. Image 1) shows as Justin robot inserts the unit oximetry device in the patient’s finger. This device is able to measure the oxygen pressure blood, but the parameters calculations are done when Justin pushes a button on the top of the device. Then Justin visualises the results displayed on the device screen. Similarly, image 2) visualises as Justin take the temperature with the thermometer. The robot has to point the laser of the thermometer at the human’s forehead. After that, Justin pushes the thermometer button and visualises the temperature on display. Image 3) represents ultrasonography, where the Justin press the human’s stomach softly and perform movements with a dummy tool, which represents the ultrasound device. Finally, images 4) and 5) shows as Justin helps to move the human’s arm with special movements for rehabilitation.

Figure 7.12 - Execution of telehealth care tasks with humans

7.6. Experiment: user study on the evaluation of force feedback effects

This article presents a user study investigating human performance when an operator is teleoperating a complex humanoid robot with a haptic interface, besides to analysing the effect of force feedback, architecture channels (2-channel vs 3-channel) and workspace scaling (1:1 vs 1:2).

7.6.1. Technical and experiment set-up

The study was carried out with twelve participants (9 males, 3 female) aged between 22-35 years (M (Media) = 25.83; SD (Standard deviation) = 4.24). This test was conducted at the DLR Robotics and Mechatronics Centre facility, where the Space Justin robot was used. The master devices that the subjects used from the control area were: two phantom devices for control each slave arms and hands, the Oculus Rift with the Xsens unit and the pedal. The detail of each device and its operation has been mentioned in subsection 7.3.

During the tests, the sensorimotor performance of every subject was measured via the "Sensomotorische Koordination" test battery (SMK, [266]) a part of the Vienna Test System of the Schuhfried GmbH.

7.6.1.1. Experimental tasks

Before starting robotic operations, subjects carried out a training test to become familiar with the task. The real experiment is formed by four sets of tasks with four conditions for each. The operator rated the contact realism and the overall workload scale [267] after each condition (four times for each task). The four sets of telerobotics tasks that have been carried out are the following:

1. First remote task (aiming): subjects had to point at the middle of four different circles (0.02 m of diameter) as accurately as possible, see Figure 7.13. The pointer is a pen mounted in a grasping adapter, which is grasped with the right robotic hand, as shown in Figure 7.14.
2. Second remote task (line drawing): subjects had to follow the drawing lines of 0.11 m, a vertical line (position A to B in Figure 7.13) and then a horizontal line (position C to D in Figure 7.13). The tools used are the same as mentioned for the first task.

Figure 7.13 - Graph paper with the four circles for the first task (grasping) and the lines for the second task (Line Drawing)

Figure 7.14 – Telerobotics system configuration and task performed by the participants

3. Third remote task (grasping): the subject had to approach the left robotic hand until the tool adapter equipped with an oximetry and grasp it (see Figure 7.14). After lifting, the object had to be put on the table and released again.
4. Forth remote task (oximetry): after task three, the oximetry unit has to be placed into an artificial finger (dummy finger), as Figure 7.14 represents. Then, the left robotic arm has to push the button of the oximetry unit, which has a diameter of 3 mm. After that, the oximetry unit is removed from the finger, and the result is visualized.

7.6.1.2. Experimental design and procedure

Four different conditions were applied systematically in each task. The goal consists of known and compares the effects based on the type of remote task. A fifth condition was implemented for the second task (line drawing), which consisted on operate manually without any telerobotic system. The four conditions implemented with different robotic architecture configurations were:

1. 2-channel architecture with computed force feedback (workspace scaling of 1:1).
2. 2-channel architecture with computed force feedback (workspace scaling of 1:2).
3. 3-channel architecture combining computed and measured force feedback (workspace scaling of 1:1).
4. 3-channel architecture combining computed and measured force feedback (workspace scaling of 1:2).

Within each condition, all tasks were performed in the following order: 1) aim, 2) line drawing, 3) grip, and 4) oximetry. Each subject completed the four conditions in a systematically varied order to control the time effects as fatigue or training. After each condition, the contact realism and the general workload scale were rated in a scale range from 1 to 20. On the other hand, the slave software logged the duration, the desired and actual position, the velocity and the computed and measured interaction forces and torques of the slave. This data was evaluated with Matlab 2013b.

7.6.1.3. Channel architecture and scaling

The present study implements 2-channel architecture with computed force feedback and a 3-channel architecture with combined computed and measured force feedback. It knows that telerobotics uses different channel architectures depending on resources and objectives. 4-channel architecture is a complete configuration since it achieves good transparency between operator and robot environment. However, a 4-channel architecture [268] cannot be implemented in this experiment since most low-cost haptic devices have no force sensor. The combination of computed and measured force feedback in a 3-channel approach leads to higher fidelity compared to systems with pure computed or measured force feedback as presents [269]. The article [270] shows that in theory, 3-channel architectures can lead to perfect transparency. Concerning 2-channel, this have disadvantages compared with 3-channel, and measured force-feedback requires a costly force-torque sensor at the slave side [C3]. Figure 7.15 and Figure 7.16 show a comparison between 2 and 3-channel architecture. As 3-channel shows, the computed force F_c is scaled down by λ_c and measured force is scaled down by λ_E .

Figure 7.15 - 2-Channel Architecture with computed Force Feedback [C3]

Figure 7.16 - 3-Channel Architecture [C3]

The other variable compared in the experiments has been the workspace scaling. The optimal scaling between master and slave depends on the system design and the task. Theoretically, 1:1 scaling mapping should lead to higher accuracy movement compared to the scaled 1:2. Nonetheless, the larger movement amplitudes of 1:1 could also decrease

performance in slow and high precision movements. It is because the hand/arm stabilization is more demanding with 2-channels architecture [C3].

7.6.2. Experiment results

The results (means and standard deviations) of the test are presented in Table 7.3:

Table 7.3 - Results of the telerobotic experiment performed with subjects

Measure	Unit	2-channel -1:1	3-channel -1:1	2-channel -1:2	3-channel -1:2	Manual
Task Duration - Aiming	sec	60,54 (22,68)	63,02 (38,83)	54,20 (23,20)	50,95 (21,96)	-
Task Duration - Line Drawing	sec	73,08 (40,38)	68,97 (40,43)	59,86 (29,31)	55,21 (33,35)	-
Task Duration - Grasping	sec	39,94 (11,84)	44,93 (18,10)	38,92 (5,04)	36,15 (13,45)	-
Task Duration - Oximetry	sec	35,71 (10,10)	32,16 (6,58)	39,91 (29,46)	27,99 (12,26)	-
Force Application (x- Axis) - Line Drawing	N	3.58 (1.47)	2.86 (1.65)	3.64 (2.0)	3.35 (1.98)	-
Positional Accuracy - Aiming	mm	1,15 (0,46)	1,48 (1,02)	1,15 (0,56)	0,81 (0,34)	-
Positional Accuracy - Line Drawing	mm	1,23 (0,48)	1,30 (0,43)	0,95 (0,31)	1,02 (0,29)	0,21 (0,21)
Workload - Aiming & Line Drawing	1-20	8.67 (4.89)	9.83 (4.1)	9.33 (4.66)	8.75 (4.65)	-
Workload - Grasping	1-20	7,92 (4,12)	8,75 (5,56)	7,25 (3,86)	7,25 (4,92)	-
Workload - Oximetry	1-20	7.67 (3.75)	8.0 (4.11)	8.25(4.77)	6.92(4.14)	-
Contact Realism - Aiming & Line Drawing 1	1-20	11.17 (4.61)	10.0 (4.75)	11.33 (4.54)	11.83 (4.43)	-
Contact Realism - Grasping	1-20	9,17 (5,01)	10,33 (4,87)	10,67 (4,81)	11,50 (4,50)	-
Contact Realism - Oximetry	1-20	10.0 (5.85)	10.75 (4.31)	10.33 (5.38)	11.92 (3.83)	-

The data has been analysed performing repeated measures ANOVA (rmANOVA). The main assumptions for this procedure, that is, normality of residuals and sphericity has

been tested by Shapiro-Wilk's test and Mauchly's test. In the case of non-normality, related-samples Friedman test as a global test and Wilcoxon signed-rank tests for pairwise comparisons were done.

The value p (probability value) is a quantitative measure to report the result of statistical hypothesis testing. It is used to contrast the results, and check if there are differences between the samples. A result is statistically significant (and allows rejecting the null hypothesis H_0) if it corresponds to a p -value equal to or less than 0.05.

The F-statistics from a repeated measures ANOVA as: $F(df_{\text{time}}-df_{\text{error}}) = F\text{-value}$. The main F ratio tests the null hypothesis that the column means are identical. In each case, the F ratio is expected to be near 1.0 if the null hypothesis is true. If F is large, the p -value will be small.

The t -value is computed for a t -test, which measures the difference in means (averages) of one or two distributions. A t -value of 0 indicates that the sample results exactly equal to the null hypothesis. As the difference between the sample data and the null hypothesis increases, the absolute value of the t -value increases.

7.6.2.1. Analysis of the results measures

After obtaining the results, relevant factors have been statistically evaluated and compared between the different task and configuration, such as the task duration, force application, position accuracy, mental workload and contact realism. The following analysis also reported the violation of the assumptions done.

- Task Duration. The task durations have been analysed for the four tasks.
 - For Aiming, the assumption of normality was violated, so Friedman test was chosen. Results indicate a significant effect of conditions ($p < .05$). Wilcoxon signed-rank tests reveal that there is a significant scaling effect on task durations in the 2-channel and 3-channel conditions ($ps < .05$ for both). The result indicates that subjects have been faster with 1:2 scaling. Moreover, there is a trend that with 1:2 scaling subjects needed less time in the 3-channel compared to the 2-channel condition ($p < .10$; one-tailed testing).
 - In the Line Drawing task, the normality was not given. Friedman analysis shows a general effect ($p < .001$). Also, Wilcoxon signed-rank tests reveal that there is the same scaling effect in the 2-channel as well as in the 3-channel conditions ($ps < .05$ for both). Although, subjects performed significantly faster the task with the 3-channel architecture in the 1:2 scaling conditions ($p < .05$, one-tailed testing) and marginally faster in the 1:1 scaling conditions ($p < .10$, one-tailed testing).
 - No significant condition effect was evident for the Grasping task, as indicated by the Friedman test.

- For Oximetry task, a marginally significant condition effect has been found for the Oximetry task ($p < .10$), with shorter times in the 3-channel compared to the 2-channel conditions, as Wilcoxon tests indicate ($p < .10$). Nevertheless, this effect only has been occurred in the 1:2 scaling conditions.
- Force Application. The forces during the Line drawing has been analysed along the x-dimension (depth). In this case, rmANOVA indicates a significant channel main effect ($F(1,11) = 8.0, p = .01$). Thereby, forces have been substantially lower in the 3-channel case, but this effect has been more pronounced in the 1:1 scaling condition. The paired-samples T-test also confirm that there are significantly lower forces with 3-channel during 1:1 scaling ($t(11) = 2.93; p = .01$) and a trend for the same effect during 1:2 scaling ($t(11) = 1.59; p < .10$, one-tailed testing).
- Positional Accuracy. This condition was explored for Aiming and Line Drawing tasks.
 - The accuracy measure for Aiming has been the distance between the aim and the subjects' point on the sheet. A rmANOVA has been performed; it reveals a significant effect of scaling ($F(1,11) = 5.0, p < .05$) with higher average accuracy in the 1:2 scaling conditions. Nevertheless, T-tests indicate that the scaling effect has been exclusively due to the 3-channel conditions ($t(11) = 2.21, p < .05$), with a relatively large distance of $M = 1.48$ mm during 1:1 scaling and significantly smaller distances of $M = 0.81$ mm in the 1:2 scaling condition. No effect has been found for the 2-channel conditions ($t(11) = 0, ns$).
 - The main performance measure for the Line Drawing task has been the average deviation from the ideal line. The data obtained were non-normal, so Friedman test has been done. The results show a highly significant effect ($p < .001$). The accuracy decreased considerably with five times higher deviations in the four telerobotic conditions ($M = 1.13$) compared to the manual condition ($M = 0.21$). The data in the manual condition neither were non-normal. Friedman test indicated a highly significant overall effect ($p < .001$) and all Wilcoxon tests comparing manual and telerobotic conditions reached significance (all $ps < .01$). The rmANOVA has been applied only to the data in the telerobotic conditions. The results indicate that there is significant scaling main effect ($F(1,11) = 7.51, p < .05$), that is, the accuracy was better with 1:2 compared to 1:1 scaling.
- Mental Workload.
 - The combined subjective rating for Aiming and Line drawing revealed that subjects perceived lower mental workload when they were working with 3-channel in the 1:2 scaling condition (significant rmANOVA Channel x scaling interaction effect, ($F(1,11) = 5.0, p < .05$). Paired-sampling T-test also shows a significant

difference between 2 and 3-channels in the 1:2 scaling conditions ($t_{1:2(11)} = 1.87$, $p < .05$, one-tailed testing).

- For Grasping, scaling effect has been found ($F(1,11) = 9.16$, $p < .05$) with lower ratings in the 1:2 compared to the 1:1 scaling condition.
- No significant effects have been found for the Oximetry task.
- Contact Realism.
 - No significant effects have been evidenced for the combined Aiming and Line Drawing ratings regarding contact realism.
 - For the Grasping task, there is a significant scaling main effect ($F(1,11) = 8.64$, $p = .01$) and a channel main effect ($F(1,11) = 5.39$, $p < .05$). It reflects higher perceived contact realism with 1:2 scaling as well as 3- channel architecture.
 - No significant effects have been found in rmANOVA for the Oximetry task.

7.6.3. Discussion

The studies conducted with different subjects have served to determine if basic movement and contact tasks, as well as more realistic tasks from the medical domain, can be performed with a complex humanoid robot controlled through a commercially available haptic input device. The results show that the precision of the movement was approximately five times lower compared to manual performance in the Line Drawing task, which is far more delicate than typical health care tasks.

- **Task completion times should be shorter?**

Concerning free movement tasks (Aiming), movements in contact (Line Drawing) and complex tool interaction (Oximetry), there is evidence for shorter completion times with the 3-channel compared to the 2-channel approach, although this effect mainly occurred when operation movements were upscaled (factor 1:2). The upscaling factor may be produced that the robot movements were performed faster, and thus, inertia effects were also more pronounced. However, the experimental conditions had no particular impact on Grasping task, perhaps due to the spatial orientation demands. Therefore, it is possible to partially assume that teleoperation tasks can be accomplished faster with 3-channel architecture, although it depends on the task and scale factor.

- **Should accuracy movement be higher during fast movements?**

During fast movements, a higher degree of movement accuracy was expected with the 3-Channel solution. For the Aiming task, the best performance was achieved with 3-channel in the 1:2 scaling situation, with the worst performance in the 1:1 scaling condition. Perhaps the additional inertia effects in the 2-channel conditions stabilized the larger movement amplitudes in the 1:1 scaling case, leading to better results compared to inertia free movements during 3-channel conditions. Regarding Line Drawing, no clear evidence

has been found. Perhaps movements were too slow to trigger any effect of Channel architecture.

- **Contact forces during robot-environment interactions should be lower?**

The initial assumption was that the contact forces during robot-environment interactions should be lower when it is working with the 3-channel approach. For this evaluation, the Line Drawing task has been analysed since it is the most relevant force regulation task. The analysis and results conclude that the forces were lower with the 3-channel compared to 2-channel architecture.

- **Subjective contact realism should be higher, and thus, mental workload lower?**

The qualifications result of the contact realism and workload showed the best results for the 3-channel architecture in the 1:2 scaling case. However, these did not reach significance in all cases. There was only clear evidence for higher contact realism with 3-channels and 1:2 scaling condition for the Grasping task. The workload was rated best in this condition, but only for the Aiming and Line Drawing tasks.

In summary, there are clear advantages of using a control approach integrating measured force feedback regarding relevant performance parameters. The disturbing effects of robot inertia when using a 2-channel approach deteriorate the performance. This effect has been only evident when using an upscaling factor (1:2) since it magnifying the negative impact of inertia. Therefore, 3-channel architecture and 1:2 scale give good results. It is acceptable for being implemented in a humanoid robot to perform telehealth care tasks.

Chapter 8

Conclusion

8.1. Conclusions

- **Chapter 3**

Methodologies are necessary for many areas, as it helps to set the right path to implement an objective. For this reason, chapter 3 shows the definition of a methodology to implement RH tasks in radiation environments, more specifically focused on particle accelerators with high levels of radiation. The methodology developed establishes a clear and sequential order with iteration flexibility to implement an RH task from scratch. However, this also allows for implementing tasks in areas where RH tasks had previously been performed. It is beneficial to facilitate the coordination of various working groups since it marks a common objective and path, where the information, development or action required at each stage is specified in the methodology. It is important in the initial phases to single out the diverse scientific knowledge focused on RH tasks, such as: the information on radiation levels and contamination in the area where a component needs to be RH replaced (Radiological team), elements of the component that need to be manipulated by the robot (Accelerator designers team), and other information on the accelerator facility that focuses on the RH. It helps establish a common language or understanding, where the requirements of each are considered. In this way, with a clear methodology, it is possible to optimise and improve the implementation of RH operations, since it is known that it is necessary at each stage. It avoids following incorrect implementation routes, which lead to loss of time and money, or lack of relevant information at certain stages, which could lead to misunderstandings or failures in the project.

- **Chapter 4**

Design guidelines are beneficial for facilities where RH operations are expected. Some accelerator facilities demand it since there are zones with high radiation. The experience in this area [J1]-[J5] has concluded that adequate guidelines should be considered during

the design phase. Applying guidelines from the very beginning of the conceptual design up to the detailed design will avoid later modifications, sometimes costly or even unfeasible. The design guidelines have to be applied to find a reasonable balance with the rest of facility requirements such as cost, maintenance schedule, availability of the facility, accuracy of positioning, etc. The guidelines presented addresses the problem in accelerator facilities. It specifies recommendations for design and selection according to the building, components and RH Equipment. It considers the influence of the different facility characteristics, which allows the optimisation of the procedures of the expected RH tasks since it is possible to design or select the most appropriate equipment and elements for each case. The great advantage is that it saves time during maintenance stops, which is a crucial factor in radiation facilities.

Furthermore, this chapter evaluates the common elements and equipment used during RH operations. It provides knowledge of the characteristics, benefits, weak points and differences on specific solutions or others more suitable for RH. This contribution helps to determine the best selection and resolution according to each situation or required requirements.

▪ Chapter 5

Chapter 5 performs several radiation tests to know and evaluate the effect of the gamma radiation in electronic devices, sensors, actuators and robotic arms. The conclusions after analysing the results are the following Table 8.1:

Table 8.1 - Results of the microcontroller under gamma radiation

Characteristics	Microcontroller	Cumulative dose (Gy)
1 Gy/s for 5 min, 1.5Gy/s for 5 min, and 5 Gy/s for 10 sec	ATmega328P	800
0.09 Gy/s for 52 min and 22 sec	ATmega64M1	283
0.18 Gy/s for 20 min and 26 sec	ATmega328P	220
0.18 Gy/s for 18 min and 6 sec	ATMegaS64M1	195

- High dose rates (1Gy/s to 5Gy/s):
 - No detectable malfunctioning has experimented during the Control Board (Arduino Uno) performance in dose rates between 1 and 1.5 Gy/s during 10 minutes. Still, irreversible fails appeared when the radiation dose was increased to 5 Gy/s (see Table 8.1).
 - The ATmega328P microcontroller was the component that causes the fatal failure in all the Arduino Uno boards. This microcontroller broke down when it reached a high cumulative dose (800 Gy).
 - The experience has led that the TID in high dose rates increases, but at the same time, decrease the duration of the electronics as Table 8.1 evidence. However, it

can lead to misunderstandings since some errors that happen with a low dose rate do not appear at a high dose rate. In this way, the experiment has evidence the sensitive response of the microcontroller exposed to gamma radiation and the need to extend its durability.

- High-medium dose rates (0.09Gy/s to 0.18Gy/s):
 - The electronic component that caused the fatal failure with lower radiation dose was the microcontroller, so it is the most sensitive component of a Control Board.
 - Lower radiation doses cause TID failure at lower accumulation doses. The result also evidences that the duration in time of the microcontroller increase when the dose rate decrease (see Table 8.1).
 - Under the same environmental conditions, the TID could be different for each microcontroller, as Table 8.1 shown. It depends on the characteristics of each one.
 - The experiments had led an interesting result; a Rad-Hard microcontroller fails before that a non-Rad-Hard microcontroller under the same conditions. Thus not only the material of the component is relevant to extend the durability of this sensitive component but also other characteristics such as dimensions (SMD or DIP package), clock frequency, voltage, and so on [141], [142].
 - The degradation of the microcontroller has been noticeable minutes before starting to fail. It is reflected in a progressive increase in the values processed by the microcontrollers of the sensors and actuators.
 - The internal temperature sensor of Microcontrollers ATmegaS64M1 and ATmega64M1 detected an internal temperature rise 2-3 minutes before failure.
 - The fatal error originated in the ATmega64M1 can be produced by a deterioration of the microcontroller due to the TID. The analysis indicates a possible internal leakage current due to the increment of temperature and current. Internally, this phenomenon is more detailed in other experiments [141]. It specifies that the accumulated ionising dose increase the leakage current, while the clock frequency decays. Undesirably, this can cause a parallel propagation delay in individual components, timing windows in the instructions executed, and other effects [141], [200], [271].
 - SEE errors were not detected during the test. If SEE error was occurred and was not detected, the reasons may be the following: 1) the error was produced in a memory part that is not possible have access, but this did not interfere with the program executed, 2) the error happens so fast and it disappears before reading the memory again, 3) a particle with sufficient high ionising power did not injected on the electronics circuits [272].

- Once the microcontrollers began to fail, their recovery was not possible after performing internal software reset, program restoration and hardware power restoration.
- The robot functioning was correct until reaching a certain accumulated dose. The radiation affected differently from each servo motor. The robotics arm operation was deteriorated due to servo motor degradation. The deterioration appeared more or less progressively until the microcontroller started to fail. From that moment, the correct robot functioning was unrecoverable.
- The robot follows the positioning of the end effector correctly until minute 25, after this moment, a progressive deterioration was reflected, and after minute 40 end effector actuator become totally affected. In this way, the accuracy and correct operation of the robot only lasted 25 minutes.
- Concerning the different methods to minimise or mitigate the radiation effects. The placement of a sensitive component outside the irradiation area or shield it with lead have given good results. In both cases, the microcontrollers did not fail, but some noise signal appeared in servo motors located in the accelerator target, being more accentuated in those without a lead shield. The mitigation method selection could be related to the facility design and the distances between the areas to locate the electronic components. It is an important topic to address during the design facility phase.
- Some temperature sensor and servo motors have become affected by radiation. It has depended on the position, dose rates and accumulated dose.

The hypotheses established at the beginning of chapter 5 have been validated. The results for each of them are as follows:

- H_1 : Radiation resistant microcontrollers are more resistant in environments with gamma radiation.

The result has indicated that not always a specific Rad-Hard microcontroller resists more time under radiation environments than others that are non Rad-Hard designed. It leads us to think that there are more factors in the design of the microcontroller that affect its deterioration, such as material, dimensions, voltage, clock frequency, etc. For example, the study presented in [141] demonstrates that the TID is related to clock frequency and supply voltage of microcontrollers. The experiments conclude that low clock frequency and low voltage tend to have lower TIDs in low-power microcontrollers. According to this, the microcontroller configured with lower clock frequency and voltage has to fail before. It has happened with the ATmegaS64M1, which operates at 3.3 v and 8 MHz. In turn, ATmega328P at 5 v and 16 MHz. On the other hand, literature also mentioned that devices with smaller features sizes present some vulnerabilities to radiation due to size reduction [142], [157]. So these are considerations to be made during the selection or Control Board design.

- H_2 : Robot performance is affected when there is gamma radiation.
The experiments results have determined that radiation can affect robot performance, degrading the servo motor or microcontroller. The difference between them is that the microcontroller failure has a relevant impact on the robot performance.
- H_3 : Place sensitive electronic devices outside of an irradiation area is the best solution for robot performance and durability.
Locate sensitive radiation devices outside the radiation area has been the best option since the microcontroller does not receive any radiation dose, and it can work for long periods. Covering the components of radiation protective material is another option because it minimises the radiation dose received, but this will accumulate radiation doses over time, so the duration will be less than if it were outside.

Concerning future work, other tests should be made to continue exploring this field. It is interesting to see how it affects the trajectory and operation of the robot. As the studies verified, it not only depends on the control electronics but also on the servo motors of each joint. Therefore, tests with commercial robots could be carried out to see their affection according to the radiation dose. It allows us to know what are the operating limits of individual robots. Furthermore, continue testing radiation-resistant electronics to know its behaviour against other COTS electronics and what other factors prolong the life of the components. Useful to know what type of electronics (Rad-Hard or not) is appropriate for each application.

▪ Chapter 6

IFMIF-DONES is a major project that will respond to current problems in nuclear reactors. This installation has particular challenges regarding the maintenance of the plant due to radiation levels. Based on the experience of other facilities and the benefits that RH provides [105], RH has been considered from the beginning of the conceptual design. Currently, DONES are in an iterative state between the definition and design phases. After working on a large project as IFMIF-DONES, the conclusion extracted are the following:

- Large projects involve the participation of a large number of specialists. It gives different points of view to develop and implement RH activities.
- The RH definition and design phases can be developed during several years in a large project. It is because other parts of the installation, such as the accelerator or the building, are being designed in parallel. Therefore, there is no definitive information from the first moment. It results in an iterative and adaptation process since it is common to change specifications and requirements as the project evolves.

- IFMIF/DONES requirements pose challenges in the field of engineering. Specific designs and customized solutions are required for the accelerator components that require a RH maintenance.
- The designs (of RHS, components, building) must allow modifications and be adapted as far as possible to new changes.
- The development of maintenance procedures and the selection/design of RH Equipment and tools will depend on the requirements and specifications defined by the other groups, such as accelerator designers, building designers, safety group, neutronic, etc.
- Communication is very important in these processes. Especially when there are multidisciplinary teams, and their knowledge must be unified.
- IFMIF-DONES has demanding requirements for RH in certain areas, specifically in the Test Cell (where the specimens to be irradiated are) and the TIR. In these cases, maintenance operations must be carried out entirely using RH. Thus, RH Equipment must have appropriate interfaces and tools for each case, for example, automatic hooks, gripper change system, self-actuating twistlocks, and so on.
- The designs of rooms, equipment and components must follow specific design guidelines to adapt them to RH. For years, there have been no official design guides. For this reason, other guides have been considered, such as the “ITER Remote Handling Code of Practice”. However, after experience in the field and review of different design guides, Chapter 4 shows the design guidelines and recommendations for particle accelerators.
- Due to high radiation levels, RH System located in some hazardous areas (e.g., TC and TIR) must be resistant to ionising radiation.
- There are a large number of signal transmission, so it is intended to use Multiplexers to decrease the number of cables in the irradiated area (see subsection 2.4). This device has to be radiation resistant to be used in the Test Cell.

IFMIF-DONES will continue in development until the accelerator and the other systems work correctly in the plant. The start of DONES operation is expected in 2030. The first material data around 2033-2035. Detailed information about the DONES timeline can be found in [273].

▪ Chapter 7

This project has shown that it is possible to carry out human health care tasks with a humanoid robot, basic tasks that Ebola patients periodically need. Moreover, this chapter has delved into analysing the iteration between human and control interface, and how the operator's response is varying the architecture channel and scale when performing some dexterity tasks. The experiments results have determined the following conclusions:

- The satisfactory mode to control a humanoid doing precision tasks with a Phantom Omni device is in position mode. The rate mode is not recommended for small work areas.
- Expanding the workspace of a control device when the operator has VR glasses is safer and preferable with an external system, especially those that don't need the use of hands (e.g., pedals).
- Visual and haptic feedback has been sufficient for telehealth care tasks, and these have not caused an overload of the stimuli.
- VR glasses increase the environment immersion in remote operations. However, it can cause fatigue if used for a long time.
- Test subjects showed significantly better performance on most tasks with the 3-channel architecture and a 1:2 scale.
- The different communication channels for haptic and visual feedback must be perfectly synchronised.

Regarding the hypothesis formulated, the responses are shown below:

- H₄: 3-channel is better than 2-channel for teleoperation tasks with a humanoid robot. 3-channel architecture gives better results in teleoperation tasks than the 2-channels. 3-channels are enough, and it would not be necessary to implement 4-channels. For this application, 3-channels have provided sufficient transparency. On the other hand, combining 3-channels with a 1:2 scale has given good results during the experiments.
- H₅: Humanoid robot can perform telehealth care with a certain precision.

Based on the results obtained, the system could be accurate enough to perform the sanitary task. During the tests, the movement precision was ~ 5 times lower compared to the manual performance during manual drawing. This task is much more delicate than some medical tasks. It means that precision is acceptable for performing certain telehealth tasks such as those implemented. But not to perform more complex operations, such as surgery.

The results obtained can also be transferred to other application fields presented in this thesis. What these fields have in common is that the operator performs skill operations

in dangerous places. The work environment is different but the control room may be the same. In this way, the experience can be useful for other fields of telerobotics. In future work, this project has to continue to be developed until it can be used to assist with the health care of sick people in hospitals. The robot's intelligence must be able to treat humans in the future without the need for human assistance.

Appendix A

Author publications and conferences

Journals

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[J2] G. Micciché, M. Ascott, A. Bakic, D. Bernardi, J. Breñosa, S. Coloma, O. Crofts, G. Di Gironimo, M. Ferre, G. Fisher, A. Ibarra, A. Karap, IG, Kiss, C. Kunert, L. Lorenzelli, G. Mitchell, M. Mittwollen, P. Pagani, S. papa, G. Porempovics, T. Tadic, M. Toth. The remote handling system of IFMIF-DONES. Fusion Engineering and Design, 146, 2786-2790. 2019

[J3] O. Nomen, D. Sanchez-Herranz, C. Oliver, I. Podadera, R. Varela, F. Ogando, F. Arranz, S. Coloma, R. Heidinger and H. Dzitko. Preliminary design of the HEBT of IFMIF DONES. Fusion Engineering and Design, 153, 111515. 2020

[J4] F. Arranz, G. Micciché, S. Coloma, D. Sánchez-Herranz, O. Nomen, M. Ferre and A. Ibarra. Remote Handling in the Accelerator Systems of DONES. IEEE Transactions on Plasma Science. 2020

[J5] D. Sánchez-Herranz, P. Ortego, O. Nomen, B. Brañas, F. Ogando, P. Sauvan and S. Coloma. Design and configurations for the Shielding of the Beam Dump of IFMIF DONES. Fusion Engineering and Design, 153, 111475. 2020

Conferences

[C1] S. Coloma, M. Ferre, R. Aracil. Telemanipulación para el mantenimiento de instalaciones con alto grado de radiación. In: Robótica para aplicaciones de inspección y mantenimiento (ROBIM). Madrid, Spain, 2016

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- [C3] M. Panzirsch, B. Weber, L. Rubio, S. Coloma, M. Ferre, and J. Artigas. Tele-health care with humanoid robots: A user study on the evaluation of force feedback effects. In: 2017 IEEE World Haptics Conference (WHC). pp. 245-250. IEEE. 2017
- [C4] M. Ferre, S. Coloma, J. Breñosa, and L. Rubio. Telerobotics Requirements for Remote Handling in Nuclear Facilities. In: WM SYMNOSIA. Phoenix, AZ (United States). 2017
- [C5] S. Coloma, M. Ferre, José M. Cogollor and G. Micciché. New Methodology to Improve Execution, Efficiency and Safety in Remote Maintenance Tasks. In: 30th Symposium on Fusion Technology. Sicily, Italy. 2018
- [C6] S. Coloma, M. Ferre, F. Arranz, G. Micciché, D. Sánchez-Herranz and O. Nomen. Remote Handling maintenance of Beam Dump in IFMIF-DONES. In: 31th Symposium on Fusion Technology. Virtual Edition. 2020

Appendix B

The software architecture of irradiated systems

B. Software architecture

The experiments under radiation have been used for different devices. Each one was executed in a specific IDE. Table B.1 shows the IDE used for each device.

Table B.1 - Software program used for each control device

Device	IDE used	Programming language
PC	Matlab, Simulink and QT program ³	C or C++
Raspberry PI	QT program	C++
Arduino Mega	Open-source Arduino Software and AVRdude	C++ (Adapted)
Arduino Uno	Open-source Arduino Software and AVRdude	C++ (Adapted)
Other microcontrollers CBs	AVR Studio 6	C and C++

The PC, Arduino Mega and Arduino Uno boards have been used for the first experiment. For the second and third experiments, the Raspberry PI was used as a PC, and the Arduino Mega to manage the control. The boards to irradiate have been: Arduinos Uno and two Control Board designed and implemented in our laboratory (Appendix C). The microcontrollers of the CBs designed were programmed via ICSP, which allows to reduce the board dimensions and facilitate their reprogramming. To understand the operation of each device, the following subsections explain in detail the software sequence and functionality.

B.1. Software sequence for experiment 1

The software architecture of experiment 1 is a little different than that of the other tests carried out. It is because the microcontroller did not control external devices such as

³ QT program for experiments 2 and 3.

actuators or sensors. These only process the information received internally to perform logical operations, and then send the information to the master. Figure B.1 shows how the system is managed by the PC (Matlab Simulink program). It indicates the instructions to be processed by the slaves, and also displays, processes and store the data received. The control system is made up of a master Control Board (Arduino Mega) and four slaves Arduinos Uno. The master board controls and manages the data frame information, and the four slaves perform the operations indicated by the master under an irradiated environment. Figure B.2 and Figure B.3 illustrate the software flowchart of the program sequence.

Figure B.1 - Configuration and communication of the devices used for experiment 1

Figure B.2 shows the sequence that Matlab PC program performs to control the system. The main tasks of this sequence are system configuration, data reading and processing from the serial ports and identification of pressed buttons (start, stop or reset). These procedures are common for the rest of the experiments. However, there are two main differences from the others. The first distinction is when there are to define or calculate the data to send. Experiment 1 gets the motor speed reference, and it is going incrementing and decrementing over time. The second one is when the PC receives the Arduino data. This experiment compares the motor angle calculated by the Arduino under radiation with the calculus done in the Matlab program (PI controller + Motor DC model).

The master Control Board (Arduino Mega) sequence can be visualized in Figure B.3. It manages the information received from the PC and the Arduinos Uno through different and independent ports serial. This Control Board allows to activate and deactivate the RS-485 port of the Module-485, depending on whether it is necessary to send or receive information. Moreover, it checks errors in the data transmission by means the CRC and packages the information received of all the microcontroller in one data frame. The advantage of the Arduino Mega is that it is possible to perform a direct and fast reset of the system pushing a hardware button.

Figure B.2 – Sequence activity flowchart of the PC. It processes the information sent and received during the experiment 1

Figure B.3 - Sequence activity flowchart of the master (Arduino Mega) for experiment 1

Figure B.4 - Sequence activity flowchart of the software (Arduino Uno) for experiment 1

The software sequence and functioning of the four Arduinos Uno are reflected in Figure B.4. Each Arduino performs its initial configuration and after that, these entries in a constant loop. It reads the data received and check it with the CRC. If the data received has a reset signal, the microcontroller must be reset. If not, the program calculates the motor angle position of a simulate DC Motor. Figure B.5 shows the control loop

implemented. Finally, when the Arduino has calculated the angle position based on the reference speed, it sends via RS-485 the motor data.

Figure B.5 - Block diagram of simplified DC MOTOR position control using a PI controller

The calculation of the angle was done with a DC motor model and its mathematic equation, see the references [274], [275]. A PI controller was added to implement a speed controller [276], [277]. Classic control remains an accessible alternative to regulate position and speed immediately for a DC motor. The results obtained show that a correctly tuned PI control is capable of maintaining the speed set to the motor even when there are disturbances that tend to modify it [276].

B.2. Software sequence for experiment 2 and 3

Experiment 2 and 3 have the same software sequence. In both cases, the slave boards control the actuation of the servo motors and the recording of the temperature value, see Figure B.6. The main difference between them is the number of slaves to be controlled, as Figure B.7 and Figure B.8 represent.

Figure B.6 - Configuration and communication of the devices for experiment 2

The Raspberry PI control has the same sequence pattern as the one that follows the PC during experiment 1 (see Figure B.2). The distinctness is on the data that Raspberry PI send to the slaves, which is different for each experiment:

- Experiment 2 calculates the servo position based on a robotic arm trajectory (previously calculated).
- Experiment 3 has defined different servo positions to send to the four CBs.

Figure B.7 - Configuration and communication of the devices for experiment 3

This execution first performs the initialization, where access to the microcontroller's memories is defined to verify their status. The program read the data received and verify them with CRC calculation. It is useful to know if all the data received is correct or not. Then, the microcontroller checks if the data frame has a reset signal.

- If there is a reset signal, so the microcontroller must be restarted.
- If there no reset signal, so the Control Board send a voltage signal (PWM) to indicate the new servo motor position. Subsequently, the microcontroller records the analog values (i.e., the temperature and potentiometer position of servo motor).

The EEPROM, SRAM and flash memories are also checked to notified if an error in the memories has been produced. After that, the microcontroller prepares the data to send, and the CRC is calculated to verify the new data values. Finally, the ports are activated, and the data frame is sent to the master via RS-485.

Figure B.8 - Sequence activity flowchart of the slaves (CBs) for experiment 2 and 3 (Software define for N slaves)

Appendix C

Rad-Hard Control Board for radiation gamma environment

C.1. Control Board design for the radiation environment

Two PCB board have been designed for the experiments of chapter 5. The goal of these PCB has been implementing a control system to manage actuators and sensors in an irradiation area, and communicate it with the control room. The CBs have the same electronic devices, except the microcontroller. The passive electronic devices have been selected considering radiation exposure, wherein some of them have natural radiation resistance due to the type of material [10]. The common passive elements are shown in Table C.1:

Table C.1 - Passive elements of the Control Board

Passive elements	Threshold level (Gy)
Cristal oscillator 8MHZ	Medium resistance
Ceramic capacitor 100nF SMD	10^4 - 10^8
Ceramic capacitor 18pF SMD	10^4 - 10^8
Resistor 10k Ω SMD	High resistance
Resistor 20k Ω SMD	High resistance

Figure C.1 - Control Boards design. a) PCB Control Board with ATmega64M1 microcontroller, b) PCB Control Board with ATmegaS64M1-KH-E microcontroller

One Control Board has been designed to integrate the ATmega64M1 [191], see Figure C.1 a). It is an 8-bit Advanced Virtual RISC (AVR) microcontroller. The second board

integrates the ATmegaS64M1-KH-E [202], see Figure C.1 b). It is the Rad-Hard version of the previous microcontroller. This space-qualified version adds a ceramic and hermetic package, wherein guaranty a TID of 30krad (according to MIL-STD-883 Method 1019) and no SEL below a LET threshold of 62.5 MeV/mg/cm2@125 °C.

Figure C.2 - Schematics of the Control Board functioning for the ATmega64M1 and ATmegaS64M1 microcontrollers

Figure C.2 shows the schematics design and Figure C.3 the routing of the PCBs. It is the same for both microcontrollers. It includes:

- The ICSP to access AVR memory and record a program directly from the computer,
- The analog and digital input/outputs.
- A system to dis/connect the microcontroller receptor pin of module 485 (programmer enabler).
- The crystal oscillator for the microcontroller clock frequency.
- The input for connecting an external power supply with a bypass capacitor.

Figure C.3 - Routing of each control board. a) for the ATmega64M1 and b) for the ATmegaS64M1

Appendix D

IFMIF/DONES

D.1 Maintenance classification

To help in the definition of maintenance priorities, ITER set up a maintenance classification of all components of the facility. The four following classes were defined:

- RH class 1st: components requiring regular planned replacement
- RH class 2nd: components that are likely to require repair or replacement.
- RH class 3rd: components that are not expected to require maintenance or replacement during the lifetime of the facility but would need to be replaced remotely should they fail.
- RH class 4th: components that do not require Remote Handling.

DONES has adopted this component classification system for the define the type and frequency of maintenance.

D.2 Test Cell dimensions

Figure D.1 and Figure D.2 show the dimensions of the Test Cell in the top and lateral views.

Figure D.1 - Test Cell top view with dimensions

Figure D.2 - Test Cell lateral view with dimensions

D.3 Biological dose rate in Test Cell

Figure D.3 - Biological dose rate distribution in the TC (Evolution in time: one day and up to one month of the shut down) [278]

Figure D.3 shows the evolution of the biological dose rate in the Test Cell. It is possible to appreciate that the radiation decay slowly over time. Even though the central zone continues to conserve high levels of radiation 28 days later. These radiation levels are not tolerable for humans.

D.4 Radiation during the maintenance period in Accelerator area

Figure D.4 contains the current studies of the total residual doses and radiation in the accelerator areas. It shows the values when the accelerator has been cooled for one day and one week.

Figure D.4 - Radiation zones during maintenance periods. 1-day (up) and 1-week (down) cooling times [279]

These values are not definitive. The data may change depending on the materials and design of the accelerator. This is currently under development, so the indicated values may change in the future.

Appendix E

The software architecture of Phantom Omni in ROS

E.1 Phantom Omni and ROS Architecture

The Phantom Omni device is controlled through the OpenHaptics Toolkit [280]. This toolkit handles complex calculations and provides low-level device control for advanced developers. In particular, the OpenHaptics Toolkit is made up of a set of libraries, such as Haptic Device API (HDAPI), Haptic Library API (HLAPI), device drivers (Phantom Device Drivers, PDD), and others. The API of the haptic device (HDAPI) is a low-level base layer for haptic devices. HDAPI allows direct control of Phantom Omni through the functions and utilities offered. It manages the configuration of the haptic device, checks its status, generates forces, etc. It is best suited for developers who are familiar with haptic paradigms since it includes those interested in haptic research, telepresence, and remote manipulations.

Figure E.1 - Phantom control software architecture in ROS

For this application, ROS has been used to access and control the device by means the Phantom Omni libraries. The architecture implementation is composed of several nodes,

which are executable programs that perform specific functions (e.g., receiving and sending data via UDP, obtaining the position parameters of the haptic device, etc.). These are individually compiled, executed and managed by the main node of ROS Master. This node is in charge of centralizing communications between all the nodes of the system. The advantage is that the nodes can communicate with each other through messages and topics to achieve a common goal. Figure E.1 shows the schema of the architecture system implemented for control the Phantom in ROS, and in turn, it is configured to interact remotely with the humanoid robot. The system is made up of the main node that executes three nodes: `omni_state`, `receive_udp` and `sendup`. The functionality of each node is as follows:

- ***Omni_state***: it contains the libraries and functionalities to access to the parameters of the Phantom Omni device. Initially, this node calibrates the Phantom parameters and starts it with ROS. Subsequently, as long as the operation of the program and device is correct, the function of the node is to obtain and calculate the parameters of the Phantom to publish the value with a frequency of 1000 Hz. It publishes two topics: `state` and `button`.
 - `State`: this topic contains information about the Phantom Haptic Interaction Point (HIP). Particularly the position and speed in the three axes (x , y , z), besides to the orientation (quaternions x , y , z , w).
 - `Button`: this topic indicates if the Phantom buttons have been pressed (the device has two buttons).

On the other hand, the `omni_state` node receives the information from the topic `force_feedback`. This topic sends the force value generated during the robotic arm collision or impact with the remote environment. This force processes to add extra damping, which pretends to stabilize the received force feedback. It is applied as a limitation to the joint control of the Phantom device.

- ***Send_udp***: the function of this node is based on sending information via UDP. To do this, firstly it receives the data from the topics `state` and `button` through its subscription. Subsequently, the information about each topic is serialized to be sent. The transmission is done via UDP in the specified Internet Protocol (IP) and port.
- ***Receive_udp***: this node configures the communication system to receive the data through UDP with the specified IP and ports. It gets the collision force (x , y , x) from the robot's end-effector. The information received is organized to be published under the topic: `force_feedback`.

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