CONTROL SYSTEM FOR REMOTE HANDLING EQUIPMENT OF NUCLEAR FUSION RESEARCH FACILITIES

By

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List of Abbreviations

ACMC: Access Cell Mast Crane

AI: Artificial Intelligence

BPM: Business Process Management

BPMN: Business Process Management Notation

CAD: Computer-Aided Design

CCR: Central Control Room

CICS: Central Instrumentation and Control System

CMMS: Computerized Maintenance Management System

CODAC: Control, Data Access, and Communication

COP: Central Operator Panel

COS: Common Operational State

CSP: Central Supervisor Panel

DEMO: Demonstration Power Plant

DT: Digital Twin

EAM: Enterprise Asset Management

EPICS: Experimental Physics and Industrial Control System

FRER: Frame Replication and Elimination for Reliability

GCL: Gate Control List

GOS: Global Operational State

HMI: Human-Machine Interface

HLCS: High-Level Control System

IFMIF: International Fusion Materials Irradiation Facility

IoT: Internet of Things

LEBT: Low Energy Beam Transport

LICS: Local Instrumentation and Control System

LLCS: Low-Level Control System

MEBT: Medium Energy Beam Transport

MPS: Machine Protection System

OPC UA: Open Platform Communications Unified Architecture

PLC: Programmable Logic Controller

OP: Operator Panel

RH: Remote Handling

RHCR: Remote Handling Control Room

SCADA: Supervisory Control and Data Acquisition

SL: Structured Language

SCS: Safety Control System

TAS: Time-Aware Shaper

TSN: Time-Sensitive Networking

VR: Virtual Reality

VTD: Virtual Task Document

WSP: Workcell Supervisor Panel

Abstract

This thesis presents a comprehensive proposal and development of the Remote Handling Control System (RHCS) for the International Fusion Materials Irradiation Facility - Demo Oriented NEutron Source (IFMIF-DONES) project, which is a key component to commercial energy from fusion. Availability goal for DONES is 70% over calendar year which together with its specifications regarding damage rate is directly linked to the main mission of DONES. Given the challenging operating environment of fusion-related facilities, mainly due to the presence of radiation and a poorly structured environment, the design and implementation of reliable, safe and flexible Remote Handling (RH) is essential to perform maintenance, inspection and monitoring tasks of complex and heavy systems and components that need to be on site assembled and maintained. The control system is of critical importance because it must integrate the human operator into the control loop (the "human-in-the-loop" approach) to enable the execution of diverse, non-repetitive operations and facilitate adaptation to unforeseen circumstances due to the unstructured nature of the environment.

The design of the RHCS poses a series of challenges that are shared by other similar installations. These challenges focus primarily on the integration of all machines and robots into a common control framework, providing a set of tools that operators can rely on when radiation prevents direct access to the maintenance area. Such a framework would be capable of offering common functionalities and interfaces to all of the machines and robots. Additionally, it would improve processes and reduce operating times.

The primary hypothesis of this work is that the performance, cost, flexibility, and robustness of RH systems can be significantly enhanced by designing a control system based on state of the art technologies available in the industry and the latest standards. This hypothesis is explored through an analysis of applicable automation levels, the use of supervisory systems for process control, the application of the Open Platform Communications Unified Architecture (OPC UA) standard unify interfaces among heterogeneus mechatronic devices, and the improvement of real-time communications with Time-Sensitive Networking (TSN) technology.

The methodology employed in this thesis combines a system design approach with practical validation to ensure the effectiveness of the proposed RHCS architecture. The development process involved the detailed design and simulation of the preliminary RHCS for IFMIF-DONES project, followed by the implementation of a comprehensive test-bench. This test-bench was utilized to simulate representative telemanipulation tasks, allowing us to integrate the main functional blocks of the control system, control strategies for telemanipulation, standardization of interfaces/data format using OPC UA and improving network capabilities using TSN. The results of the solution described were demonstrated through the execution of real RH procedure on the test bench, showing the improvement on execution times, number of errors and reduced cognitive load on the operator.

Resumen

Esta tesis presenta una propuesta integral y el desarrollo del Sistema de Control de Manipulación Remota (en inglés Remote Handling Control System o RHCS) para el proyecto IFMIF-DONES (International Fusion Materials Irradiation Facility - Demo Oriented NEutron Source), que es un componente clave para la energía comercial a partir de la fusión. El objetivo de disponibilidad de DONES es del 70% a lo largo del año natural, que junto con sus especificaciones relativas a la tasa de daños, está directamente relacionado con la misión principal de DONES. Dado el difícil entorno operativo de las instalaciones relacionadas con la fusión, debido principalmente a la presencia de radiación y a un entorno poco estructurado, el diseño y la implantación de un sistema de manipulación remota (en inglés Remote Handling o RH) fiable, seguro y flexible es esencial para realizar tareas de mantenimiento, inspección y supervisión de sistemas y componentes complejos y pesados que deben montarse y mantenerse in situ. El sistema de control es de vital importancia porque debe integrar al operador humano en el bucle de control (el enfoque «human-in-the-loop») para permitir la ejecución de operaciones diversas y no repetitivas y facilitar la adaptación a circunstancias imprevistas debidas a la naturaleza no estructurada del entorno.

El diseño del RHCS plantea una serie de retos que comparten otras instalaciones similares. Estos retos se centran principalmente en la integración de todas las máquinas y robots en un marco de control común, que ofrezca un conjunto de herramientas en el que los operarios puedan confiar cuando la radiación impida el acceso directo a la zona de mantenimiento. Dicho marco sería capaz de ofrecer funcionalidades e interfaces comunes a todas las máquinas y robots. Además, mejoraría los procesos y reduciría los tiempos de operación.

La hipótesis principal de este trabajo es que el rendimiento, el coste, la flexibilidad y la robustez de los sistemas de RH pueden mejorarse significativamente diseñando un sistema de control basado en las tecnologías más avanzadas disponibles en la industria y en los estándares más recientes. Esta hipótesis se explora mediante un análisis de los niveles de automatización aplicables, el uso de sistemas supervisores para el control de procesos, la aplicación del estándar OPC UA para unificar interfaces entre dispositivos mecatrónicos heterogéneos, y la mejora de las comunicaciones en tiempo real con la tecnología TSN.

La metodología empleada en esta tesis combina un enfoque de diseño de sistemas con la validación práctica para garantizar la eficacia de la arquitectura propuesta para el Sistema de Control de Manipulación Remota. El proceso de desarrollo incluyó el diseño detallado y la simulación del Sistema de Control de Manipulación Remota preliminar para el proyecto IFMIF-DONES, seguido de la implementación de un completo banco de pruebas. Este banco de pruebas se utilizó para simular tareas de telemanipulación representativas, lo que nos permitió integrar los principales bloques funcionales del sistema de control, las estrategias de control para la telemanipulación, la estandarización de interfaces/formato de datos mediante OPC UA y la mejora de las capacidades de red mediante TSN. Los

resultados de la solución descrita se demostraron mediante la ejecución de un procedimiento real de manipulacion remota en el banco de pruebas, mostrando la mejora en los tiempos de ejecución, la reducción del número de errores y de la carga cognitiva del operador.

Chapter 1
Introduction

This chapter provides an **overview of nuclear fusion** as a promising pathway toward sustainable, clean energy, contrasting its benefits with traditional nuclear fission. Fusion's inherent safety, reduced waste, and abundant fuel sources highlight its advantages, although significant challenges remain in transitioning from experimental setups to practical applications.

A detailed **introduction to the IFMIF-DONES** project is presented, emphasizing its role as a neutron source facility critical for developing materials capable of withstanding the extreme conditions of future fusion reactors like DEMO. The **RH systems** at IFMIF-DONES are identified as essential for **maintaining activated components** in high-radiation environments, ensuring operational efficiency, and minimizing downtime.

The chapter outlines the primary goals of the thesis: to develop a **modular control framework** for RH systems that integrates **industrial technologies and standards** while addressing the facility's unique operational constraints. Key objectives include reducing maintenance times through automation, enhancing operator assistance, and validating these solutions within a flexible, scalable control architecture.

By setting the stage for subsequent chapters, this introduction situates the thesis within the broader EUROfusion roadmap and highlights its contributions to advancing RH technology for fusion-related facilities.

1 Introduction

Nuclear fusion represents one of the most promising paths toward a sustainable and virtually limitless source of clean energy. In contrast to nuclear fission, which relies on the splitting of heavy atomic nuclei, nuclear fusion is based on the principle of merging light nuclei, typically hydrogen isotopes, to form heavier elements such as helium. This process is the same as that used to power the Sun and other stars [1].

The advantages of nuclear fusion over traditional fission reactors are considerable. Firstly, the production of waste by fusion reactions is significantly lower than that of traditional fission reactions [2]. The principal byproducts of nuclear fusion are helium, an inert gas, and energetic neutrons. While these neutrons can activate surrounding materials, the resultant radioactivity is generally shorter-lived than the waste produced by fission, which can remain hazardous for thousands of years. Secondly, fusion does not carry the same risk of catastrophic accidents. Fusion reactions require extremely high temperatures and pressures to be sustained, and any disturbance to these conditions results in a rapid cessation of the reaction, rather than an uncontrolled chain reaction as happens in fission.

Furthermore, the fuel for nuclear fusion—typically isotopes of hydrogen such as deuterium and tritium—is widely available[3]. Deuterium can be extracted from seawater, and tritium can be bred from lithium, produced in particle accelerators, or obtained as a subproduct from fision reactors. This contrasts with the uranium required for fission reactors, which is much less abundant and a matter of geopolitical sensitivity.

While these advantages highlight the promise of fusion energy, significant technological challenges must be overcome to transition from experimental setups to practical, commercial fusion reactors. These include the management of high heat and particle loads, as well as the development of neutron-resistant materials[4]. Tritium handling and breeding, as well as remote maintenance, are also considered crucial issues that are common to both magnetic and inertial fusion approaches[5].

The conditions required to sustain nuclear fusion reactions, which include temperatures in the range of millions of degrees and sufficient plasma confinement, have thus far been achievable only in experimental setups like tokamaks and stellarators. The ITER project represents a leading example of these efforts[6] [7]. However, as fusion technology progresses, particularly with initiatives such as IFMIF-DONES, the possibility of harnessing fusion energy on a commercial scale is becoming increasingly realistic. The IFMIF-DONES project, which is closely related to ITER, is a neutron source facility designed to test materials for future fusion reactors, including DEMO[8], which will follow ITER[9].

The IFMIF-DONES project aims to create an intense neutron source for testing fusion reactor materials [10]. It utilizes a 40 MeV deuteron beam impinging on a liquid lithium target to generate a high neutron flux similar to those that could be expected on the future fusion power plants[11]. These neutrons will impact on different samples of materials, mainly reduced activation ferritic martensitic steels like EUROFER[12]. Therefore, the facility faces radiation risks, including atmospheric activation, tools and component activation, and potential equipment damage[13]. This facility is currently under construction and is expected to be finished by 2034, and is considered critical for the development of future fusion power plants [14].

This thesis focuses on the critical role of remote handling systems within the IFMIF-DONES project, focusing on its control system and addressing the technological challenges of integrating heterogeneous and complex mechatronic devices into a single control room providing all the required functionality to execute remote interventions. A modular architecture will be proposed, comprising the main functionalities implemented in independent functional blocks. This allows flexibility in adjusting the control system to meet specific installation needs, through the addition or removal of blocks. To this end, a control framework will be proposed that leverages both industry standards and commercial technologies. The objective of this framework is to execute remote maintenance operations within the designated timeframes, adhering to the scheduled periods, with the aim of achieving the plant availability goal established by the project. As the utilization of control system tools progresses, the execution of RH operations will become increasingly faster, thanks to the provision of enhanced operator assistance and the automation of non-critical processes that do not necessitate human intervention. Consequently, the RH control system emerges as a pivotal component in the optimization of plant availability, which will be key to obtaining results in time to serve as input for ITER and DEMO and to advance the roadmap to commercial fusion power.

1.1 EUROfusion Roadmap

On 9 October 2014, fusion research bodies from European Union member states and Switzerland signed an agreement to cement European collaboration on fusion research and EUROfusion, the European Consortium for the Development of Fusion Energy, was born. Presently EUROfusion supports and funds fusion research activities on behalf of the European Commission’s Euratom programme within 26 EU member states, while Switzerland, Norway and the United Kingdom participate in the activities with their national fusion budgets.

The EUROfusion roadmap described in

Figure 1 forms the basis for the programme of EUROfusion and provides a clear and structured way forward to commercial energy from fusion.

Since 2012, when the first version of the Roadmap was published, the European fusion community has made significant advances in many areas. These include successfully employing tokamak walls made of metal, gaining a greatly advanced understanding of the material properties that will be required by ITER and DEMO. Recent highlights are the world record fusion energy of 59 MJoule achieved in the JET tokamak by burning only 170 micrograms of the deuterium-tritium fuel, and the completion of the pre-conceptual design phase of DEMO, the first device aimed to produce fusion electricity[1].

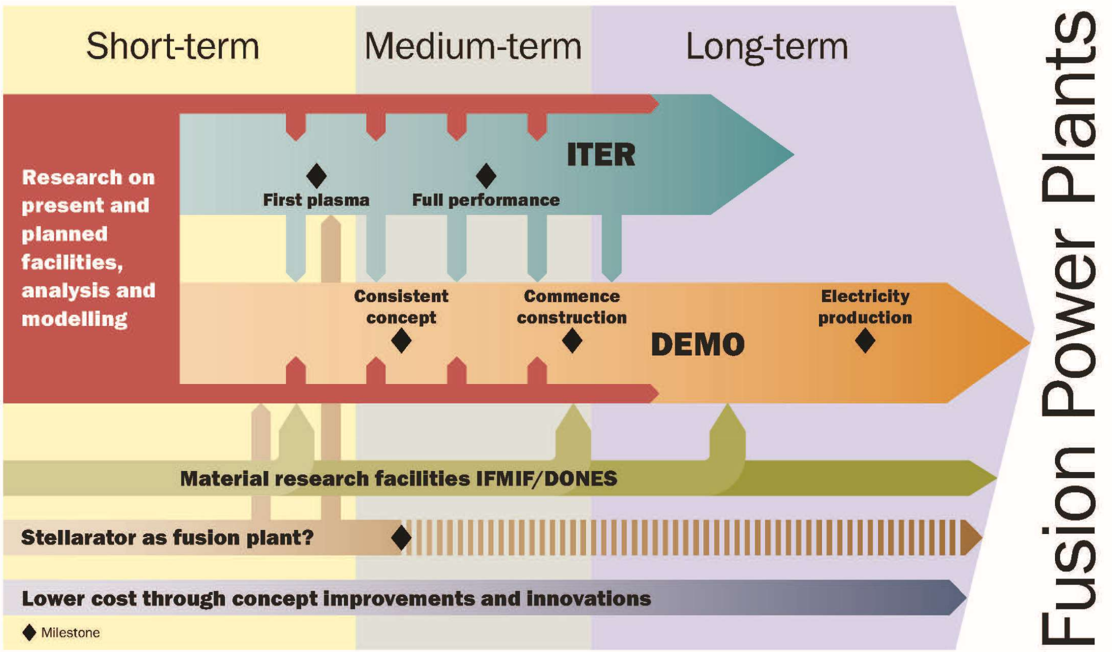


Figure 1: EUROfusion roadmap towards commercial energy from fusion [15]

1.2 IFMIF-DONES

The mission of the IFMIF-DONES (International Fusion Materials Irradiation Facility – Demo Oriented NEutron Source) project is to develop a database of the effects of fusion-like neutron irradiation on materials required for the construction of fusion power reactors, and for the comparative evaluation of the radiation response of materials. For this purpose, it is necessary to build a neutron source that produces high energy neutrons with sufficient intensity and irradiation volume. It is a radiological facility, which implies that there will be a certain degree of radiation with its safety implications, but it will not have to follow all the regulations that apply to nuclear facilities.

The main objectives of the DONES Program are:

- Provide a neutron source that produces fusion-like neutrons with sufficient intensity and irradiation volume.
- Generate materials irradiation test data for the design, licensing, construction and safe operation of a fusion demonstration power reactor.
- Create a database for comparative evaluation of radiation responses of materials, hand in hand with computational materials science.

- Develop a working program of complementary experiments of interest to other scientific and technological areas.

The IFMIF-DONES facility is the central element of the DONES Program. To meet these objectives over the last few years, different projects have been launched, which together form the DONES program [2]. The timeline of the project is detailed in Figure 2.

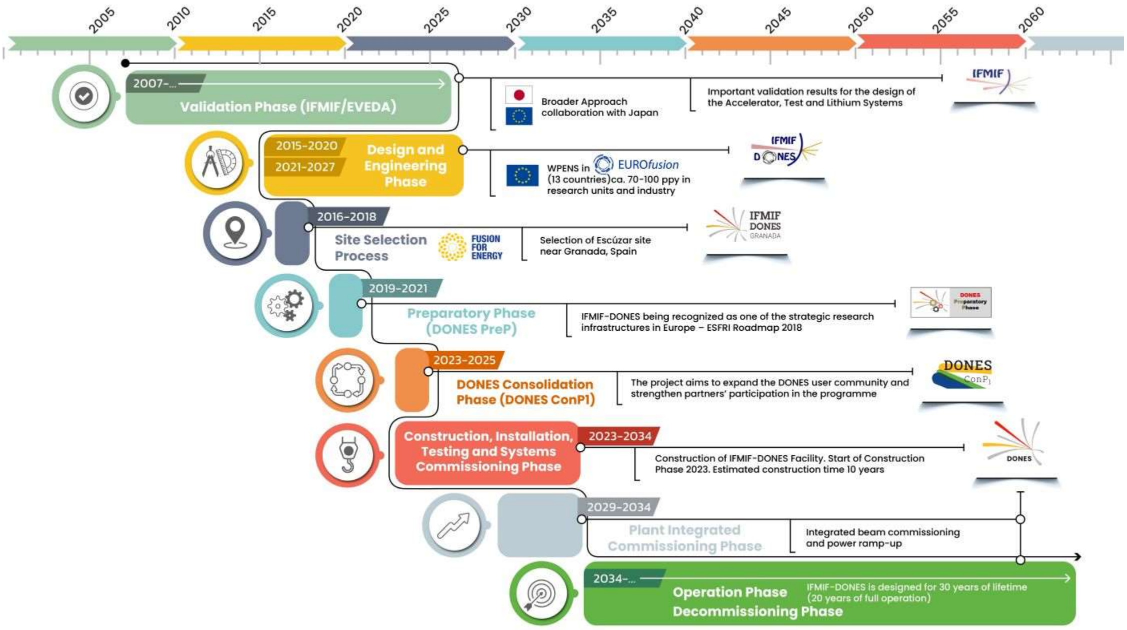


Figure 2: DONES program phases [16]

As shown in the timeline, the construction of the IFMIF-DONES facility has already started and several key buildings have been constructed at the time of writing. Among the complex systems required to achieve the objectives of the DONES programme, the RH systems stand out as critical enablers in the construction and commissioning phase, as they will allow the manipulation and installation of heavy components inside the main building. However, they will become crucial during the operational phase, when the facility will be in a radiation environment. From this point until the decommissioning phase, they will be of paramount importance as they will be the only means of interacting with those components that are activated by radiation, so they must provide safe and efficient operation and maintenance of the facility in the long term.

1.3 Remote Handling systems

RH systems are essential tools in environments where direct human intervention is either unfeasible or highly dangerous. These systems enable operators to manipulate objects or equipment from a safe distance using mechanical or robotic devices that replicate the operator's movements and actions in a remote environment. These systems are crucial in various industries, including nuclear power plants[17], mining [18], underwater exploration [19], and space missions[20]. Examples of mechatronic devices commonly present in RH systems include telemanipulators, transport platforms or cranes.

Remotely operated vehicles (ROVs) are commonly utilized in the context of underwater exploration for the inspection of offshore oil rigs and underwater pipelines, deep-sea mining and oceanographic research as discussed in [21]. These systems are required to function in extreme environments that are characterised by high pressure and limited visibility. ROVs are equipped with advanced imaging and sonar technology, which enables them to navigate and perform tasks in a three-dimensional, unstructured environment, where precise maneuvering is critical.

Space exploration represents another area where the use of RH systems is essential. The vast distances involved in space missions present significant challenges, particularly in the management of communication bandwidth and latency, with latency having a larger impact [22]. It is imperative that RH systems guarantee the reliable transmission of data and the precise control of processes, despite the inherent delays. However, in [23] the importance of comprehensive understanding of system capabilities, improved situational awareness, and reduced cognitive load are highlighted as key factors for trustworthy Remote Handling systems.

In the field of medicine, the introduction of RH systems has led to significant advancements in minimally invasive surgery. In [24], a comprehensive review of systems such as the Da Vinci outlines the capacity to facilitate intricate surgical procedures with enhanced precision, control, and flexibility for surgeons, while concurrently reducing patient recovery time. The design of these medical robots underscores the significance of haptic feedback and real-time responsiveness for doctors, additional patient data, secure communication, and safety/privacy concerns [25].

In the context of nuclear facilities, RH systems play a crucial role in ensuring the safe operation and maintenance of nuclear reactors, as well as in the decommissioning of nuclear plants[26]. These systems are designed with the specific purpose of handling radioactive materials and performing complex tasks such as Fuel processing, reactor maintenance, reactor decommissioning, transportation of active material or incident management. The primary objective in the design of these systems is to reduce human exposure to radiation while maintaining the high degree of precision and reliability that is essential for their intended function.

These examples demonstrate the extensive applicability and critical importance of RH systems across diverse fields. Each application presents a unique set of challenges, not only affecting the design and implementation of RH systems but also drive ongoing research and development aimed at enhancing their capabilities and expanding their potential. The integration of these advanced systems into complex, unstructured, and often hostile environments continues to challenge the boundaries of technology. For the particular case of RH in fusion-related facilities, one of the main challenges is to homogenize mechatronic devices and tools with very different morphologies and control strategies, resulting in a unique system capable of offering a common set of functionalities.

1.4 RH in fusion-related facilities

In the context of fusion-related facilities, RH technology is particularly crucial due to the hazardous environments that severely restrict human access. In these settings, RH systems are employed to perform a range of tasks, such as inspection, measurement, and maintenance, all of which are essential for the safe and efficient operation of the facility as discussed in [19-25]. The ability to carry out these tasks remotely not only reduces personnel exposure to radiation but also minimizes facility downtime and ensures that maintenance can be performed in otherwise inaccessible areas.

The automation of processes associated with Remote Handling is inextricably linked to the time required to complete a maintenance campaign. Downtime for maintenance campaigns is a subject of study due to its impact on the operability of the facilities. The study conducted by [29] examines the potential implications of a future commercial fusion reactor. One of the key findings is that the optimal duration of planned maintenance is determined by striking a balance between the cost of a faster Remote Handling system and the cost of lower plant availability, which is a source of revenue. Related studies have indicated that a minimum availability of 75% is necessary, concluding that the duration of maintenance for fusion power plants directly affects availability and commercial viability.

Maintenance shutdowns are required to maintain the integrity of components exposed to radiation, which is present in all fusion-related facilities to varying degrees. During this period, the facility is unable to produce valuable scientific data or advance research. In addition to maintenance, RH systems also play a crucial role in the installation and commissioning of new components within the facility.

As technology evolves, new components and upgrades are regularly introduced to improve the performance and safety. Remote Handling is essential for the safe installation of these components, particularly when dealing with radioactive materials or delicate equipment that requires precise handling. One of the primary objectives of any RH system is to enhance situational awareness and control accuracy. These concepts are fundamental to the operation of remote handling systems, allowing humans to extend their physical capabilities into environments where direct presence is impractical or inadvisable.

1.4.1 Telemanipulation and telepresence

The majority of Remote Handling systems deployed in fusion-related facilities incorporate two fundamental concepts:

1. Telemanipulation: It is described as the use of a mechanical hand-arm device to reproduce the movements of a human operator [30]. The operator's physical movements are translated into corresponding actions by the telemanipulator, thereby enabling precise and immediate control. Telemanipulation is especially advantageous in situations that necessitate real-time and dexterous manipulation skills.
2. Telepresence: Telepresence is the experience of being present at a remote location through immersive technology that allows manipulation and control of the remote

environment [31]. This is frequently accomplished through the utilization of cameras, sensors, and haptic feedback systems that furnish the operator with visual, auditory, and tactile data.

Among the various categories of Remote Handling systems, telemanipulation systems are a particularly prominent and well-studied area of research. Historically, these systems were conceived as an extension of the operator, with the assumption that the skill and experience of the user directly determined the efficiency and safety of the tasks performed [32]. However, this reliance on human skill introduces significant variability in execution times and other issues that can negatively impact the scheduling of critical tasks, particularly in facilities such as IFMIF-DONES, where maintenance time has a direct impact on the facility's performance.

1.5 Motivation

Over the decades, important advancements have been made in the development of RH technologies. Significant progress have been made on the telemanipulators precision [33] and force-feedback strategies [34] [35], the use of virtual reality to represent the remote environment [36], device usability by means of haptic shared control [37] or the creation of virtual environments dedicated to train operators [38]. As a result, RH systems have evolved to become more sophisticated, incorporating advanced features such as real-time communication, force feedback, motion scaling, and autonomous operational modes. A principal element in the realization of these advances is the RH control system, which unifies the heterogeneous range of RH devices into a unified system from the perspective of the facility.

Nevertheless, these systems are not yet at the level of autonomy and intelligence that can be found in the manufacturing industry. While sectors like automotive manufacturing have achieved remarkable levels of automation and efficiency through structured environments and repetitive tasks, the hazardous nature of fusion facilities imposes unique challenges. The presence of intense radiation, strong magnetic fields, and high temperatures can lead to the rapid degradation of electronic components, making it difficult to rely solely on autonomous systems. Furthermore, the unstructured nature of the environment, coupled with the vast array of potential scenarios and operations, underscores the necessity for flexible systems capable of adapting to a diverse spectrum of tasks. Consequently, human-in-the-loop (HITL) control remains essential in fusion environments [39], allowing human operators to intervene in complex and unpredictable situations where full automation is not yet viable. Additionally, there is a low level of standardization due to the high specialization of the devices and systems that are required to accommodate the unique needs of each project.

This work is centered on the development of a control system that is capable of providing the functionality required to perform remote handling tasks in a safe and efficient manner for IFMIF-DONES facility. The objective of this project is to generate a neutron source to irradiate samples of materials, creating a radiation spectrum similar to the one inside a fusion reactor. This implies working in an environment where radiation will be a limiting factor, and where the machine's operating time must be optimized as much as possible. To this end, it will be necessary to reduce maintenance times to a minimum by parallelizing operations in different areas and automating/guiding the operator in as many actions as possible.

To achieve this goal is necessary to define a reference architecture for the RH control system, focusing on the technical components and functionalities required for the maintenance and operation of activated components. However, the design of the control system is intrinsically linked to the organizational framework within which it operates. The intended use of the RH system has a direct impact on how the control architecture should be designed, particularly in terms of operational processes, user roles, task execution, and coordination with central systems like the CICS.

The IFMIF-DONES project is unlikely to have the human or economic resources to develop a highly customized RH solution, as is the case in ITER. For this reason, in this work we suggest the implementation of a control framework based on mature and well proven technologies from the manufacturing and robotics industry to the field of fusion-related facilities as a possible compromise solution to fulfill the operational needs of the project. Our proposal describes a control framework that prioritizes standardisation of interfaces, communications, data formats and interoperability, enabling the integration of commercial off-the-shelf (COTS) solutions and facilitating the adoption of future technologies. This industrial based approach, which forms the foundation of the thesis, serves to reduce the overall complexity and cost of RH systems, by ensuring their long-term viability and adaptability in an ever-evolving technological landscape.

1.6 Objectives

The main goal of this thesis is to develop a control framework for RH systems, with a focus on the IFMIF-DONES project. During more than 4 years of active participation in the IFMIF-DONES project, it has been possible to identify the main needs of the facility in terms of RH. One of the most important challenges facing this project (as well as fusion plants of the future [5]) is to reduce maintenance times by introducing autonomous systems capable of completing routine tasks. To address this challenge, the hypothesis of this thesis suggests the possibility of improving the performance, functionality and cost of RH control systems using industrial technologies and standards. To validate this hypothesis, the following objectives have been established:

- O1. Demonstrate the feasibility of using industrial systems for RH operations: prove that RH operations for IFMIF-DONES can primarily rely on commercial off-the-shelf (COTS) industrial systems and standards, ensuring compatibility and leveraging the robustness of proven industrial solutions.
- O2. Achieve high availability through industrial solutions: validate that industrial systems are capable of achieving the high availability required for RH systems in a fusion-related facility, thereby ensuring operational continuity and reliability under demanding conditions.

- O3. Evaluate the application of real-time networks: assess the effectiveness of real-time networking technologies, such as TSN, for the optimized management of data and control events in RH systems, focusing on performance metrics such as latency, determinism, and scalability.
- O4. Design the reference architecture for RH systems: based on the conclusions drawn from the preceding objectives, develop a reference design for the RH systems of IFMIF-DONES. This architecture will provide a modular, scalable, and integrative framework that aligns with the operational needs and technological constraints of the facility.
- O5. Integrate emerging technologies: explore and incorporate cutting-edge technologies such as OPC UA for semantic interoperability, AI for operational assistance, and Virtual Reality (VR) for training and visualization, ensuring that the proposed design is future-proof and adaptable.
- O6. Evaluate knowledge management approaches for RH: propose methodologies, such as ontology-driven frameworks, to standardize and enhance knowledge representation and management within RH operations, enabling interoperability and knowledge reuse across systems and projects.
- O7. Provide a scalable blueprint for future facilities: ensure that the proposed RH system design not only meets the specific requirements of IFMIF-DONES but also sets a benchmark for future fusion facilities, such as DEMO, contributing to the global advancement of Remote Handling technologies.
- O8. Experimentally validate RH control systems: Ensure all proposed frameworks, technologies, and architectures are experimentally tested to demonstrate their feasibility, robustness, and effectiveness under operational conditions.

These objectives address both the technical and operational aspects of the RH systems, ensuring a comprehensive approach based on a control framework that can meet the current needs of the project and support future enhancements as the facility evolves. To address these objectives and propose a concrete design for the RH Control System, the following tasks or activities will be performed:

- T1. Identification of requirements: analyze and define high-level requirements for the RH System based on the operational context and project-specific challenges.
- T2. Development of a control framework: design a control architecture composed of various software and hardware modules, including network communication protocols and standardized data formats for seamless integration of RH devices into a dedicated control room.
- T3. Process and workflow definition: establish process workflows to ensure the effective use of RH systems, optimizing operational efficiency and safety.
- T4. Intervention time improvement: explore automation and the use of expert systems to support operators and reduce intervention times during RH operations.
- T5. Experimental validation: implement and validate the proposed framework through a telemanipulation testbed to test key concepts and assess their viability.

1.7 Document structure

The structure of this thesis will follow a line of argument that will go from the generic to the specific. Figure 3 seeks to summarize this process, as well as the main components of the IFMIF-DONES control system architecture that will be studied in this work.

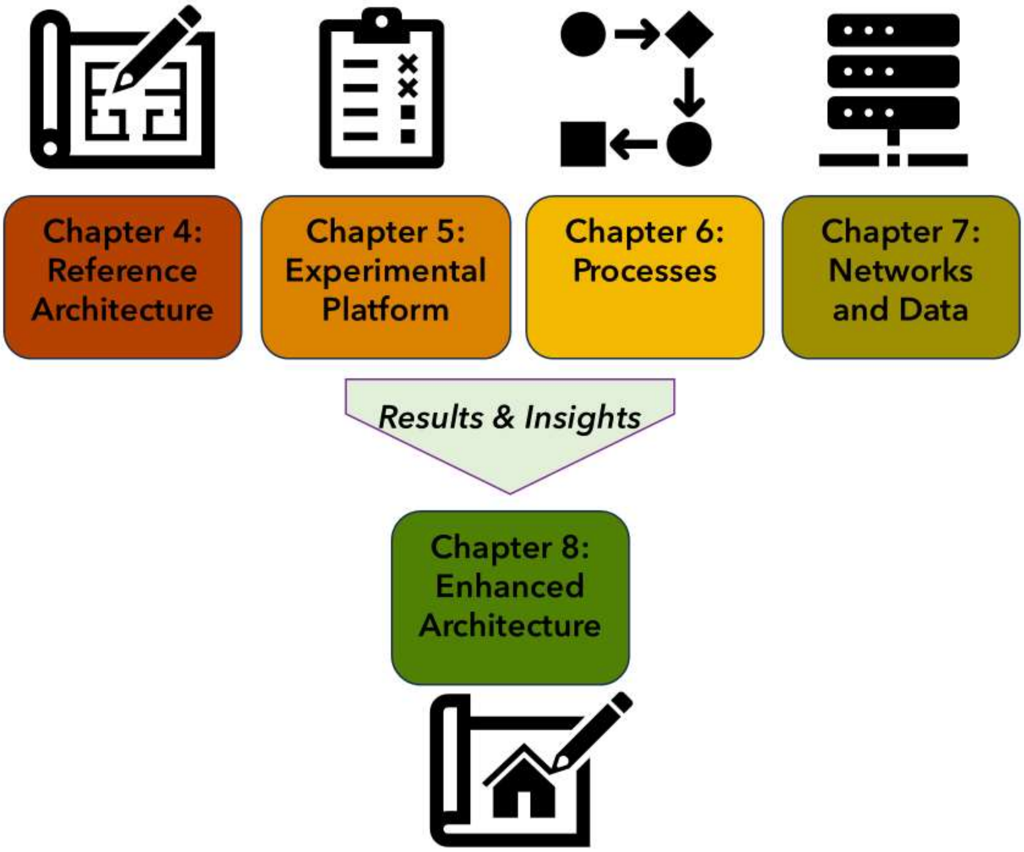


Figure 3: Document structure. Key contributions are summarized in five blocks corresponding to chapters 4-8.

To facilitate the reader's understanding of the contributions of this work (presented in chapters 4-8), chapters 2 and 3 have been included. The purpose of chapters 2 and 3 is twofold: firstly, to provide a review of the state of the art, and secondly, to place the reader in the context of the IFMIF-DONES project.

- **Chapter 2: State-of-the-art.** This chapter reviews the foundational concepts and technologies for RH systems, including maintenance strategies, existing frameworks like those in JET and ITER, and enabling technologies such as OPC UA, TSN, and advanced HMIs. These insights establish the technological baseline for developing scalable and interoperable RH systems at IFMIF-DONES.
- **Chapter 3: IFMIF-DONES context.** This chapter provides an overview of the design and requirements of the IFMIF-DONES RH system, based on foundational

WPENS documents. It discusses the need for RH systems in maintaining highly activated components under extreme conditions and outlines their key functionalities, such as material handling and equipment refurbishment. The chapter revisits a preliminary RHCS architecture, identifying gaps in modularity and adaptability, which are addressed in later chapters.

- **Chapter 4: Reference Architecture for the Remote Handling Control System at IFMIF-DONES**. This chapter defines the reference architecture for the RHCS in IFMIF-DONES, focusing on its modular structure, hierarchical levels, and interaction with the plant-wide control system. It includes a description of the RH systems' components, their functionalities, and an initial network layout. The architecture introduced in this chapter focuses on providing the core capabilities necessary to address the initial challenges of an RH system.
- **Chapter 5: Experimental setup: UGR-DONES control laboratory.** This chapter details the experimental setup at the UGR-DONES control laboratory, which serves as a testbed for validating the proposed RHCS. The lab replicates key RH tasks using a robotic cell with components such as a 6-DOF robotic arm and VR-based operator tools.
- **Chapter 6: RH Processes at IFMIF-DONES**. A process-oriented approach is presented to define the roles, responsibilities, and workflows required for RH operations and maintenance campaigns. This chapter emphasizes reducing intervention times, integrating commercial tools, and enhancing automation while maintaining operator involvement.
- **Chapter 7: Networks and Data**. This chapter analyzes the network solutions for RH systems, categorizes data flows, and discusses performance and reliability requirements. The applicability of TSN is evaluated experimentally, demonstrating its capability to provide deterministic communication under high traffic conditions.
- **Chapter 8: Enhanced Remote Handling Control System**. Building on results and insights from previous chapters, an enhanced logical and physical architecture for the RHCS is proposed, integrating advanced technologies such as TSN, OPC UA, and AI-enabled ROS tools. In contrast to the design presented in Chapter 4, this chapter introduces advanced functionalities aimed at enhancing the efficiency, automation, and intelligence of the RH system.

1.8 Framework of this work

This thesis is oriented towards the research and development of advanced control systems for Remote Handling in the context of fusion research, addressing the unique challenges of this environment and proposing technological solutions focused on the particular use case of the IFMIF-DONES project. This work has been supported by funds from the projects:

- WPENS: This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 EUROfusion). The second phase of this project will end on 2025. Throughout this thesis, several references are made to reports and documents from the WPENS project, which are not publicly accessible. These documents

have been invaluable in shaping the research and supporting the proposed solutions. The author wishes to express sincere gratitude to the WPENS project for granting access to this essential information.

- “FEDER - Suministro, instalación y configuración del equipamiento necesario para la puesta en marcha de la instalación IFMIF-DONES”. Regional project funded by Junta de Andalucia.

- “AMIGA 8. Estudio con precusores de SKA de la evolución de galaxias en entornos extremos reguladas a grandes escalas. Nuevas tecnologías para SKA y su red de centros regionales. Financiado por MICIN/ AEI /10.13039/501100011033/ y por FEDER, -Una manera de hacer Europa-. PID2021-123930OB-C22”. National project funded by the government of Spain.

- “EU DAIS Project (No. 101007273-2 within the KDT Calls and PCI2021-121967) DAIS (https://dais-project.eu/) has received funding from the KDT Joint Undertaking (JU) under grant agreement No 101007273. The JU receives support from the European Union’s Horizon 2020 research and innovation programme and Sweden, Spain, Portugal, Belgium, Germany, Slovenia, Czech Republic, Netherlands, Denmark, Norway, Turkey”

The work developed here has been partially validated through the delivery and review of several technical reports to the IFMIF-DONES project team. These reports have been part of the so-called EUROfusion workpackage WPENS (Work Package Early Neutron Source), whose main objective is to be ready for the construction of IFMIF-DONES as soon as possible. A large number of Research Units from all over Europe, as well as third parties from industry, have been involved working on different aspects of the DONES scope of work. The University of Granada has participated in this phase in collaboration with Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT).

Chapter 2
State-of-the-art

This chapter reviews the state-of-the-art in RH systems, providing a foundation for the development of the RHCS at IFMIF-DONES. It explores key concepts in remote maintenance management, highlighting the importance of integrating RH considerations during the early design phases of fusion-related facilities to ensure effective maintenance in high-radiation environments.

A comparison of existing RH systems, including **JET, ITER, and CFETR**, reveals the evolution from bespoke solutions to scalable, interoperable frameworks. Insights from these facilities emphasize advancements in modular control architectures, automation, and the use of standardized technologies. Additionally, **control frameworks** like **OPC UA** and **ROS2** are assessed for their potential to enable seamless interoperability and advanced functionalities in RH systems.

The chapter also examines **industrial networking** technologies, such as **TSN**, and their ability to deliver deterministic, high-bandwidth communication critical for RH operations. Finally, **human-machine interfaces** (HMIs) and innovative input devices, such as haptic controllers and VR systems, are discussed for their role in enhancing operator efficiency and precision.

This synthesis of concepts and technologies provides a comprehensive basis for the modular, scalable designs required for IFMIF-DONES, bridging the gap between current capabilities and future needs.

2 State-of-the-art

This section introduces key concepts to help the reader better understand the context of this work. It provides an overview of remote maintenance management, fusion-related facilities implementing remote handling systems, control frameworks used in such setups, and critical aspects related to their communication networks.

2.1 Overview of relevant facilities using RH

For the development of this work, some of the main fusion facilities in the world have been taken as a reference. All fusion-related facilities require highly specialized RH systems to handle maintenance and operations in harsh, radioactive environments. The common challenges for these systems include precision, safety, and the need for reliable teleoperation. However, each facility also presents unique demands: JET focuses on maintaining operational tokamak components with proven RH techniques, ITER scales up these operations with more automation and integration due to its larger size and complexity, and CFETR aims to innovate and test new RH technologies for future applications. Each one is analyzed in more detail below.

2.1.1 JET

JET (Joint European Torus) is the world's largest and most powerful operational tokamak, aimed at advancing fusion research by studying plasma behavior under conditions relevant to future fusion reactors. Its primary objective is to develop the scientific and technical basis for fusion energy, contributing crucial insights for ITER and beyond. Located in Culham (UK) is one of the facilities with the most extensive experience in RH operations for the maintenance and upgrading of its fusion reactor. Over four decades of operations have resulted in one of the most mature RH systems in the field. This has led to the creation of RACE [https://race.ukaea.uk/], a research center with a strong focus on remote applications in challenging environments. RACE contributes to the design of major fusion projects worldwide, including ITER and DEMO.

The JET Remote Handling System employs a 'man in the loop' approach, relying on a dexterous two-armed tele-manipulator as key element providing the operator with "remote hands" inside the Torus. This device was named originally as Master Slave Servo-Manipulator (MSM), and it was introduced inside the reactor using a robotic boom as described in [51]. This system has been upgraded several times to accommodate new necessities and improvements, becoming MASCOT 6 [52] which is well established and proven through thousands of successful hours of operation in remote reconfiguration.

The article [53] provides a comprehensive examination of the RH system. In addition to a comprehensive, low-latency CCTV viewing system, operations at JET utilise synthetic views created by a virtual reality system which is constantly updated in real-time with position data relating to the robotic systems. The ODS is the central JET remote handling operations support tool, proved essential for visualisation and tracking of operations, particularly due to the increasing complexity of remote tasks. RACE re-designed JET ODS to meet the requirements of ITER and DEMO, creating the Operation Management System

(OMS). One important lesson learnt from JET stated in [54] remarks that this kind of facilities and machines have a natural tendency to become larger, more complex, and more hazardous, inescapably leading to require increased levels of remote maintenance. Figure 4 Shows the overview of JET RH system extracted from [53].

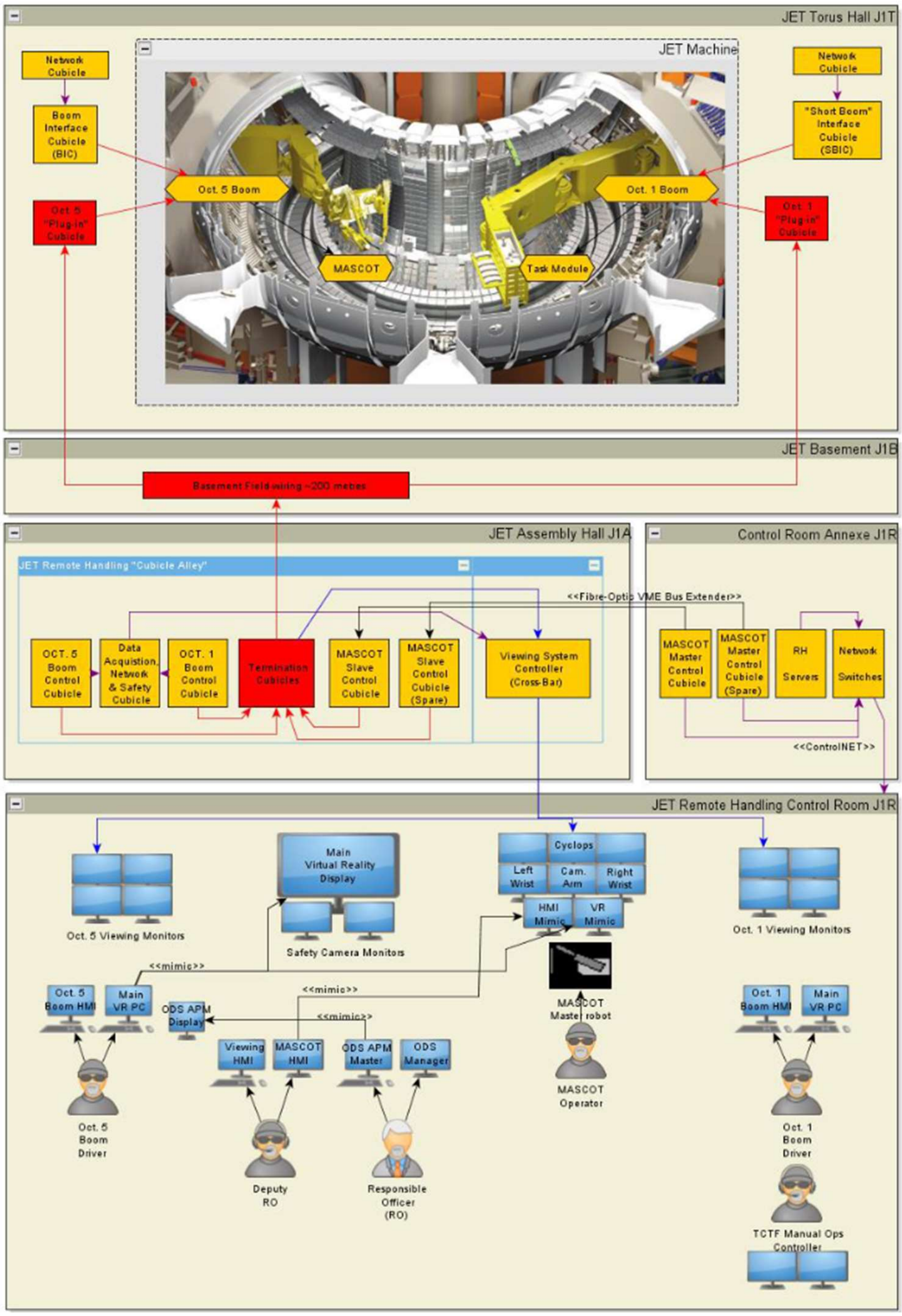


Figure 4: JET RH System Overview from [53]. The control room is dedicated exclusively to RH, with stations for different roles that allow the coordination and execution of RH interventions.

Figure 4 shows a dedicated control room with workstations statically linked to the 3 main robotic systems: Octant 1 and 5 Booms, and MASCOT. For MASCOT control, a master device is used (see Figure 39). The control electronics are distributed in 2 rooms, one closer to the reactor and the other in the assembly hall, so that the electronics are protected from radiation. In addition to the RH devices, their control systems, and interfaces, a number of users with an associated role are defined. This aspect is critical to take into account in the development of the control system, since these will be the end users who exploit the functionality of the same.

It is imperative to acknowledge that the control system under consideration is more than 30 years of age. Despite the recent investment of over 400,000 hours in its enhancement and preparation for the final phase of decommissioning at JET, the system remains technologically outdated and reliant on bespoke solutions. This characteristic poses significant challenges in terms of integration with commercial tools and devices, leading to increased costs and the necessity of a substantial in-house team of experts capable of handling these tasks. For this purpose, JET has a dedicated center called RACE (Remote Applications in Challenging Environments), where experts in mechanics, electronics, control systems and software work on developing these systems.

2.1.2 ITER

The ITER (International Thermonuclear Experimental Reactor) project represents one of the most ambitious and promising initiatives in the field of clean fusion energy. The project's objective is to demonstrate the viability of nuclear fusion as a clean and virtually unlimited source of energy. The facility is situated in Cadarache, in the south of France, and is the result of collaboration between 35 countries. ITER, as JET, employs a tokamak to produce fusion reactions.

One of the primary goals of ITER is to achieve a net energy gain, which entails producing more energy than is consumed to initiate and maintain the fusion reaction. To accomplish this, it will be essential to develop new technologies and devices to keep the plant operational. This will ensure that all the knowledge and experience gained along the way (or in Latin, ITER) can be leveraged to develop the commercial nuclear fusion reactor of the future.

The ITER RH system is a key component in ITER operation. In [55] the authors describe it as a complex collection and integration of numerous systems, each one at its turn being the integration of diverse technologies into a coherent, space constrained, nuclearized design. The article provides an overview of the main components of ITER RH, and can be complemented by [56] to get basic principles of fusion reactor maintenance.

The system has been divided into 7 major equipment systems (each of them includes operator interfaces, equipment and controllers) to be provided from contributors worldwide including Europe, Japan, India, China, and Korea[57]. All of them will be controlled from a dedicated control room, which will consist of a set of standard work-cells that will be dynamically linked to different devices. This standardization approach is quite challenging, especially for the master devices used for telemanipulation. The study conducted in [58] shows that tele-manipulator control (using Haption device, Figure 16) for different slave arms was achieved and tasks carried out successfully using both master–slave pairings, although the performance is not as good as with dedicated master–slave telemanipulators such as MASCOT at JET.

According to [59], the RH control system shown in Figure 6 is integrated and coordinated through the hierarchical structure of ITER Control, Data Access, and Communication (CODAC) system. Therefore, it has to provide central monitoring and coordination with the main control room and provide control of remote maintenance tasks to the RH operators. Each RH equipment control system is divided into two layers: the High-Level provides operator interfaces, and the Low-Level containing instrumentation and control (I&C) cubicles.

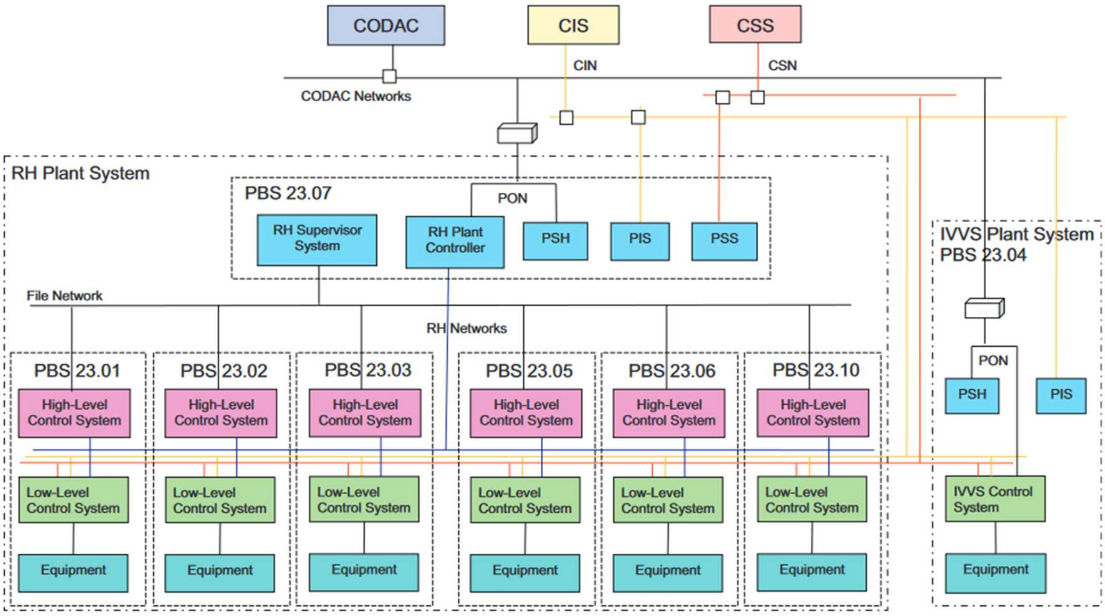


Figure 5: ITER RH control system architecture [59]. Is divided into six different systems plus the camera system (IVVS) to cover different parts of the machine, but all of them are interconnected internally and with the Central Control System.

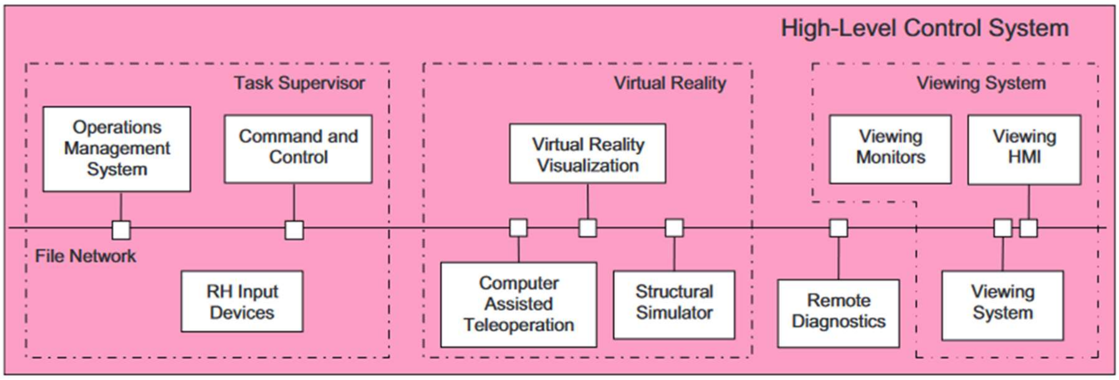


Figure 6: Detail of the ITER RH high-level control system modules [59].

ITER project encourages designers to use standard COTS components. For CODAC the standard approach is to use EPICS framework and Siemens S7 Programmable Logic Controllers (PLCs), but this approach is not appropriate for the human-in-the-loop approach of RH. An alternative standard framework called GENROBOT is under development, which is a robotic framework that aims to become a standard solution for the RH systems of the future fusion power plant. This is a proprietary solution developed by GTD for ITER project.

For a large project with the economic capacity of ITER, it is rational to consider this approach. However, for smaller projects with more limited resources, such as IFMIF-DONES, it is not feasible to assume the cost of developing and maintaining a specific control framework for RH.

2.1.3 CFETR

CFETR is a Chinese national project designed as the next step after ITER. While ITER focuses on proving the scientific feasibility of fusion, CFETR aims to bridge the gap between ITER and a fully operational fusion power plant (DEMO). CFETR will focus on demonstrating the technologies needed for continuous operation, such as breeding tritium fuel, achieving long-duration plasma control, and developing the materials and systems necessary for a commercial fusion reactor. A detailed overview of the project can be found in [60].

Although both projects have a tokamak at their core, the requirements in terms of RH are different. While ITER's RH system is conceived towards demonstrating feasibility of machine maintenance in a research environment, CFETR's RH system is being developed with a focus on continuous operation and integration into a commercial fusion power plant environment, necessitating advancements in automation and operational efficiency.

A recent publication from 2022 [61] analyze the CFETR RH control system, which is divided into 4 layers:

1. The central control layer, which embodies the communication interface with the central control system (CCS).
2. The RH plant supervision layer, which is responsible for monitoring the operation status of the whole RH system.
3. The operation control layer, which is the interface of human-machine interaction.
4. The device control layer, which is used for the equipment movement and logic control.

The first layer relies on EPICS, which is the control framework used for the CCS at CFETR and ITER. The supervision layer uses OpenSplice (or ROS2), and a unified control protocol standard is proposed to interact with RH equipment controllers. This unique interface is provided by the System Controller, which is a Linux controller that provides task control for the corresponding subsystem. Figure 7 shows the architecture of the RH control system, which is very similar to the ITER's one.

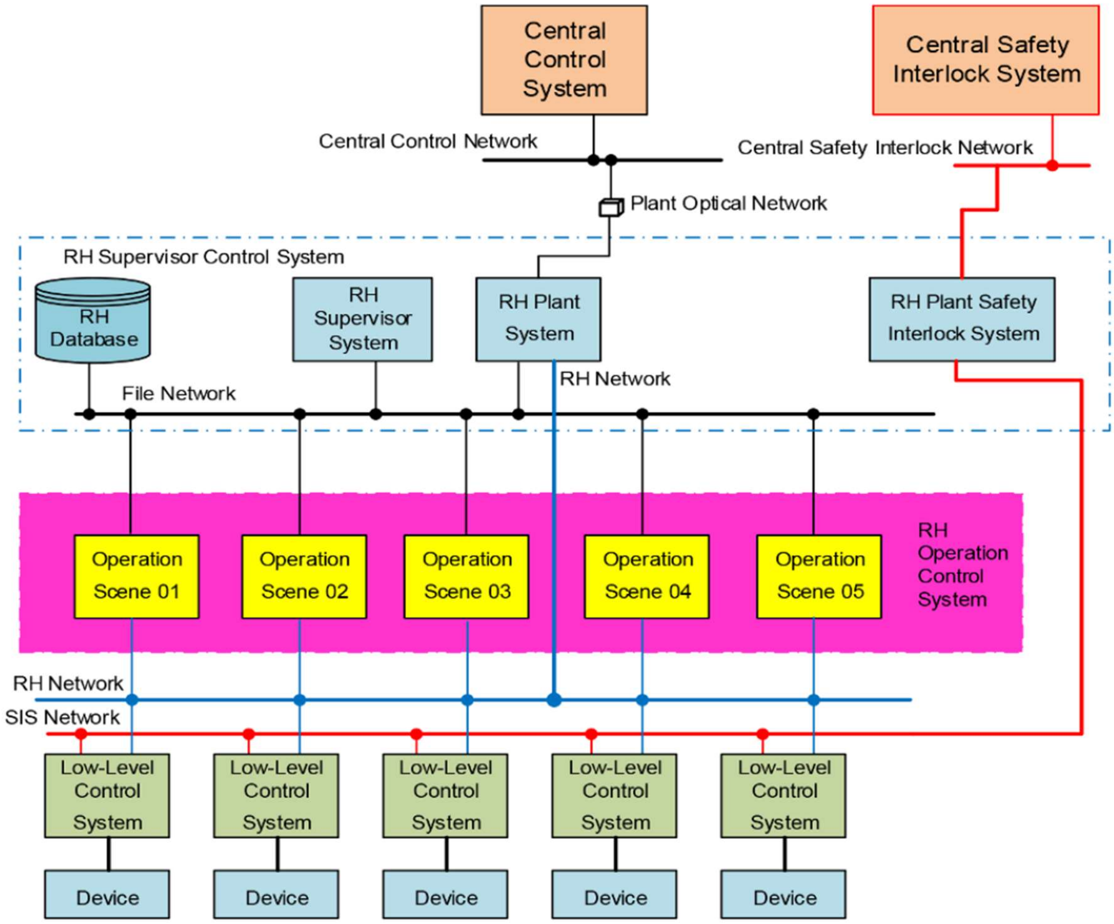


Figure 7: CFETR RH control system architecture [61]. It shows a similar architecture to ITER, but unifies Interlocks and Safety in a single module.

Some interesting conclusions extracted from the publications mentioned on this section are:

1. It is better to adopt mature industrial products (COTS) or technologies as much as possible and establish cooperation with industry to reduce the risks in building the RH system.
2. Test platforms are crucial to verify performance of the key components, to assess the reliability of RH equipment and to examine the feasibility of control strategies.

2.2 Remote maintenance management

The primary function of the RH systems at IFMIF-DONES will be to conduct maintenance in areas with high radiation levels or where handling extremely heavy components is required. These operations necessitate meticulous study and planning well in advance, making maintenance considerations a critical aspect of the design phase itself. Any failure of activated components (those with residual radiation) without the necessary remote handling mechanisms for replacement, repair, or manipulation would render them permanently unusable, as direct human intervention would no longer be feasible under such conditions.

Thus, early planning of maintenance activities in radiation-exposed facilities is essential to save both time and financial resources in the long term. This approach requires the integration of maintenance needs into the initial design phases, ensuring alignment with the requirements and constraints of other multidisciplinary groups. Furthermore, effective coordination of all activities is paramount to achieving the operational and maintenance objectives of the facility [40].

A maintenance expert system is a useful tool for coordination, planning and management. It will allow centralized management of critical infrastructure, predictive maintenance scheduling, and resource coordination. This is essential in a facility where unplanned downtime can severely impact research progress. The integration of this kind of tool within the control room dedicated to RH and the interaction with other components of the control system must be crucial. Some of the commercial alternatives are described below, as well as some customized tools that could be useful in the case of IFMIF-DONES. Subsequently, a concrete proposal will be developed in Section 6.4.

2.2.1 Commercial solutions

Several commercial software systems are commonly employed in various industries for managing maintenance operations. Among these, Business Process Management (BPM), Enterprise Asset Management (EAM), Computerized Maintenance Management Systems (CMMS), and Manufacturing Execution Systems (MES) are notable examples:

- BPM systems are designed to model, automate, monitor, and optimize organizational processes, ensuring greater efficiency and alignment of workflows with business goals. In the context of maintenance operations, BMP notation (BPMN) can be applied to model and manage maintenance processes as described in [41]. Some well-known commercial BPM solutions are IBM Business Process Manager and Bonita BPM.

- EAM systems, such as IBM Maximo and Hexagon EAM, provide comprehensive functionality for managing assets, scheduling maintenance tasks, and optimizing resource allocation. The objective of EAM is to prolong the service life and maximize utilization of the assets via adoption of leading-edge standards, practices, and technology. These systems are designed for large-scale, asset-intensive environments and focus on maximizing asset lifespan and reducing downtime through predictive maintenance [42]. Their features for managing both planned and reactive maintenance make them relevant for fusion facilities, where the health of high-value assets is critical.
- CMMS platforms, like MaintainX and Fiix, focus more specifically on maintenance activities, providing tools for scheduling, tracking, and documenting all maintenance work. These systems are typically more cost-effective and simpler to deploy than full EAM suites, while still offering valuable features like work order management, equipment history, and preventive maintenance planning. CMMS is evolving towards integrating real-time condition monitoring and predictive maintenance. The ability to collect data from various sensors (e.g., temperature, vibration) remotely or locally improves system availability and asset life cycle management [43].
- Finally, MES solutions like Siemens SIMATIC IT or GE Digital's Proficy provide real-time control and monitoring of production operations, including maintenance activities. These systems are primarily concerned with the operational level, facilitating the execution of tasks in coordination with production schedules. While MES systems are often less focused on maintenance per se, studies such as [44] affirm that can be successfully applied to maintenance management.

Advanced technologies such as augmented reality, real-time condition monitoring, and geographic information systems are essential to successfully manage complex maintenance scenarios. These technologies help streamline maintenance interventions, improve performance, reduce errors, and support less experienced technicians by providing them with real-time assistance. These insights highlight the importance of integrating real-time monitoring, new technologies, and data standardization to enhance maintenance efficiency.

2.2.2 Custom solutions

JET is one of the most experienced fusion facilities in the world. For years they have been using a system called Operation Documentation System(ODS) as an expert system to support RH procedures. It offers visual process maps (called Active Process Map), step-by-step task tracking, and user logging for accountability as shown in Figure 8. Operators can visualize target positions and simulate procedures in VR before actual execution to avoid collisions and errors. ODS also records the progress of tasks and generates detailed reports on completion times, personnel involved, and tool usage.

It uses a semi-structured language that is easily interpretable by the operators and allows establishing a series of rules in the description of the procedures, as well as making references to pre-programmed sequences that can be used by the operators (the so-called teach files).By integrating real-time data with VR systems and tracking in-vessel time, ODS enhances safety and coordination, especially when multiple teams are working in parallel. The system's ability to adapt to changes during operation allows for dynamic task management, improving the overall efficiency and safety of RH operations at JET [45].

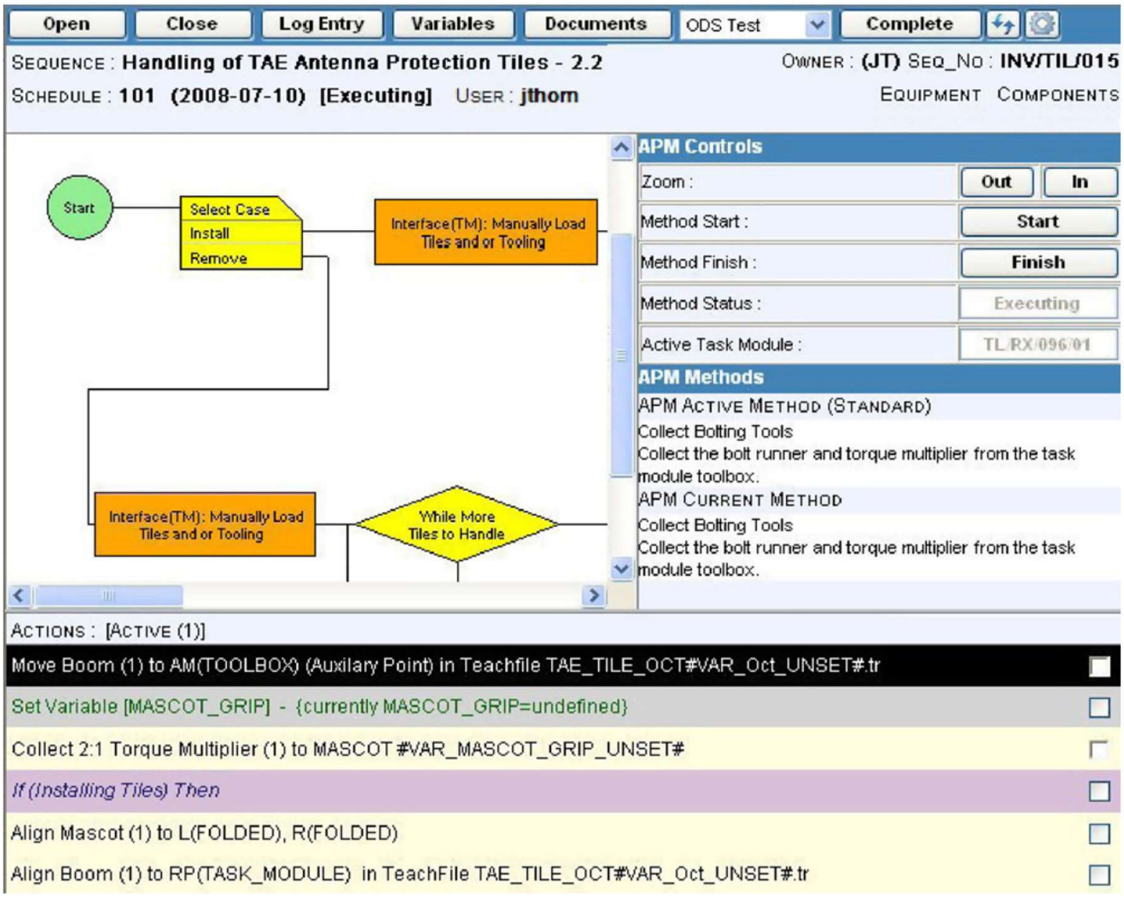


Figure 8: Main view of ODS interface [45]. The Active Process Map is the main component of the panel, guiding the users through the sequence of RH procedures and providing instructions.

ITER is developing the evolution of this system, under the name of Operation Management System (OMS). It is an in-house software developed by GTD company to manage Remote Handling operations at ITER. The OMS is part of ITER's RH High-Level Control System, designed to plan, execute, and analyze RH operations, such as operations with robots, cranes, and mobile platforms [46]. Structurally, the OMS organizes operations into four hierarchical levels: super-tasks, sub-tasks, methods, and steps. Super-tasks are high-level flows of sub-tasks, while sub-tasks are composed of methods, and methods consist of individual steps. Each step can include detailed information about the tools, equipment, and components required, offering operators comprehensive guidance on how to proceed with each operation.

The OMS provides three different applications: Task Builder, Task Executor and Task Analysis. The OMS Task Builder (Figure 9) is primarily used to create, edit, release, and manage RH tasks and Repeat Files, with additional functions like user profile management and Equipment Management System (EMS) and Structured Language (SL) command library handling available based on user access levels. RH tasks are organized hierarchically into Supertasks and Subtasks, with specific modes in OMS Builder dedicated to each. In *Subtask mode*, users create a Process Map containing Methods, IF/While statements, and Start/End blocks and can also define and edit Methods and their constituent Steps. *Supertask mode* allows users to design Process Maps that incorporate Subtasks and control structures, creating a layered approach for RH operations management. Additionally, comments and multimedia files can be attached to any Steps, Methods, Subtasks, or Supertasks for enhanced task detail and documentation.

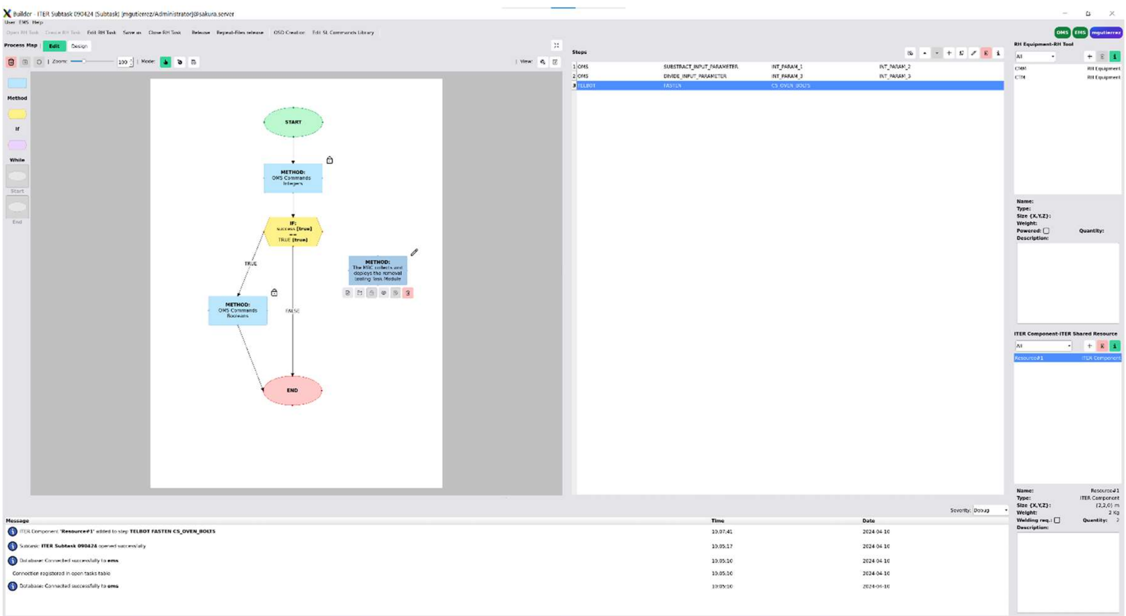


Figure 9: Task Builder panel from OMS allows to define RH tasks in the preparation phase [47].

The OMS Task Executor (Figure 10) is designed to run tasks previously created within the OMS Task Builder. Based on user access level, it supports the execution of either Supertasks (restricted to Superusers and Administrators) or Subtasks. During execution, the application enables users to interface with external systems to take control of RH devices or simulate operations in virtual scenarios. Operators can initiate, skip, abort, and complete steps, as well as attach multimedia files or annotate actions with comments and fault notes.

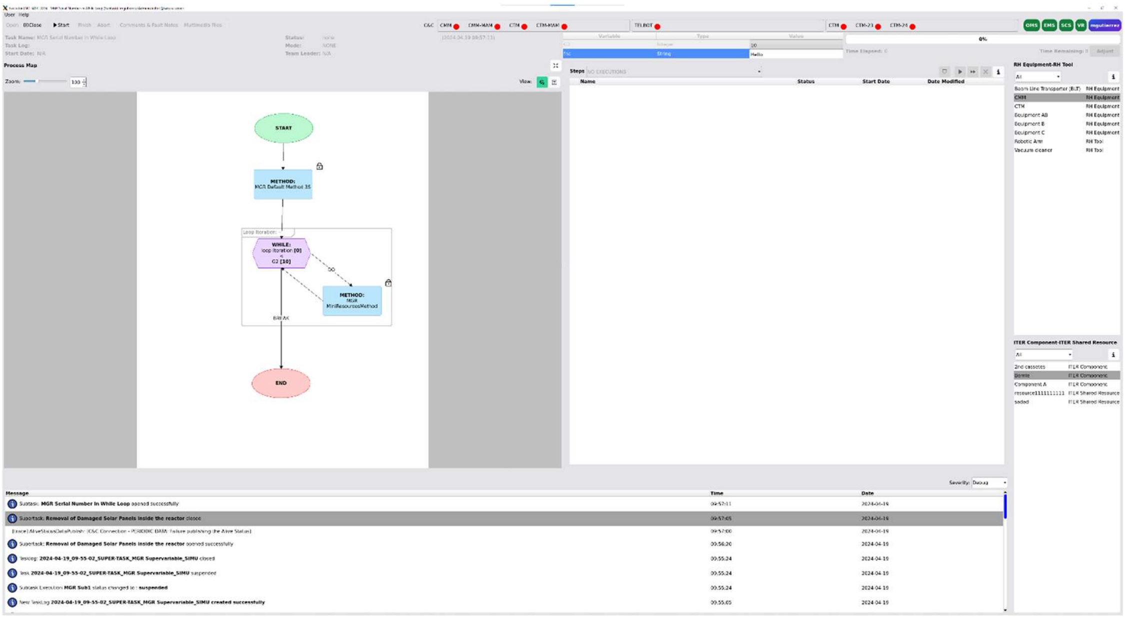


Figure 10: Task Executor panel from OMS allows operators to run tasks showing the workflow and detailed instructions [48]. Shows the process map on the left side, the sequence of steps that RH operator must follow on the center, RH equipment and tooling required on the right side, and progress on the top right corner.

All data from the execution are logged in the OMS and EMS databases, forming a comprehensive Tasklog. This log can later be analyzed and used to generate reports in the OMS Task Analysis application (Figure 11). In addition to this, operators can attach comments and multimedia files to the different Task Logs entries associated with a determined event such as the Start of an execution or the End of an execution.

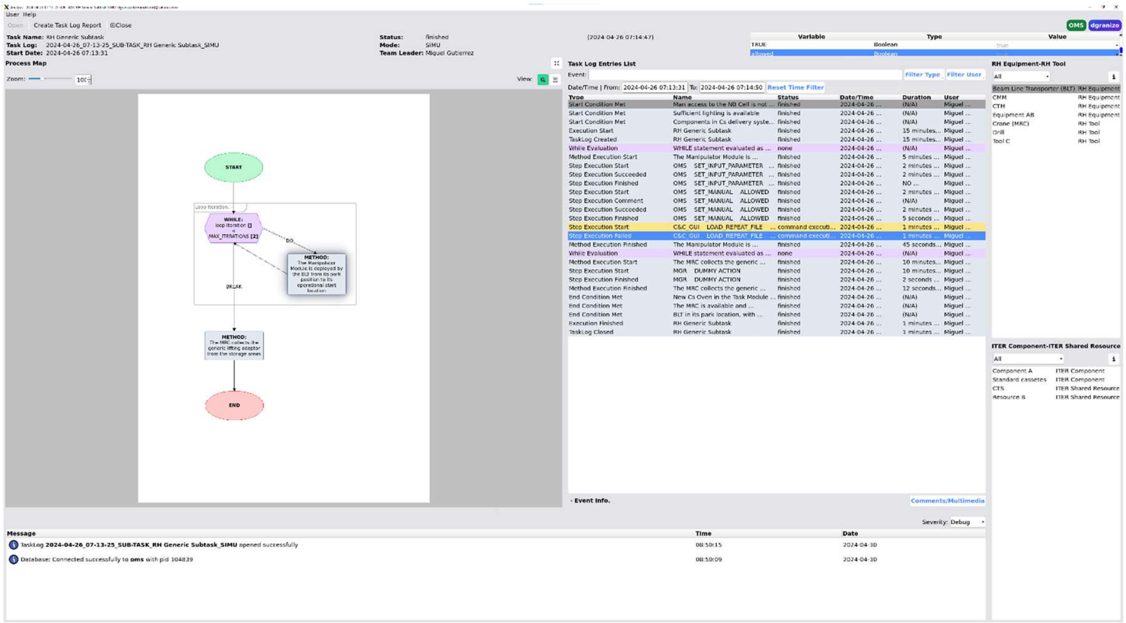


Figure 11: Task Analysis panel from OMS shows the different logs and evidences collected by operators after task is completed [49].

The system is a complex piece of software that interacts with different databases and control modules. The functionality of each application is tailored to the responsibilities of the active user, providing customs views according to the user role. Furthermore, the system can operate in different modes, including simulation, mock-up, or real execution, allowing operators to train on new tasks before performing them in the actual environment. More details about the tool can be found on the manuals provided by GTD [48], [49], [50].

2.3 Control System frameworks

The primary objective of this thesis is to develop a robust architecture for RH control systems, prioritizing interoperability, standardization, reusability, and maintainability rather than relying on entirely custom solutions, as seen in other facilities requiring RH. These attributes can be enhanced by using a suitable control framework.

The concept "control framework" refers to a structured set of software tools, protocols, and standards designed to facilitate the development, integration, and management of control systems. It provides a unified environment for communication, data exchange, and system coordination, ensuring that various subsystems—such as scientific instruments, industrial automation devices, or remote handling equipment—can operate seamlessly and reliably. Six potential candidates have been evaluated for this purpose: EPICS, GENROBOT, SIEMENS, OPC UA, ROS2 and CORTEX.

This section offers an overview of main features of the most relevant control frameworks and relevant references. Based on this information, Section 4.4.1 will provide a comparison to extends the work presented in [62], summarize the key features of each in Table 8, and select the most suitable control frameworks for RH in DONES.

2.3.1 EPICS

Currently proposed for the central control of the plant to interface with the different subsystems, EPICS (Experimental Physics and Industrial Control System) is an open-source framework designed for creating distributed control systems with critical real-time requirements. A recent revision of this framework can be found in [63]. EPICS is particularly suited for facilities such as particle accelerators, telescopes, and similar scientific instruments, offering Supervisory Control and Data Acquisition (SCADA) capabilities and supporting a client/server model for systems with numerous networked devices. On the downside, while EPICS excels at managing automated instrumentation, it lacks the necessary functionalities for controlling mechatronic devices involved in complex telemanipulation tasks.

2.3.2 GENROBOT

Due to ITER's unique requirements for RH devices, the GENROBOT control framework was developed specifically for this purpose. GENROBOT serves as the generic software controller for ITER [64], providing a unified development environment for all RH controllers. It features a common interface between RH equipment and higher-level control layers, utilizing the Controller Interface Protocol (CIP). Running on cPCI controllers, GENROBOT includes libraries compatible with Linux and Windows, facilitating integration and telemanipulation. However, as it is still under development, GENROBOT is not yet a fully mature solution.

2.3.3 SIEMENS

As a widely adopted industrial solution for automating power plants, manufacturing, and material handling, TIA Portal by Siemens represents one of the most important industrial alternatives. In recent years Siemens has focused many of its products towards the integration of robotic systems as presented in [65], mainly by opening interfaces (such as the Standard Robot Command Interface) for communication with robotic controllers from the main manufacturers of robotic systems on the market. These interfaces increasingly allow lower level control and allow integration of robots from different manufacturers in a single engineering software. TIA Portal serves as the framework’s core, offering tools for configuration, programming, testing, and diagnostics. Nevertheless, the integration of the specific drivers depends entirely on Siemens reducing the user flexibility to adapt the solutions, and any modification or development will be more complex than other open-source alternatives.

2.3.4 ROS2

ROS 2 (Robot Operating System 2) is an open-source framework for developing robotic applications that provides advanced tools for real-time communication, modular software development, and hardware abstraction. Unlike ROS which is mainly used in academic and research environments, this version has been developed with an industrial focus and it is meant to be used in the production environment. This leap from the purely academic environment to the industrial world has been one of the major proposals introduced in this new version, and has been widely supported by the community and put under study in works such as [66]. ROS2 use Data Distribution Service (DDS) middleware to ensure reliable, low-latency communication, which is critical for teleoperation and feedback control in remote handling tasks. In addition, its support for multiple programming languages and standardized interfaces facilitates integration with various robotic devices, enabling the development of robust and adaptable remote handling solutions. The main drawback would be the relative lack of companies working with this system, although there is a large community of experts but they are mostly from academia.

2.3.5 OPC UA

OPC UA is the industry-standard protocol for secure and reliable data exchange in industrial automation and other sectors. It is platform-independent and ensures seamless communication between devices from various vendors. As an open standard, OPC UA is built on internet technologies like TCP/IP, HTTP, and Web Sockets. It also provides a set of services and a basic information model. Managed by the OPC Foundation, this standard abstracts specific PLC/controller protocols (such as Modbus, Profibus, etc.) into a standardized interface, enabling HMI/SCADA systems to interact with a "middle-man" that converts generic OPC read/write requests into device-specific commands, and vice versa [16]. However, the scope of OPC UA doesn't go as far as covering control system functionalities such as programming any type of logic or planning trajectories.

2.3.6 CORTEX

CorteX, developed by RACE for the nuclear industry, addresses limitations in existing robotic control frameworks by offering a versatile and comprehensive solution. It excels in real-time performance, maintainability, extensibility, and interoperability, making it well-suited for the demanding requirements of nuclear applications. CorteX is organized around "simplexes," self-describing data structures that enable seamless integration and modularity. The system is highly efficient, offering consistent memory usage and low-latency operation, critical for real-time environments. CorteX also integrates with existing technologies like ROS and supports continuous integration and automated testing, ensuring long-term reliability and adaptability to future advancements. More details about this can be found on [67]. However, it is a proprietary solution and requires considerable effort for integration as there are no commercial systems that integrate it or standard interfaces that facilitate its use.

2.4 Industrial Networking

Another relevant component within the control system, and in general of any Information Technology (IT) or Operational Technology (OT) system, is its network and communications infrastructure. In modern industrial automation and process control systems, information serves as a foundational element for effective operation. One of the greatest challenges lies in ensuring its proper provision, distribution, and processing in a timely manner as discussed in [68]. Achieving this depends heavily on robust communication systems, often referred to as "industrial networks," which are specifically designed to meet the demanding requirements of these environments.

The development of industrial networks has evolved significantly, transitioning from proprietary and isolated protocols to more integrated and standardized systems. Early automation systems relied on isolated, specialized protocols like Modbus, Profibus, and DeviceNet, which were specifically designed for industrial environments. While effective in delivering reliable, low-latency communication in dedicated segments, these protocols lacked flexibility and interoperability across different platforms, creating challenges as industrial systems became more complex and interconnected.

Remote Handling systems are composed of different components and devices, each with different traffic profiles and communication requirements. Telemanipulators will require real-time communication with minimum latencies between the master haptic device located in the control room and the slave robot located in the operating area. On the other hand, protection and safety systems will require deterministic behavior with limited delivery times and reliability in package delivery. For the video camera system dedicated to providing a view of the working environment to the operators, a high bandwidth will be required. These are some of the examples that will be further analyzed in detail in chapter 7. In this section, some basic concepts are given that will allow a better understanding of the problems described.

2.4.1 Requirements of Real-Time Industrial Networks

Industrial control applications, such as those used in robotics, manufacturing, and high-precision assembly, require communication networks with specific characteristics. These include:

- Low Latency: Industrial systems, particularly those with real-time control needs, depend on low-latency communication to ensure rapid response times. High latency can lead to inefficiencies or even critical failures, especially in applications like robotic control or automated safety systems.
- High Reliability: Industrial environments are prone to various sources of interference and failure. Network communication needs to be reliable and resilient to ensure continuous operation, even under harsh conditions.
- Deterministic Behavior: Unlike standard Ethernet, which may vary in data delivery timing, industrial applications need predictable (deterministic) timing. This allows

operators to accurately anticipate and control the timing of each communication, which is crucial in time-sensitive operations like robot motion control or synchronized multi-device systems.

The extended use of robotic systems equipped with multitude of sensors and devices introduces a wide range of response times as shown in Figure 12 extracted from [69].

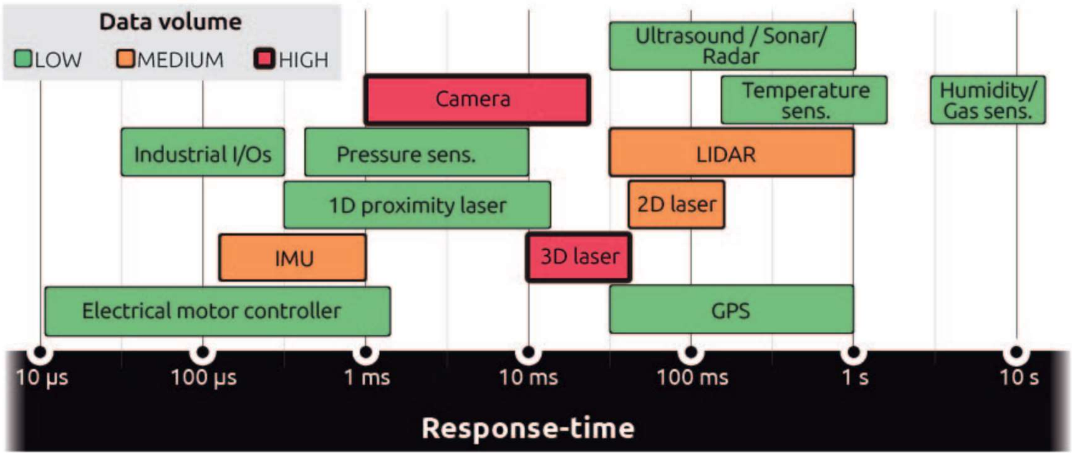


Figure 12: Typical response times for robotic components extracted from [69]

This heterogeneity in devices and the consequent need to establish a common basis for their communications, has led to Ethernet-based solutions have gained traction in industrial environments, due to their broad compatibility, scalability, and ability to support a wide range of applications. However, standard Ethernet was not originally designed for real-time applications, as it follows a "best-effort" delivery approach, which can lead to variable latencies and unpredictability in data delivery—two factors that are incompatible with the strict requirements of industrial control systems. This limitation has driven the need for an evolution in Ethernet standards to meet the stringent demands of industrial and real-time applications.

2.4.2 Quality of Service (QoS) and Traffic Prioritization

Another critical component in real-time industrial networks is Quality of Service (QoS), which enables the prioritization of critical data packets over less time-sensitive data. QoS mechanisms categorize and prioritize traffic, ensuring that high-priority packets, such as those carrying real-time control commands or safety signals, are delivered ahead of other types of traffic. This minimizes the risk of latency spikes that could disrupt the performance of sensitive applications.

Traditional Ethernet networks have limited capabilities for traffic prioritization, mainly relying on mechanisms like VLAN tagging (IEEE 802.1Q). It includes a Priority Code Point (PCP) field (3 bits) in the VLAN tag to assign priorities (0-7) to traffic. However, it does not inherently provide deterministic behavior; the PCP-based prioritization influences packet handling but relies on the underlying network to implement queuing and scheduling.

2.4.3 Emerging Concept of Converged Networks in Industrial Applications

With the increasing complexity of industrial systems, there is a growing trend toward "network convergence," where a single network infrastructure supports multiple types of traffic—control, diagnostics, video, and management. The idea of a converged network is to streamline communication by integrating diverse data flows within the same network, reducing infrastructure costs and simplifying network management.

Network convergence introduces unique challenges, particularly in balancing the distinct requirements of each type of data flow. For example, while control data might require low latency and deterministic timing, video and diagnostic data can tolerate higher latency but demand higher bandwidth.

2.4.4 TSN

The evolution of industrial networks toward Ethernet-based solutions has addressed many challenges, but achieving real-time communication with deterministic behavior remains a critical hurdle. TSN emerges as a transformative technology to overcome these challenges, building upon the Ethernet framework to meet the stringent requirements of industrial applications.

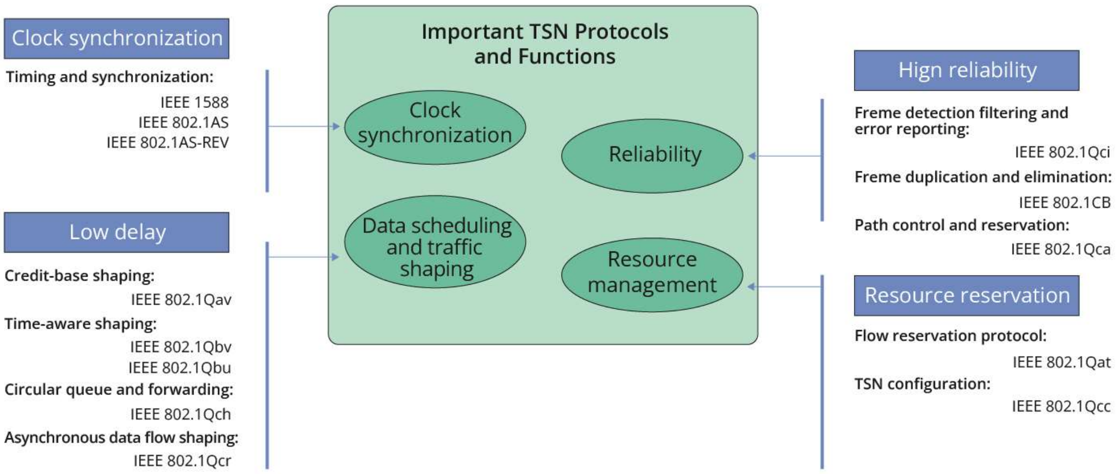


Figure 13: TSN standards and functions from [70]

TSN introduces a set of IEEE 802.1 standards as shown in Figure 13 designed to ensure low latency, deterministic communication, and fault tolerance. This enables the integration of diverse traffic types—real-time control signals, video streams, diagnostics, and data management—within a single converged network. By leveraging TSN, industrial systems can achieve the following key benefits:

- Deterministic Communication: TSN ensures that critical traffic meets strict timing constraints through mechanisms like time-aware scheduling (IEEE 802.1Qbv), which organizes traffic into predefined time slots. This is crucial for applications requiring synchronized operations, such as robot motion control and safety-critical systems.

- Quality of Service (QoS): TSN enhances traditional Ethernet by providing advanced traffic prioritization and resource reservation capabilities. Through standards like IEEE 802.1Qcc, TSN allocates network resources to ensure bandwidth availability for time-critical streams, even under high traffic loads.

- Fault Tolerance and Redundancy: To ensure network reliability, TSN incorporates features such as frame replication and elimination for reliability (IEEE 802.1CB). This protects critical data flows from disruption due to packet loss or link failures.

Unlike traditional industrial Ethernet protocols, TSN does not require proprietary hardware or software, making it a more flexible and scalable solution for diverse industrial environments. It provides a standardized approach to deterministic communication, enabling interoperability between devices from different vendors.
TSN is particularly relevant for use cases requiring precise synchronization and real-time responses, such as:

- Robotics: Coordinated motion control across multiple robotic arms or between robots and auxiliary devices.

- Machine Vision: High-bandwidth, time-critical video streams for quality inspection and defect detection.

- Safety Systems: Rapid dissemination of alarms and interlocks to prevent accidents or equipment damage.

These uses cases aligns quite well with the traffic profiles described at the beginning of this section for RH. By integrating TSN into control systems, IFMIF-DONES can leverage its advanced capabilities to manage the complex and heterogeneous traffic flows. The adoption of TSN would not only address the limitations of traditional Ethernet but also enable the seamless convergence of diverse networks, reducing complexity and infrastructure costs while enhancing performance and reliability. The applicability of this technology to the RH Control System of IFMIF-DONES will be discussed in Section 7.3.

2.5 HMIs and special input devices

In RH operations, the effectiveness and safety of the tasks are significantly influenced by the quality of the design of HMIs. As highlighted in [27], human-centered design is crucial to ensuring that operators have clear visibility of important information, allowing critical elements and events to capture the user's attention effectively.

RH operations can be executed across a spectrum of automation levels, ranging from fully manual control to fully automated processes using preprogrammed sequences or teach-and-repeat files (more details can be found in Appendix A: Automation in Remote Handling Systems). The ability to switch between these levels of automation depending on the task complexity and operational requirements is a vital aspect of RH systems. When an operator needs to take manual control, the design and functionality of the HMI become critical to the success of the operation. In such scenarios, user-friendly and intuitive interfaces reduce the cognitive load on the operator, enabling them to perform tasks more efficiently and with greater precision.

2.5.1 Input devices

To facilitate manual control, the use of master devices such as joysticks, master arms, or 3D mouses is highly recommended. These devices allow operators to execute complex maneuvers with high accuracy and dexterity since they provide intuitive control schemes that align with human motor skills. Cranes and other mobile devices typically use joysticks as the one shown in Figure 14 with different buttons that allow the operator to move over a plane comfortably and easily.

Figure 14: Industrial grade joystick manufactured by Spobu [71].

SpaceMouse or similar devices that are widely used for CAD design for 3D navigation. Simply press, pan, tilt or pull the joystick to intuitively pan, zoom and rotate the 3D plane as shown in Figure 15. This can be used as an input device to directly control the tool pose, or as a regular mouse to navigate more easily through the virtual environment. Due to its low cost and ease of use, it is recommended to include it in each workstation since all operators of the RH control room to interact (at least) with the Virtual Reality System.

Figure 15: SpaceMouse from 3DConnexion showing the different gestures used to navigate the 3D space [72].

Haptic devices are a special category of input devices that actively provide physical sensations back to the user. One example can be the thimble presented in [73] that measures the forces applied by a user during manipulation of virtual and real objects. This feedback can range from simple vibrations to complex force simulations, allowing users to feel resistance, texture, or even the weight of virtual objects. The key difference lies in the bidirectional interaction: haptic devices both receive input from the user and provided tactile information back. These devices are designed to provide to the operator "a sense of being there" by the use of force-feedback techniques combined with visual immersion using cameras and virtual environments. This conventional approach has been studied in [74], [75], [76], showing that the concept has evolved towards providing "a sense of feeling what to do", where the operator can be assisted by intelligent systems to execute the task in a more efficient way by providing visual guidance and guiding forces. This external guidance can be especially helpful on task that has been proved to be complex due to the variance of the time required for the operators and the failed attempts. The main challenges in completing tasks that require precise force control, such as assembly, bolting, and peg-in-hole operations, are significant variance in task completion time, particularly in the grasping and placing phases rather than in movement or transport. Grasping is especially challenging, with a high number of failed attempts due to components slipping. The transition from free-space to contact is critical, consuming a large amount of time, and rotational errors are particularly difficult to manage, leading to unsuccessful placements.

Figure 16: Virtuose 6D from Haption (left)[77] and Sigma.7 (right)[78] . The right side picture is from the International Space Station [79].

One of the most widely adopted haptic devices for this pourpose is the Virtuose6D from Haption, providing high force feedback in the 6 degrees of freedom with a large workspace. Similarly, the Sigma.7 is another commertial solution that has been used in telemedicine and space applications. These devices can be combined with an additional Scale1 device to completely mimic the working space covered by the telemanipulator mounted on the Access Cell Mast Crane (ACMC), integrating the control of both devices on a single interface, and reducing the number of operators involved.

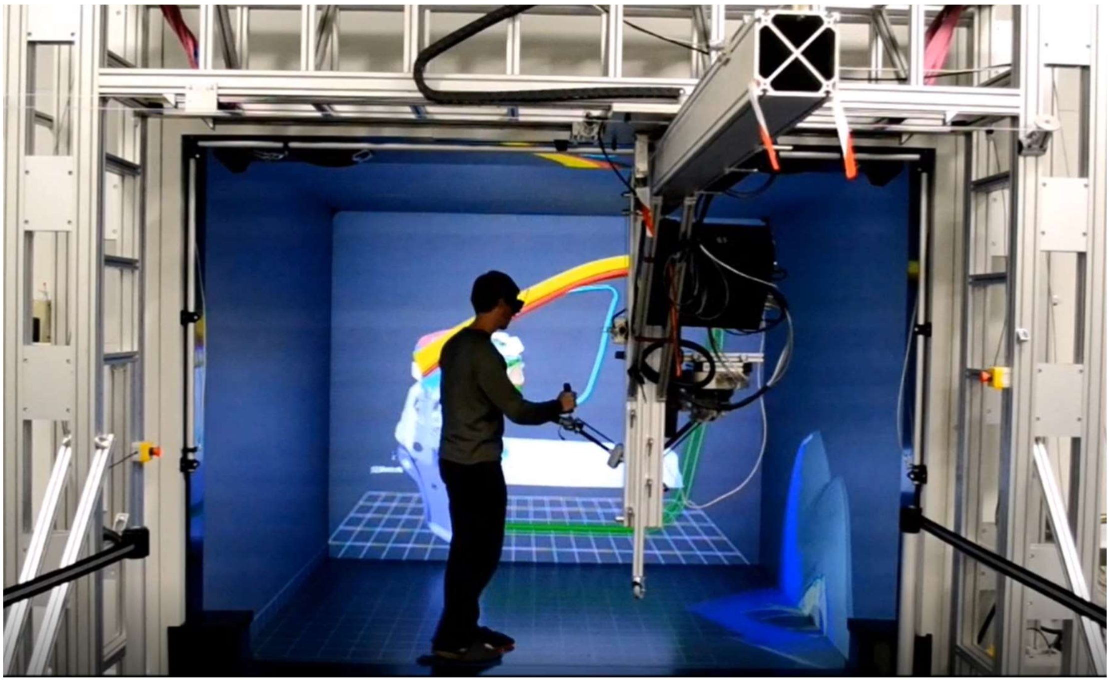


Figure 17:Virtuose 6D mounted on a Scale1 from Haption[77].

2.5.2 Control panels

In addition to hardware interfaces, the graphic component of the HMI must also be carefully designed. This includes the layout of the control screens, the hierarchy of menus, and the responsiveness of the system to user inputs. The interface should prioritize the display of essential data, such as system status, alerts, and real-time feedback from the RH devices, while minimizing distractions or non-essential information that could overwhelm the operator. For each equipment controller, a dedicated control panel shall provide the functionality for:

- Displaying/setting the controller operating mode and operating state
- Displaying/setting controller parameters
- Displaying equipment status information
- Sending commands to control the equipment system
- Displaying and logging equipment controller messages such as information, events, and alarms

The layout and organization of the control panels must follow the same general design principles, so that all mimics have a coherent appearance. To do so, it will be recommended to stablish guidelines and rules for the designers. The basic layout stablished for DONES RH control panels were described in [80] as shown in Figure 18.

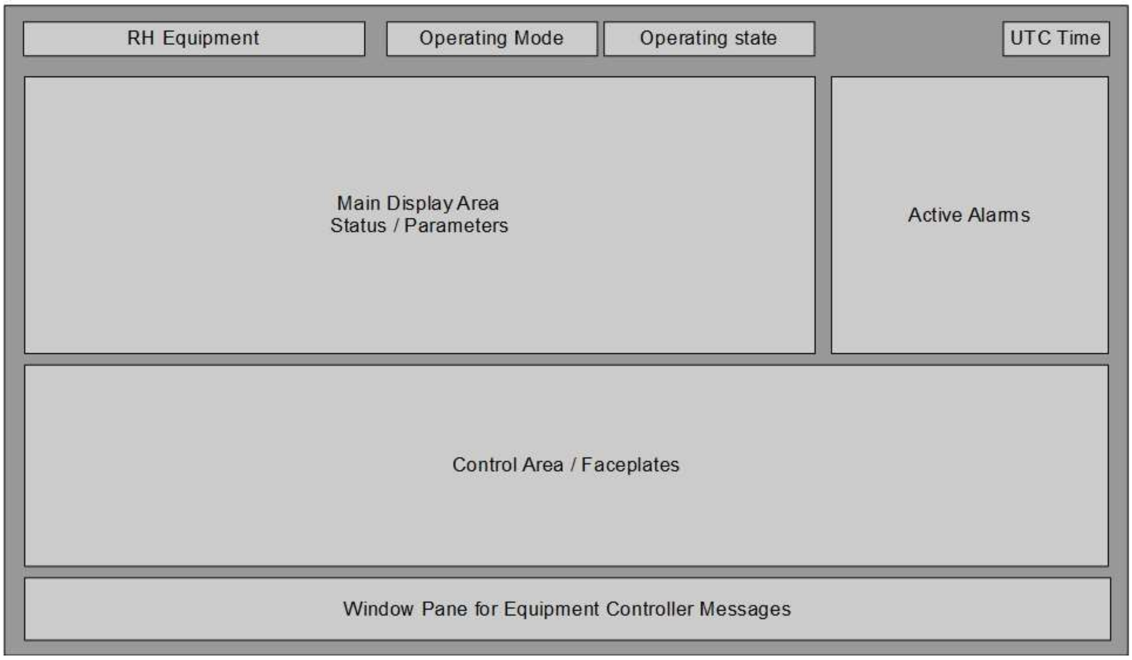


Figure 18: RH control panel layout proposal and organization of the different display areas [80].

2.5.3 New technologies

Assuming that the use of lots of sensors and complex electronics in the part of the slave robot is not possible, the use of new technologies are mainly limited to the user interface and the haptic devices that are available in the control room. There are solutions focused on capturing precise motion of the user without providing such detailed haptic feedback that can be useful for certain manipulation tasks. The work presented in [36] analyze the use of COTS VR tools and controllers for telemanipulation tasks. The authors states that operations can be performed precisely and visual guidance can be easily integrated into the virtual scene. Gross motor tasks can be performed without much mental effort, but when manipulation tasks change from gross to fine it may be important to design VR robot control systems that can support users (changing the magnitude in gain in mapping human movement to robot movement).

Other hot topic in human-machine interaction research during the last years is Human Motion Gesture Recognition. In the literature we can find works in which the interaction with telemanipulation systems by means of Head-Mounted Devices (HMDs) is analyzed. In [81], a setup composed of a VR headset and a Leap Motion detector (used for optical hand tracking) is proposed. The operation provides kinesthetic teaching via a digital twin of the robot which the operator cyber-physically guides to perform a task. Its key enabler is the concept of a virtual reality interactive marker, which serves as a simplified end effector of the digital twin robot. In virtual reality, the operator can interact with the marker using bare hand. Then, the status (e.g. position/orientation) of the marker is transformed to the corresponding joint space command to the remote robot so that its end effector can follow the marker.

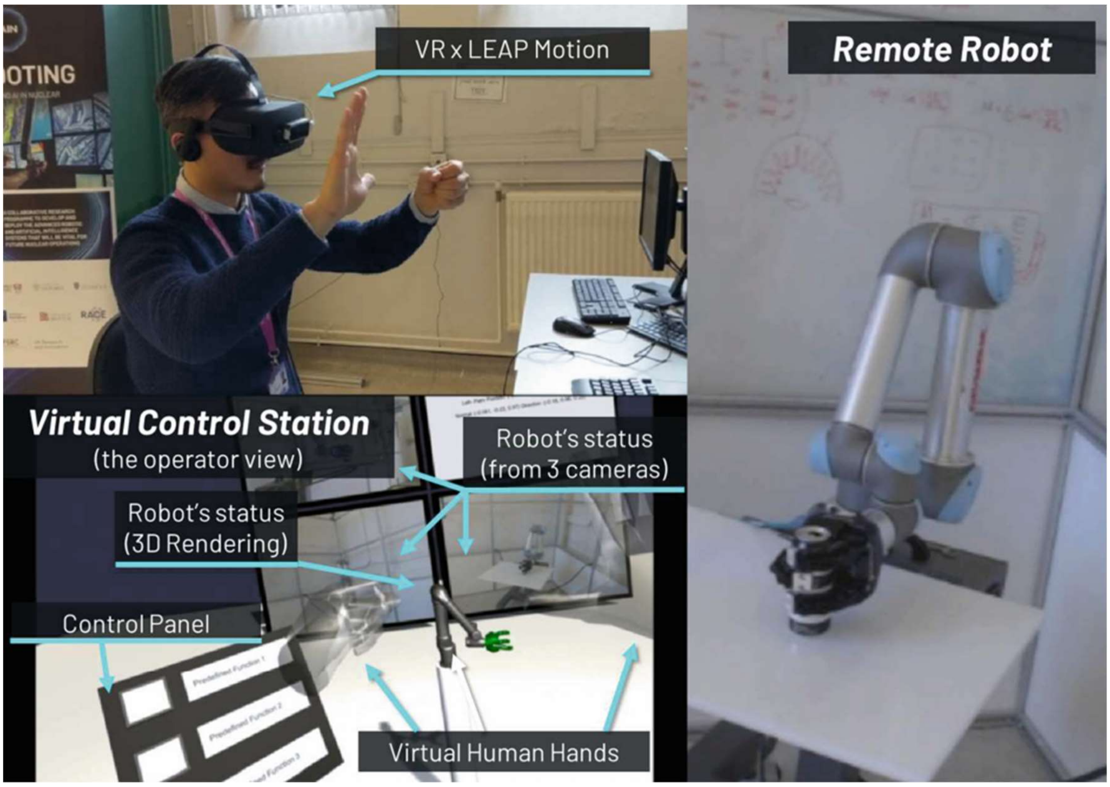


Figure 19: Teleoperation system using Virtual Reality and a Leap Motion for optical hand tracking [81]

One interesting aspect to consider is the integration of Augmented Reality (AR) into HMIs for RH operations. AR can overlay crucial information directly onto the operator's view, providing real-time data without the need to look away from the task at hand. This could be particularly beneficial in environments where the operator needs to maintain constant visual contact with the RH device while also monitoring multiple data streams. Recent publications from CERN probes that AR and Mixed Reality (MR) enhance multi-user collaboration due to the possibility of presenting custom information according to the user role [82], and can also improve the operator's environmental awareness and achieve better collision avoidance [83].

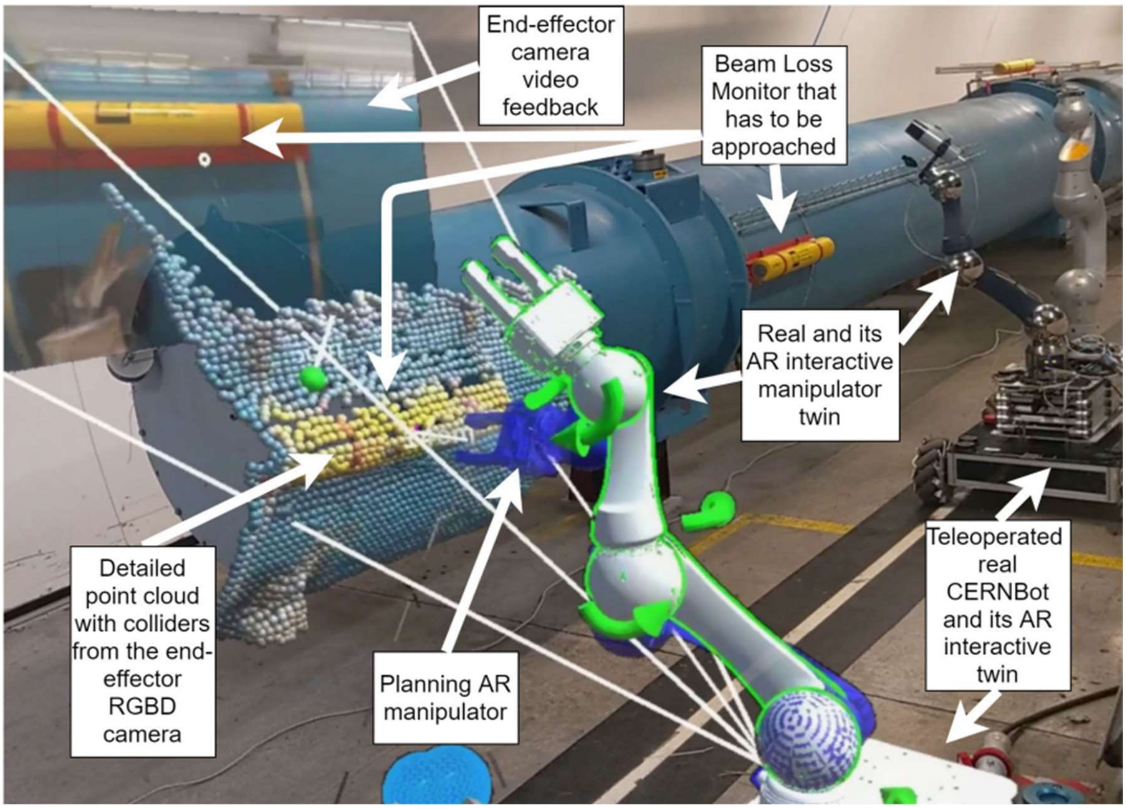


Figure 20: CERN robot and its digital twin from the operator's perspective using MR interface [82]

Chapter 3
IFMIF-DONES context

This chapter provides a comprehensive **overview of the IFMIF-DONES RH System** design, using foundational reports and documents from the **Work Package Early Neutron Source (WPENS)** as its primary reference. It will provide the basis for the reader to understand why Remote Handling systems are needed in this facility and what kind of devices and functions they comprise.

The chapter outlines the **plant's major systems and their hierarchical integration**, emphasizing the operational and maintenance challenges posed by highly activated components in extreme environments. It explores the critical **role of RH systems in enabling safe, effective, and continuous maintenance operations**, highlighting specific functionalities such as material handling, target assembly and replacement, and equipment refurbishment. Examples of RH devices, including telemanipulators, cranes, and manipulators, further illustrate the breadth of operational requirements.

A **preliminary RHCS architecture**, defined in WPENS documents, is revisited and critically analyzed. This design organizes RH control into three vertical layers—Safety, Interlocks, and Operation—across three horizontal layers corresponding to plant-wide control layer. Despite its foundational importance, gaps in modularity, adaptability, and integration are identified, paving the way for the proposal of the RHCS design, which is further developed in subsequent chapters as the core contribution of this thesis.

3 IFMIF-DONES context

The IFMIF-DONES Project consists of 5 major systems, 3 of which will require RH for installation, maintenance, operation and upgrade. The functioning of the plant and its different subsystems has been described in the Plant Description Document [47], an internal project document that periodically includes the advances and new developments contributed by the Research Units. Figure 21 describes the plant operation scheme, showing its main systems and their layout.

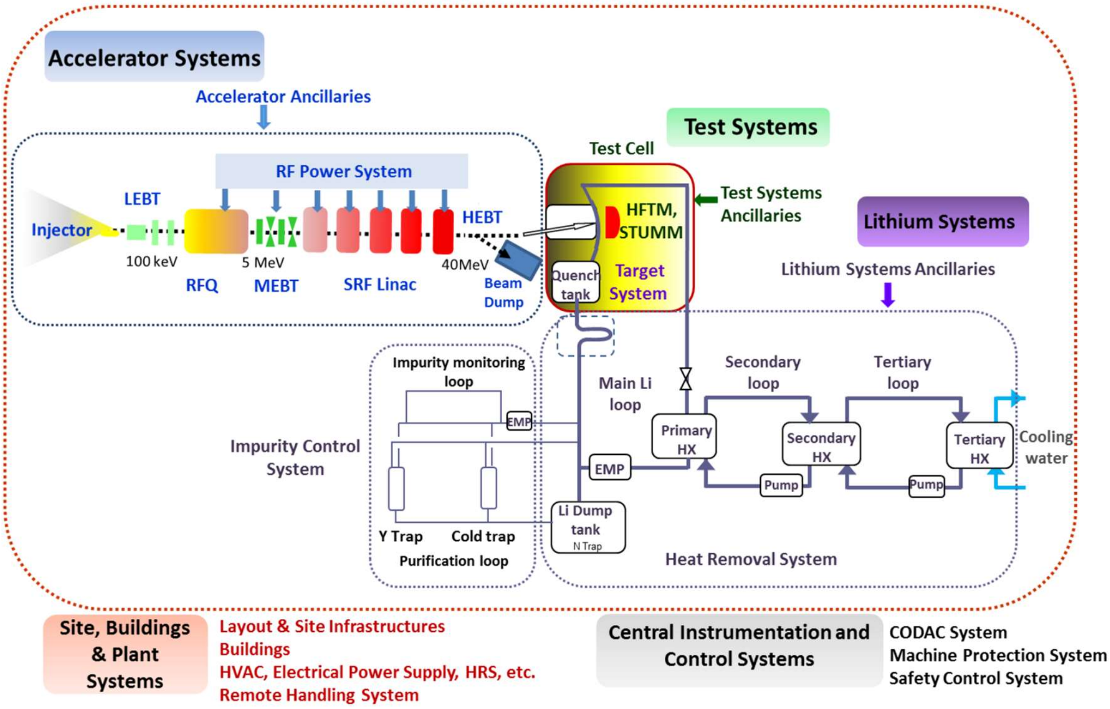


Figure 21: IFMIF-DONES schematic Plant Configuration [14]. Five major systems are shown in color blocks.

The systems responsible for generating and delivering the high-power beam are classified as the Accelerator Systems (Figure 22). Most of the components of the accelerator will be maintained hands-on (manually by workers), but some of the components from the High Energy Beam Transport (HEBT) will be highly activated parts due to the high energy of the beam at that stage of the accelerator, and in particular the Beam Dump. The project also contemplates the introduction of a second accelerator in the future, which would increase the performance of the facility.

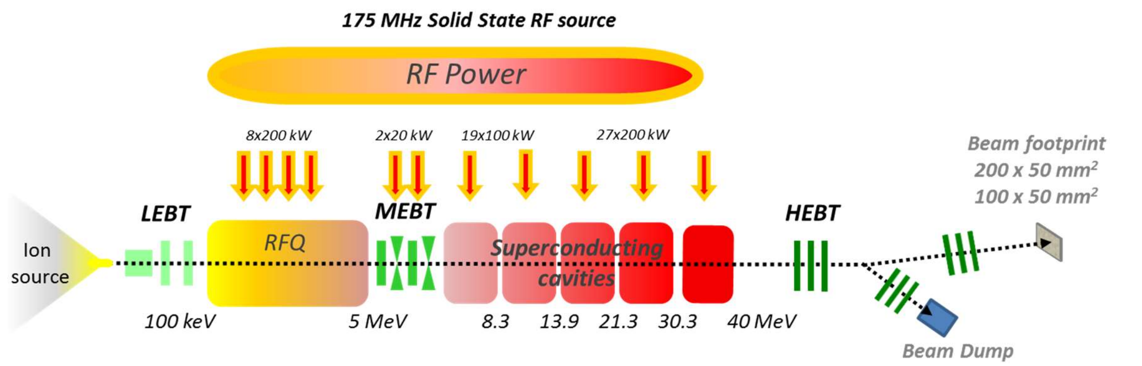


Figure 22: DONES Accelerator Systems conceptual design [84]. It is divided in three sections according to the energy level of the particles: Low Energy Beam Transport (LEBT), Medium Energy Beam Transport (MEBT) and High Energy Beam Transport (HEBT).

The systems associated with the management of the Lithium Target are referred to as the Lithium Systems (Figure 23). The Main Li loop will require remote maintenance due to the presence of tritium and berilium, which is highly dangerous and will be present on pipes, pumps and specially on the dedicated traps to purify the lithium.

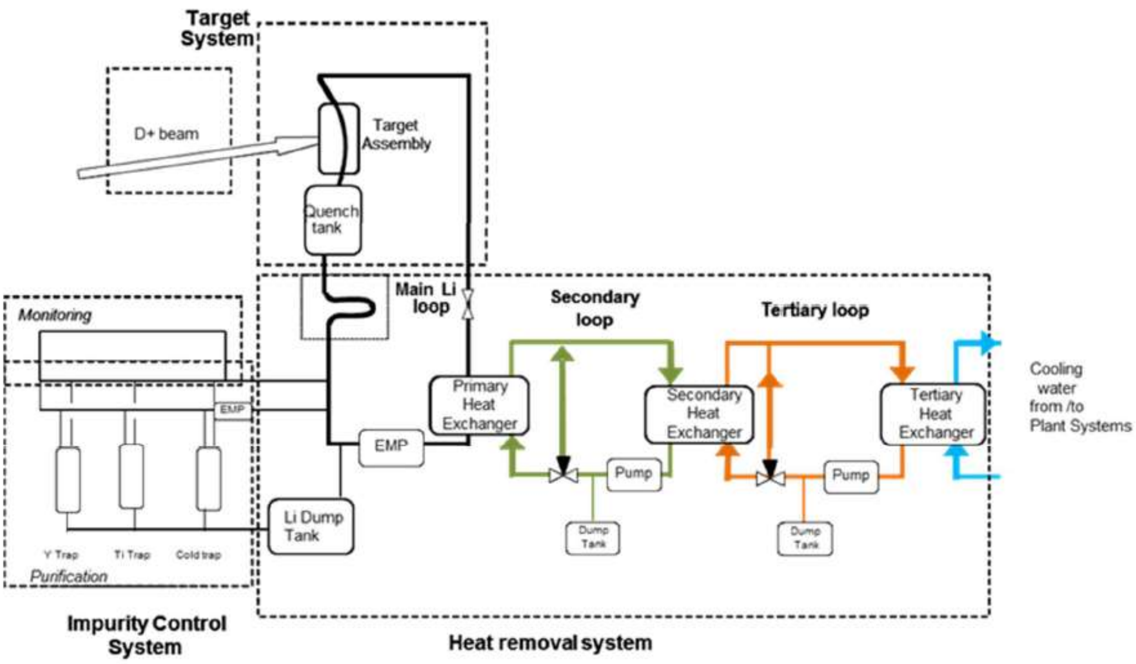


Figure 23: Basic configuration of the Lithium Systems [85]

The Test Systems (TS) encompass the systems in charge of the irradiation test module(s), the Test Cell, and their supporting components. The most relevant component in DONES facility is the High Flux Test Module (HFTM), that hosts the material samples during irradiation. RH operation is mandatory to lift the heavy plugs that seals the Test Cell and complete the different steps required to install and replace the components inside the pit. Figure 24 shows the main components of the Test System, the interfaces with the Accelerator and Lithium Systems, and other connections for cooling and control signals.

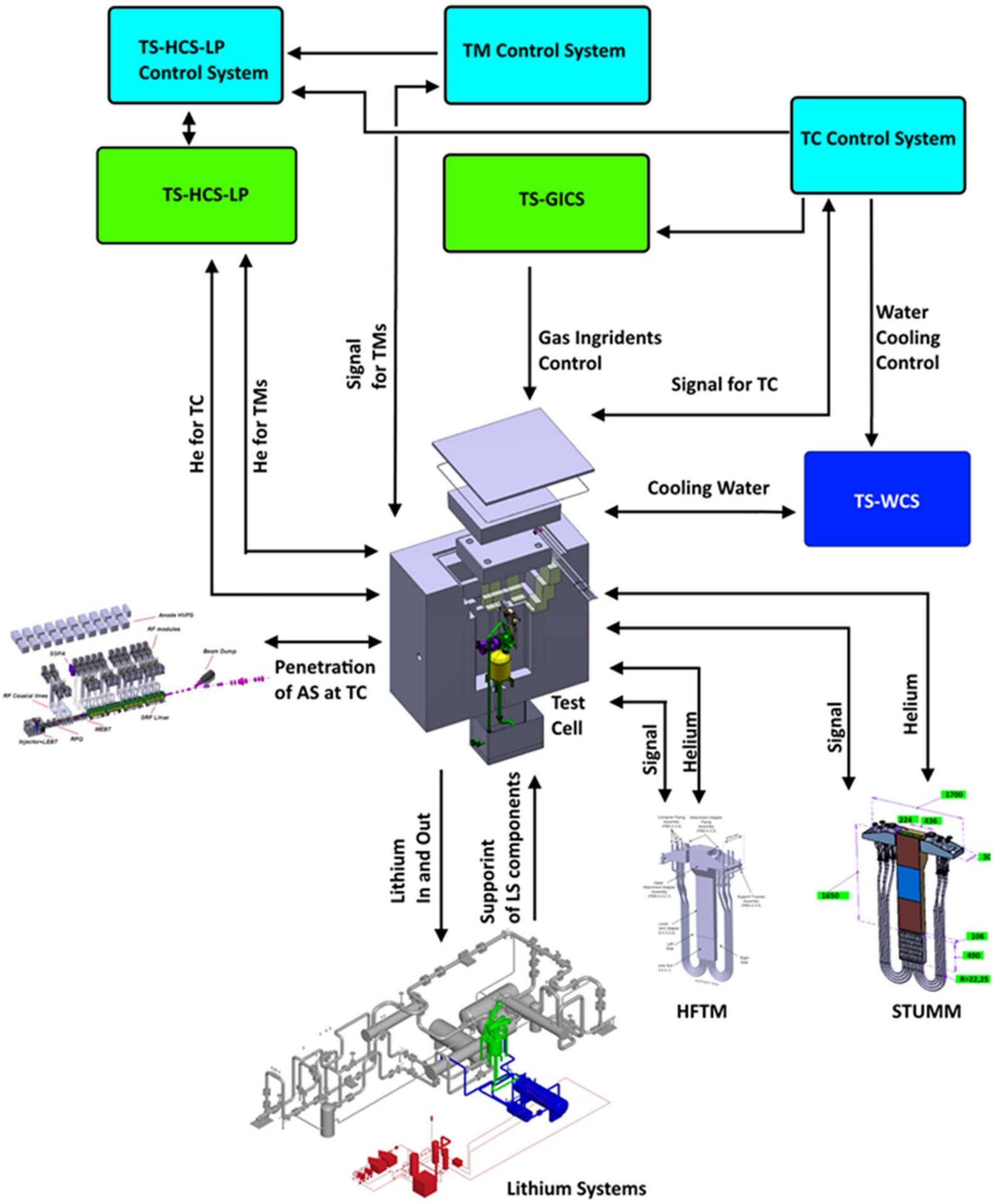


Figure 24: Functional diagram of the Test Systems [85]

The Central Instrumentation and Control Systems (CICS) oversee the overall control of the Plant, while the Site Building and Plant Systems (PS) include the buildings and systems that provide power, cooling, ventilation, remote handling of components, and other essential services to the various subsystems.

The Plant Breakdown Structure (PBS) [86] contains the hierarchical organization of the Plant in different areas (PBS level 1), systems (PBS level 2), sub-systems (PBS level 3) etc. According to this classification, Remote Handling System (PBS 3.5) is a system of Site, Building and Plant Systems, and contains the sub-systems detailed in Table 1.

PBS Number						PBS Item
1	2	3	4	5	6	
1						Not used
2						Not used
3						Site, Buildings and Plant Systems
	5					Remote Handling System
		1				RH for the Plant Systems
		2				RH for the Lithium Systems
		3				RH for the Test Systems
		4				RH for the Accelerator Systems
		5				Local Instrumentation and Control Subsystem (LICS) of RH system
4						Test Systems
5						Lithium Systems (LS)
6						Accelerator Systems
7						Not used
8						Central Instrumentation and Control Systems (CICS)
	1					Not used
	2					Control, Data Access and Communication (CODAC) System
		1				Supervision & Central Control Subsystem (SCC)
		2				Timing Subsystem (TMS)
		3				Data Management Subsystem (DMS)
		4				Central Control Room Equipment and Human-Machine Interface Subsystem (CRS)
		5				Alarms & Warnings Subsystem (AWS)
		6				Control and Data Communication Subsystem (CDCS)
	3					Machine Protection System (MPS)
		1				Central Interlock Subsystem (CIS)
		2				Interlock Data Communication Subsystem (IDCS)
	4					Safety Control System (SCS)
		1				Plant Safety Subsystem (PSS)
		2				Occupational Safety Subsystem (OSS)
		3				Personnel Access Safety Subsystem (PASS)
		4				Radiation Monitoring Subsystem for the Environment and Safety (RAMSES)
		5				Safety Data Communication Subsystem (SDCS)

Table 1: DONES Plant Breakdown Structure of Remote Handling System. Levels 2 and 3 are shown only for Remote Handling and Central instrumentation and Control System.

3.1 Analysis of project inputs and needs

The operation of the IFMIF-DONES Plant must be structured to meet the material requirements for DEMO, as outlined in previous sections. Consequently, the operational schedule of IFMIF-DONES will be aligned with the International Fusion Roadmap, closely tied to the timeline of DEMO. The plant is designed with a minimum operational lifespan of 30 years, which includes at least 20 years dedicated to irradiation experiments, conducted around the clock in three shifts, 24 hours a day, 7 days a week. Furthermore, the facility aims to achieve an average operational availability of 70% annually, ensuring consistent and reliable performance throughout its lifespan. This requirement demands for the maintenance system to be as rapid as possible, as it happens in facilities like ITER[6] and in general all fusion-related facilities as discussed in [7].

3.1.1 Safety

In terms of safety, the strategy for the IFMIF-DONES project is guided by several top-level requirements:

- Worker, Public, and Environmental Protection: The facility must be designed, constructed, and operated to safeguard workers, the public, and the environment from potential hazards at all stages of the project.
- Hazard Identification and Minimization: All risks to the public and workers must be identified and reduced to levels below prescribed safety limits.
- Accident Prevention and Mitigation: Measures must be in place to prevent accidents and minimize the consequences of any abnormal events that may occur.
- Radioactive Waste Management: The project must minimize the hazards and volumes of radioactive waste produced during routine operations and decommissioning, ensuring that these levels are kept as low as reasonably achievable (ALARA).
- Decommissioning and Closure Planning: A comprehensive plan for safe decommissioning and closure must be developed from the early planning and design stages.
- Continuous Improvement: The project must incorporate feedback mechanisms to continuously improve safety by learning from both positive and negative experiences.

3.1.2 Maintenance plan

In the Maintenance Management Plan of DONES [85], the concept of maintenance is defined as:

"The Management, Control, Execution and Quality of those activities which ensures that Facilities and Process Plant and Equipment (PPE) are available in the required condition to meet the business objectives."

IFMIF-DONES must operate intensively, with a focus on maximizing radiation damage annually. This necessitates the design of highly reliable and available systems, although the inevitable degradation of components and materials requires periodic maintenance. Critical systems such as the Target Assembly and Test Modules, along with other components, will need regular maintenance to ensure optimal performance. The proposed maintenance schedule represented in Figure 25 includes a yearly cycle (green areas represent the irradiation periods) with two preventive maintenance periods: a short one of 3 days and a longer one of 20 days, with the latter primarily focusing on the Lithium and Test systems, as well as some Accelerator systems. The facility will incorporate a comprehensive Maintenance Plan that outlines strategies, schedules, and organizational frameworks for maintenance activities. Remote Handling capabilities will be essential to limit personnel exposure, particularly in areas where direct intervention would exceed administrative safety limits.

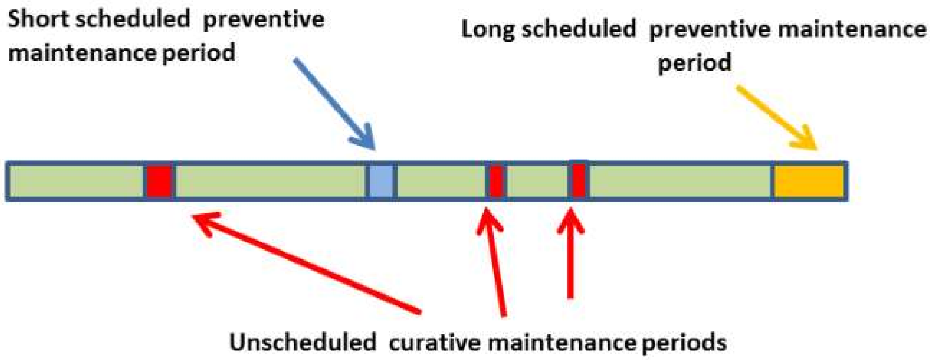


Figure 25: Scheme of the main operation scenarios along one-year irradiation[85]

The maintenance strategy for the facility gives the possibility to keep updated the preventive maintenance program and to reduce the corrective one by preventing predicted failures. Figure 26 represents the different types of maintenance that are considered, leading to cost reduction and improved reliability.

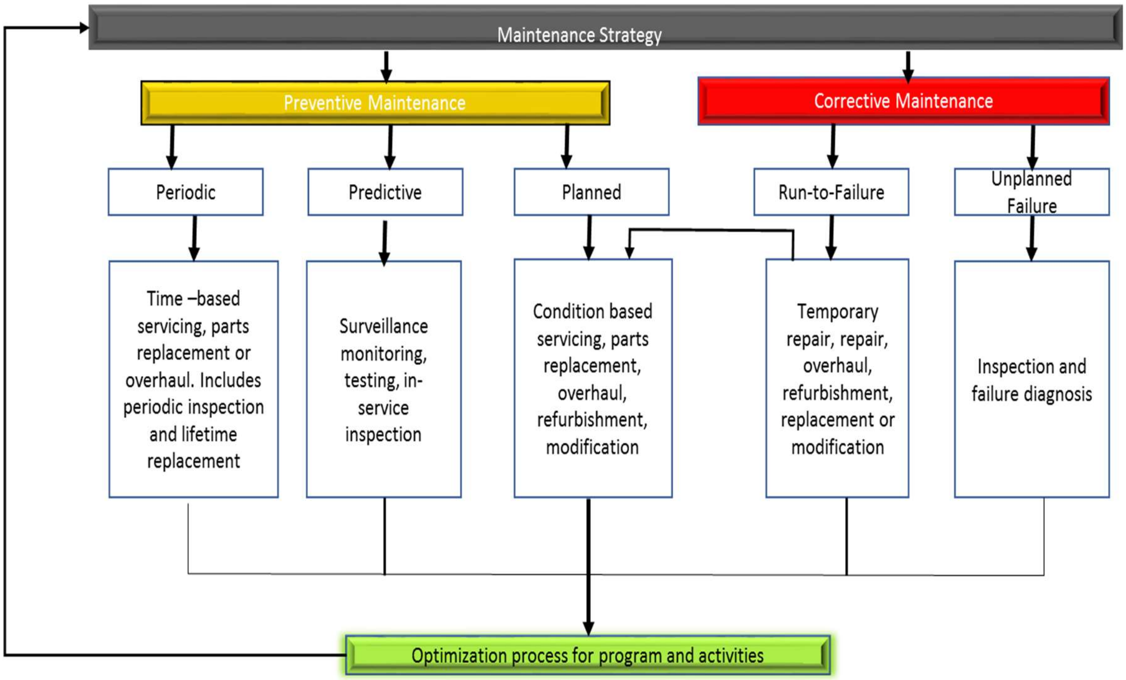


Figure 26: Maintenance strategy overview [85]. Preventive maintenance simplifies maintenance and can be scheduled to create maintenance campaigns that increase total plant time availability.

Preventive maintenance will require efficient condition monitoring to evaluate long-term equipment degradation. The goal should be to reduce corrective maintenance as much as possible, minimizing the number of unscheduled interventions and reducing the variability on the maintenance times.

From the operational perspective, the facility must consider maintenance when defining plant modes. The maintenance modes of the plant, as described by [84], have been categorized as follows:

- Long Beam Stop Planned Maintenance (LBSPM): This period, tentatively set for 20 days each year, involves major maintenance activities such as the replacement of the Target Assembly in the Lithium Systems (LS), as well as tasks in the Accelerator Systems (AS), Test Systems (TS), and Building & Plant Systems (B&PS).
- Short Beam Stop Planned Maintenance (SBSPM): Scheduled for 3 days per year, this period includes maintenance tasks such as the replacement of components like the injector disk in the AS, along with necessary activities in the TS, LS, and B&PS.
- Irradiation Compatible Planned Maintenance (ICPM): Planned to cover approximately 342 days per year, this maintenance mode includes activities across the facility that do not require the interruption of irradiation and are scheduled outside the LBSPM and SBSPM periods.

- Unplanned Maintenance (UPM): This category accounts for unforeseen maintenance needs, where the specific component requiring attention is unknown in advance, and it may or may not necessitate stopping the beam.

This structured approach ensures that maintenance is carried out efficiently while minimizing the impact on the facility's operation.

3.1.3 IFMIF-DONES Operation Modes

Plant operation is represented by Global Operational States (GOS) and Common Operational States (COS), as described in the document [87]. The former represents the plant state at the Central Instrumentation and Control System (CICS) level, while the latter represents the state at the subsystem or LICS level. Figure 27 shows how each subsystem should report its COS to the CICS, which will determine the operating mode of the plant.

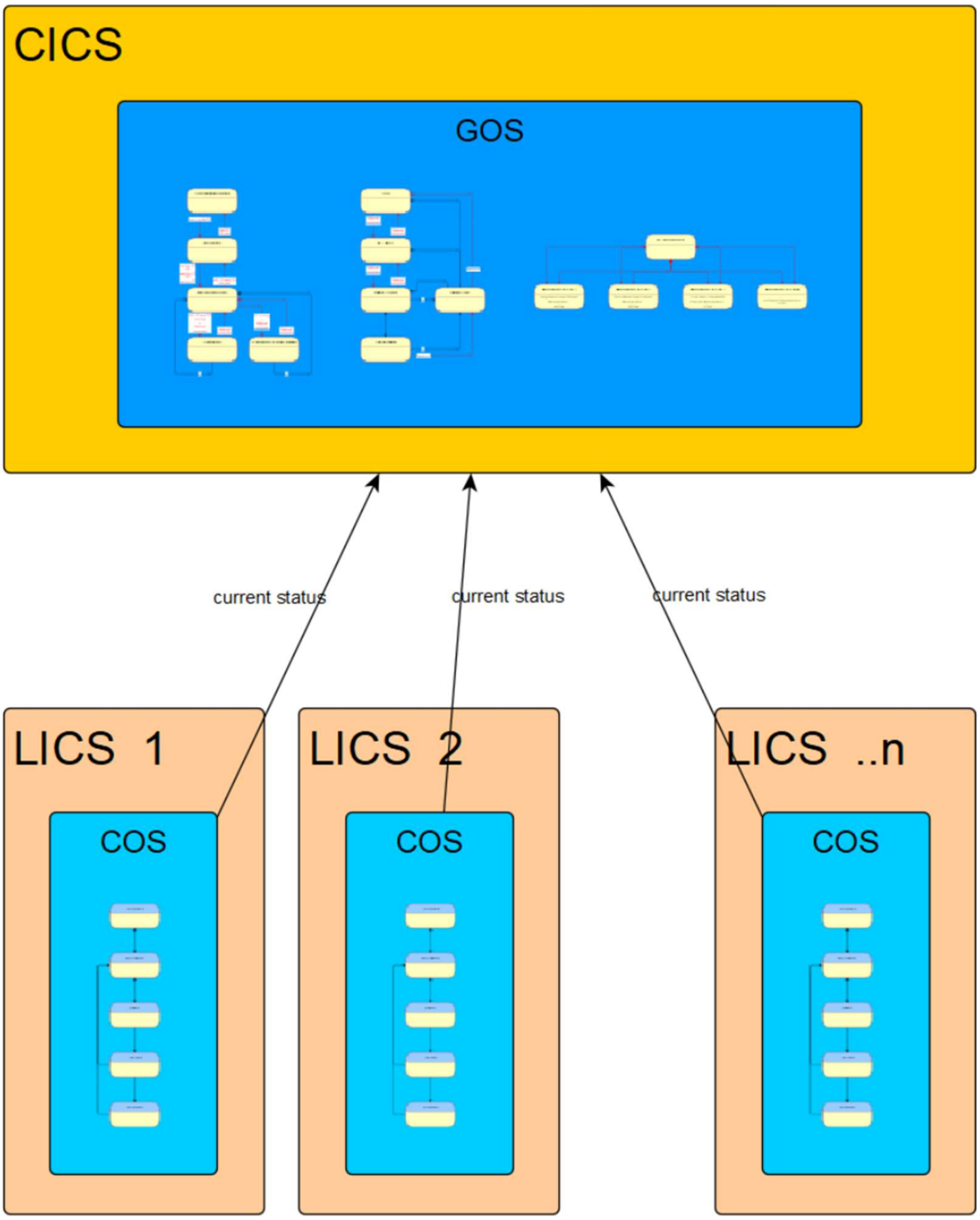


Figure 27: Simplified interaction regarding Operational States [87]. CICS defines the GOS according to the COS reported by each LICS.

The GOS is composed of three modes that provide information on: general plant status (Plant Mode), maintenance activities (Maintenance Mode) and beam status (Beam Mode). These modes are combined in different matrices that identify for each Plant Mode what kind of maintenance activities can be performed (Maintenance Mode) and in which operating mode the accelerator can be found (Beam Mode). To better understand the RH processes, we will take a look at the Maintenance Mode, described in Table 2 :

Maintenance Mode Name	Description
NO MAINTENANCE	No maintenance operations in progress
MAINTENANCE TYPE 1 (LBSPM)	Long period of time established for planned maintenance operations
MAINTENANCE TYPE 2 (SBSPM)	Short period of time established for planned maintenance operations
MAINTENANCE TYPE 3 (ICPM)	Planned maintenance operations compatible during IRRADIATION
MAINTENANCE TYPE 4 (UPM)	Maintenance operations unplanned

Table 2: Maintenance Modes description

Each mode will serve to identify the status of the rest of the plant's systems, allowing the RH LICS to know their operating status without having direct visibility of them and maintaining the philosophy imposed by the CICS. In this way, from the RH Control Room it will be possible to know which components are in operation and which are stopped and ready for maintenance.

3.1.4 Remote maintenance categories

The system responsible owner and the safety manager must define the requirements in terms of RH for the components considering different factors such as activation levels, criticality of the component or condition monitoring capabilities. The RH categorization as described in the Maintenance Management Plan is below:

- RH 1: components requiring regular planned replacement
- RH 2: components that are likely to require repair or replacement
- RH 3: 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 4: components that do not require remote handling

According to the previous definitions, Table 3 shows some example of relevant components extracted from DONES Maintenance Matrix [85].

System	Components	Zone	Zone Classification	Maintenance Freq., yrs.	RH Class	Strategy
Lithium System	Target assembly	Test Cell	Prohibited	2	1	Conservative
	FDSs	Test Cell	Prohibited	Not planned	3	Progressive
	Valves	Lithium loop	Restricted	Not planned	2	Conservative
Test System	High Flux Test Module (HFTM)	Test Cell	Prohibited	2	1	Conservative
	PCPs	Test Cell	Prohibited	Non-scheduled	3	Progressive
Accelerator System	High Flux Test Module (HFTM)	Test Cell	Prohibited	2	1	Conservative
	Vacuum pumps	Target Interface Room	Restricted	Few years	1	Conservative
	Isolation valves	Target Interface Room	Restricted	Not planned	3	Progressive

Table 3: Examples of component RH classification from DONES Maintenance Matrix [85]

3.1.5 Components to be manipulated via RH

The main components requiring RH have been identified and classified by the project. This activity has been crucial to study weights and sizes, that will impose the design requirements for the different RH devices. However, this process is bidirectional, and in some cases the component to be manipulated shall be adapted to the capabilities of the existing RH devices. Designers of DONES systems must take into account the feedback from the RH team, adapting the design to fulfill RH needs.

This approach is essential to achieving good RH capabilities, especially in terms of mechanical interfaces and payloads. Table 4 shows some of the main components requiring RH, and its main characteristics:

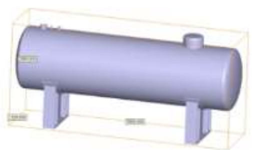
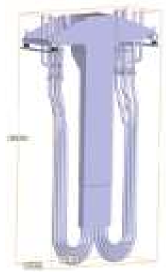
Component	Zone	Weights and size of component	Picture
Target assembly	TC (LS)	Weight 0.87 t 1.83m x 2.38m x 2.16m	
Dump tank	Li loop area (LS)	Weight (Unknown) 1.53 m x 5.55 m + 2.55	
Upper Top Shielding Plugs	Test Cell (TS)	Weight Max 120 t 5.657m x 4.465 m x 1.250m	
High Flux Test Module (TM)	Test Cell (TS)	Weight <1t 1.700 m x 0.635 m x 2.850 m	

Table 4: Examples of component manipulated via RH

3.1.6 RH functions

The missions of the IFMIF-DONES Remote Handling System are described in [84] as below:

- To protect workers from ionizing radiation during maintenance of activated components, by providing and operating a system of remotely operated tools, equipment and procedures to be used inside the plant.
- To contribute to maintenance planning for those components that require remote maintenance.
- To provide and operate the necessary equipment to support hands-on installation of components.

The Remote Handling Design Description Document [88] collects some of the main functions expected of the system, which is summarized on Table 5:

Function	Comment
MF1 Replace HFTM and TA	Exchange of High Flux Test Module in the Test Cell once the irradiation campaign is completed.
MF2 Refurbish Target System	Replacing mechanical clamps of the TS
MF3 Refurbish Impurity Control System	Inspection and replacement of hot and cold traps of LS
MF4 Refurbish Heat Removal System	Inspection and replacement of Primary Heat Exchanger of LS
MF5 Refurbish Target Interface Room	Inspection and replacement of vacuum lines, beam pipes, valves and diagnostic components
MF6 Refurbish Radiation Interface Room	Inspection and replacement of vacuum lines, beam pipes, valves, steering magnets and diagnostic components
MF7 Refurbish Beam Dump	Inspection and replacement of cartridge
MF8 Installation during commissioning	Support installation of DONES systems, specially for heavy components
MF9 Decommissioning after facility shutdown	Processing and dismantling activated parts of the facility after final plant shutdown
MF10 Testing components	Support execution of acceptance tests on installed components

Table 5: Main functions of RH system in DONES

3.1.7 RH Equipment

This section aims to provide an overview of the main RH equipment that has been designed until now for DONES. This is an ongoing work, and not all the equipment displayed on the PBS [Table 1] has been designed yet. The equipment introduced here have been extracted from the Remote Handling Design Description Document of DONES [88].

3.1.7.1 Cranes

The RH operations inside the Test Cell will be carried out by two cranes. These two pieces of equipment are fundamental parts of the RH systems, due to their high load capacity, precision and the fact that they will serve as a transport platform for other equipment.

The Heavy Ropes Overhead Crane (HROC) is the RH device with the highest payload in the DONES facility (140 tons). It's main purpose is to lift the plugs that are sealing the Test Cell during irradiation. It has 6 DOF, and a positional accuracy of 5mm on XY and 1mm on Z. Figure 28 provides the 3D view of the HROC:

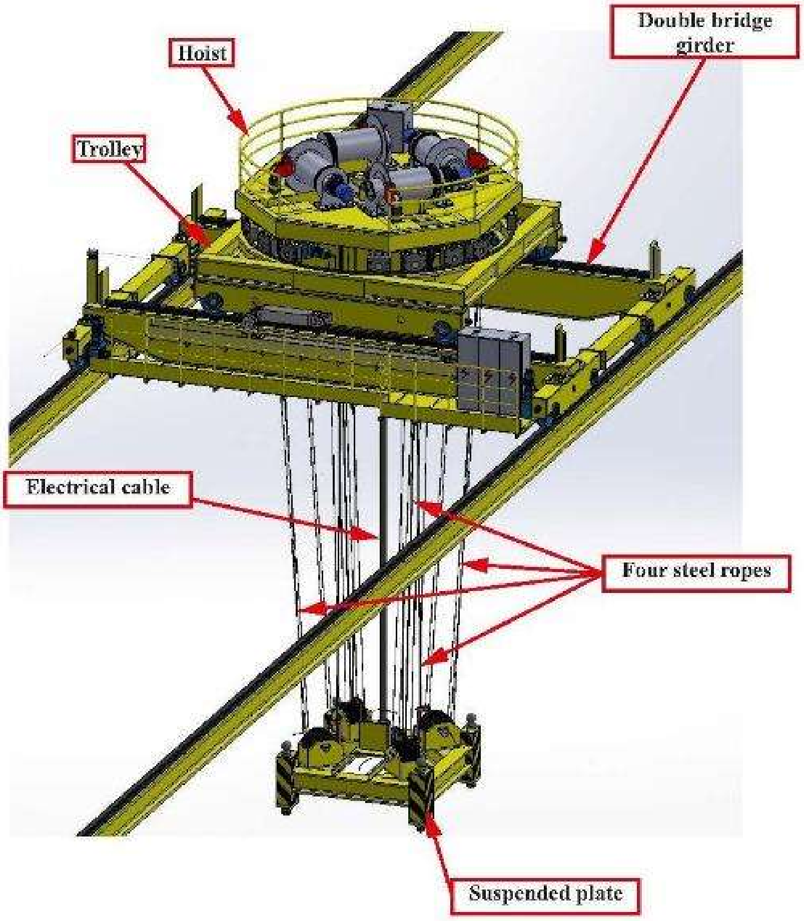


Figure 28: 3D View of the HROC and its main components [88].

The ACMC is a nuclear grade triple beam overhead crane equipped with a telescopic mast (Figure 29). The payload at the end of the boom is 2 tons, and the positional accuracy will be 10mm. It will cover the entire Access Cell layout (52,71 x 20 x 15 m), ensuring that the boom can reach the bottom of the Test Cell.

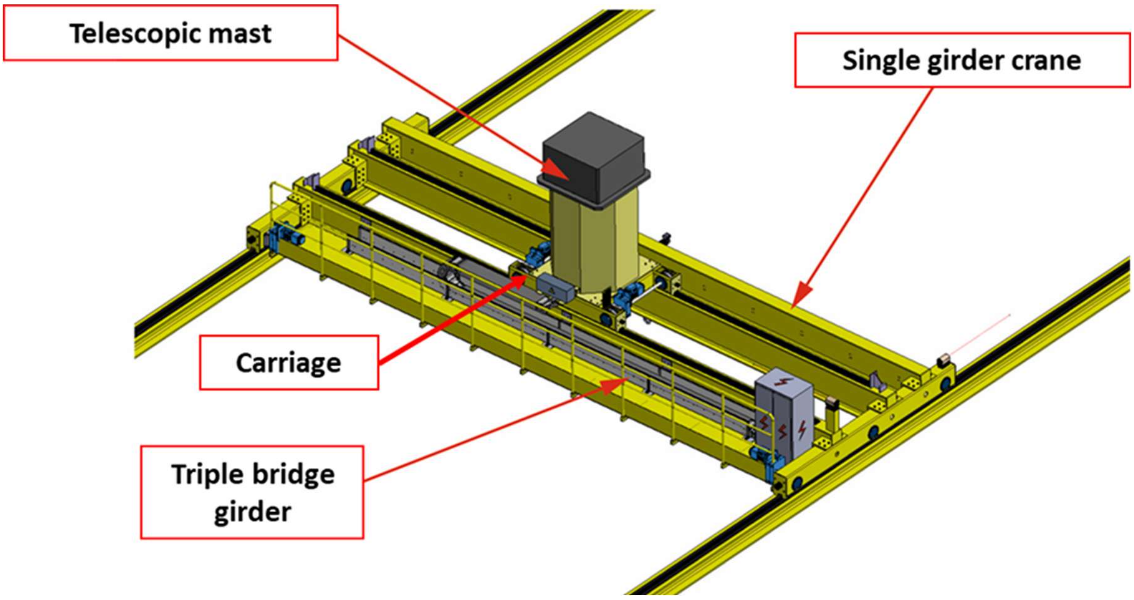


Figure 29: 3D View of the ACMC and its main components [88].

It will be installed in the Access Cell to support and locate manipulators at the correct position in the TC and therefore allowing the RH operations carried out by that servomanipulator. The telescopic mast is equipped with a Gripper Change System (GCS) to allow connection of different end effectors including a Mast Grapple for vertical handling of components up to 2 tons. Figure 30 show the different interfaces with other robotic systems (Robotic Arm and Parallel Kinematic Manipulator), support structures and tooling.

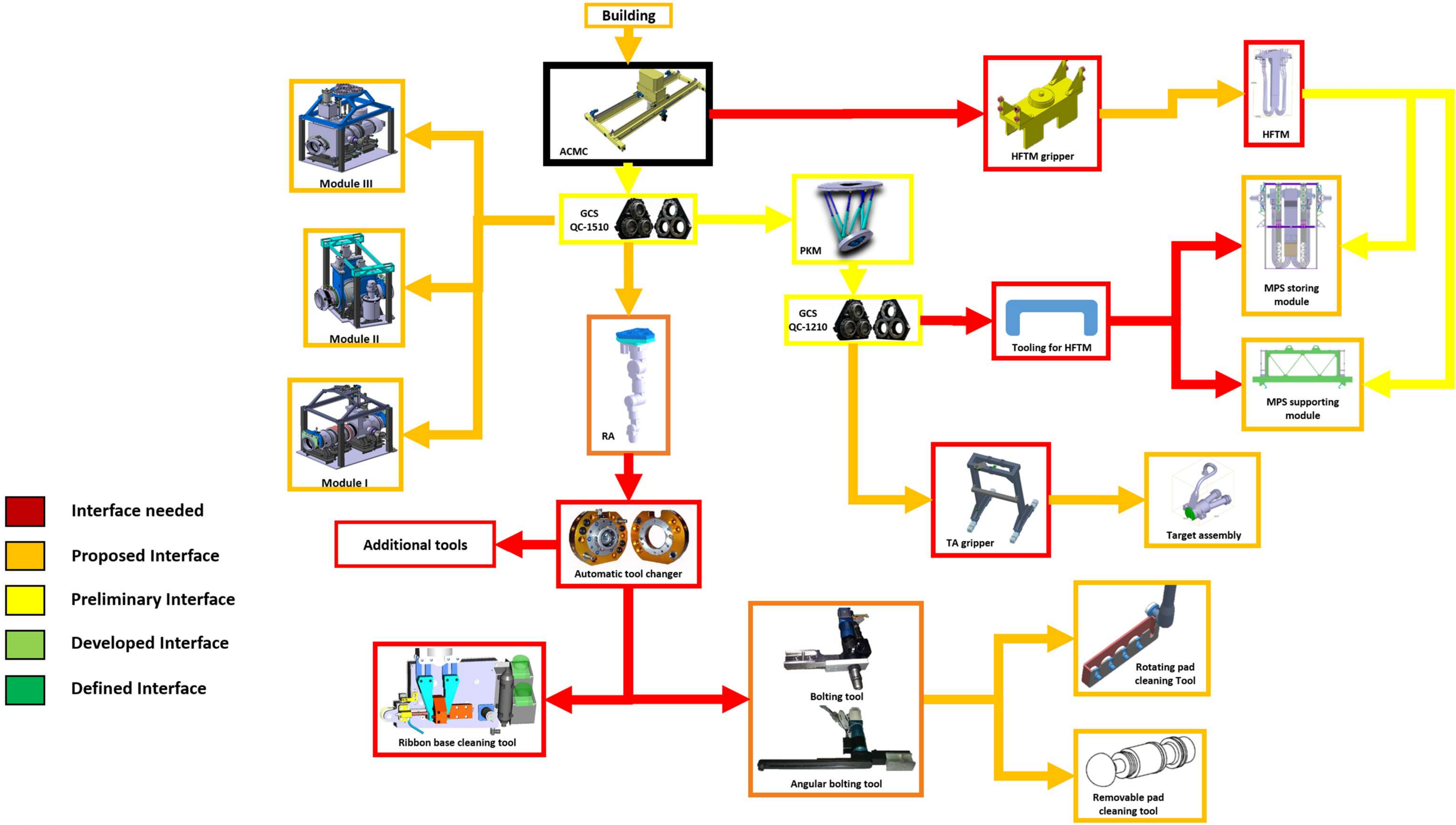


Figure 30: ACMC interfaces with different tools and support structures to manipulate heavy components [88].

3.1.7.2 Robotic devices

One of the devices foreseen to perform support intervention in the DONES test cell is a seven DOF tele-manipulator. It will be based on an industrial robotic arm, but some of the components will be modified to withstand the conditions on the irradiation zone. The system will be composed of three parts: the slave (robotic arm) attached to the ACMC, the controller (outside the radiation area), and the master (haptic device) in the RH Control Room.

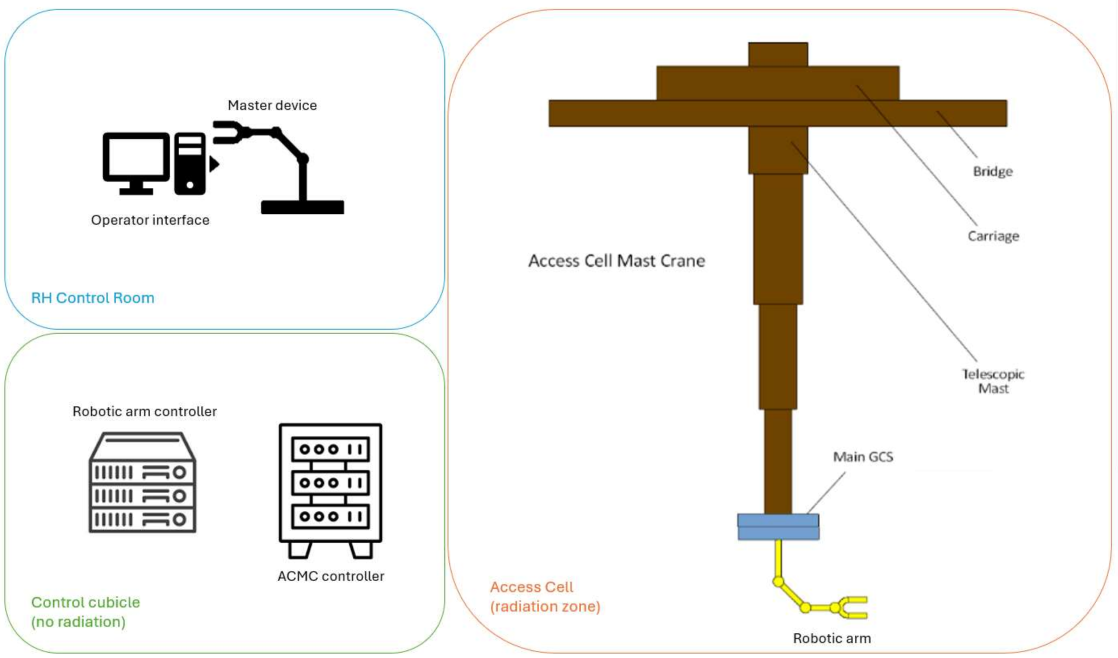


Figure 31: Diagram of tele manipulator attached to ACMC and its components. The device inside the radiation zone, but the control electronics are located on a different room protected from radiation.

The selection of an input device that is well-suited to the tasks to be performed constitutes a critical aspect. In Section 2.5, a presentation was given of several of the most common alternatives that can be found in RH control rooms. In this case, for the control of a telemanipulator, the most common solution is to use a haptic device that possesses the same degrees of freedom as the robotic arm to be controlled. The master-slave design of a telemanipulator can be of two types according to the mechanical structure:

- Isomorphic: both devices have the same morphology, mapping the movements of each joint and making direct and inverse kinematics simpler.
- Heterogeneous: the morphology of master and slave device are not the same, which means that the master device will be used as a joystick to control the Tool Center Point (TCP) of the slave. The control algorithm is complicated and the forward and inverse solution of kinematics and dynamics need to be converted.

In Figure 31 the master-slave telemanipulator have an isomorphic configuration, allowing precise control on the robotic arm posture to avoid possible collision on narrow spaces with many collision points (e.g., when moving the RA between pipes).

Other example is the Parallel Kinematic Manipulator (PKM), which could be controlled using a heterogeneous configuration. This device will be used mainly for the positioning of components inside the Test Cell with precision of 1mm. In this situation will be easier for the operator to control the TCP using the master device as a joystick. The robotic device will be attached to the ACMC using the GCS, and will be capable of handling components up to 2 tons. The CAD design of the component is shown in Figure 32.

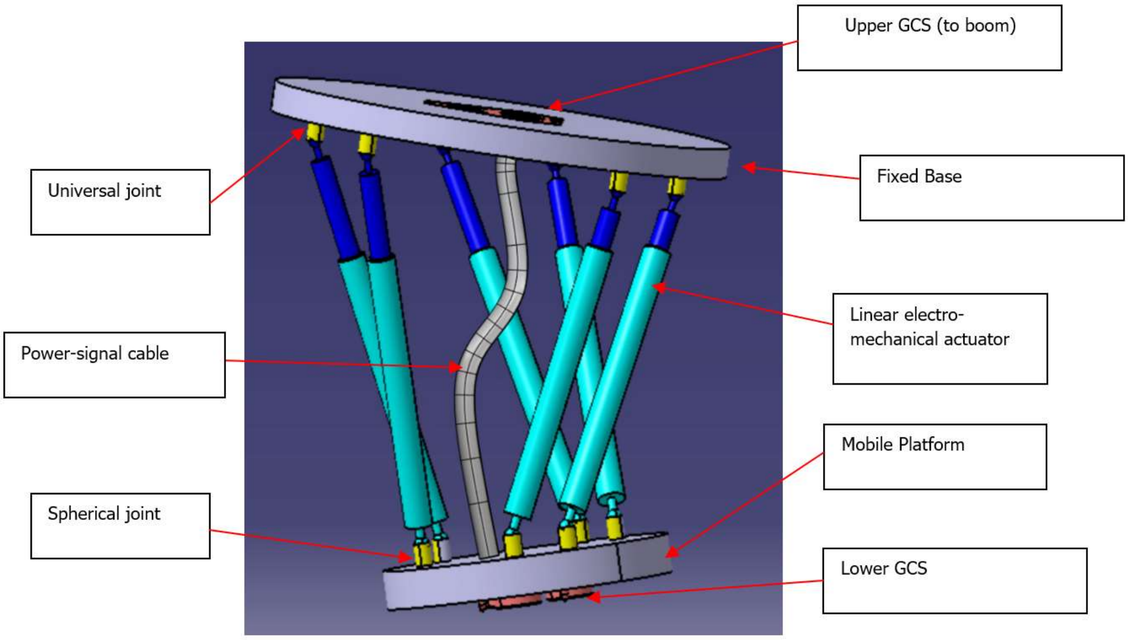


Figure 32: 3D view of PKM and main components [88].

3.1.7.3 Tooling

Finally, it is worth mentioning the use of tools coupled to the telemanipulators by means of automatic exchangers. These exchangers, like the GCS, allow to mechanically couple two devices and to pass electrical, hydraulic or pneumatic connections between them. Among the tools to be highlighted are the boolting tool, the cleaning tools and grippers. Figure 33 shows as example the intefaces and possible configurations for the tooling of the robotic arm attached to the ACMC.

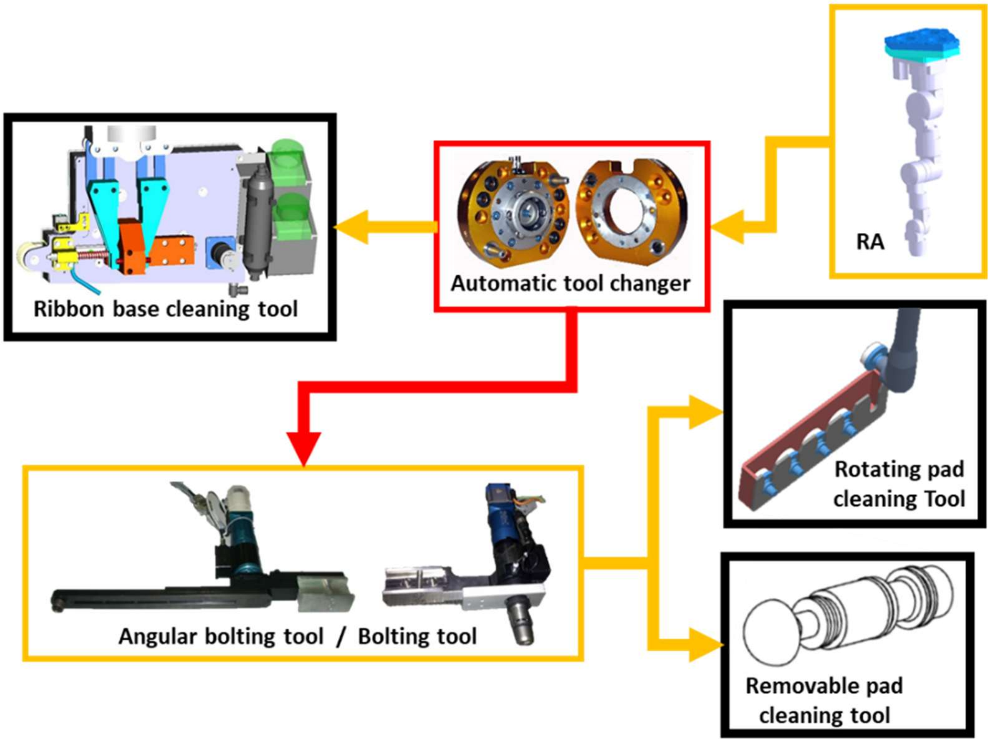


Figure 33: Interfaces for tooling for the ACMC RA [88].

3.2 RH System requirements

The Remote Handling System (RHS), and the different Remote Handling Equipment (RHE) of IFMIF-DONES has been designed on the basis of the following general requirements described on [84]:

Req. ID	Description
RHS1	RHS shall be capable of performing all the required RH operations and procedures foreseen in the DONES maintenance plan (MMP)
RHS2	RHS shall be capable of fulfilling the maintenance schedule of DONES
RHS3	RHS shall be conceived and designed for safe, prompt and feasible recovery and rescue.
RHS4	RHS shall be integrated with the general standards (control system*, communication network, interfaces, control panel, etc.) of other DONES systems.
RHS5	RHE shall be flexible enough to cope with reasonable upgrades of the facility.

Req. ID	Description
RHS6	The cost of RHE must be acceptable, but a balance must be found between the increased cost and the possibility of facility upgrades.
RHS7	RHE and tooling will perform maintenance tasks in a high activated environment and then they must be designed to ensure their performances for at least one fully maintenance cycle. Use of Rad Hard components is mandatory.
RHS8	RHE must be designed for easy decontamination and maintenance
RHS9	RHE must be designed to perform the maintenance tasks within a set time limits.

Table 6: Remote Handling System top level requirements as described in [84]

These requirements from Table 6 are the starting point for the definition of the RHCS of IFMIF-DONES. Analyzing this input requirements, there is one affecting the definition of the RHCS (RHS4) where the control system is explicitly mentioned. The requirement imposes that the RHCS must follow the plant standards in terms of control systems (* that can be understood as the use of the same control framework), networks, control panels… However, the general approach described by the CICS at [89] focus on the control of the accelerator and other distributed instrumentation does not seems adequate for the RHCS, making it necessary to develop a specialized local control architecture under the coordination and supervision of the CICS.

3.2.1 CICS and LICS

IFMIF-DONES Project has selected to adopt a distributed control approach as described by [89]. The Instrumentation and Control (I&C) System follows a hierarchical structure, starting with the Central Instrumentation and Control Systems (CICS) at the top, down to the LICS. Each LICS will be an autonomous system that will manage its own control loops (fine-grained control), but at the same time will be supervised and controlled (coarse-grained control) from the CICS. The basic structure of DONES I&C System is described in Figure 34.

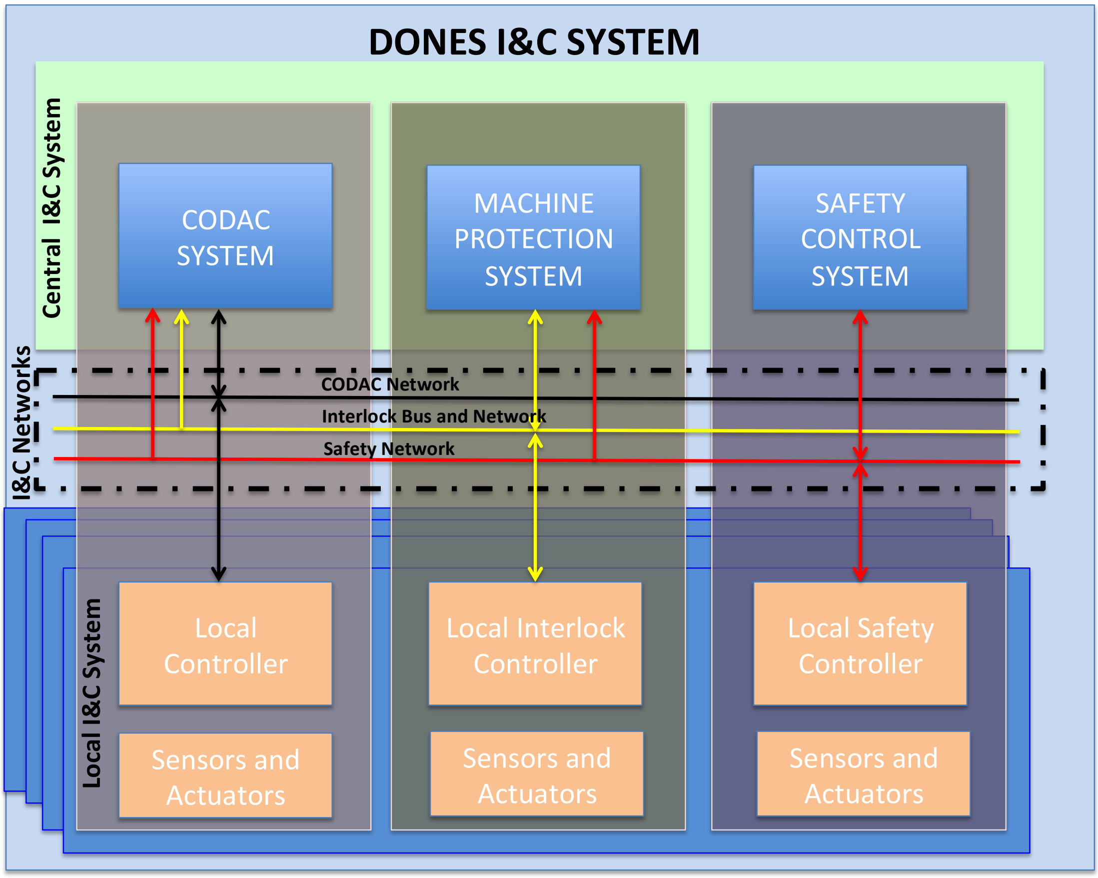


Figure 34: DONES I&C System. CICS is on top controlling the different LICS of the plant. [89]

The CICS is composed of three systems: The CODAC is responsible for coordinating plant systems, The Machine Protection System (MPS) is responsible for implementing all investment protection strategies, and The Safety Control System (SCS) provides protection functions relating to personnel or the environment. Each of these systems has dedicated networks and buses that interconnect them with different LICS, which must replicate this functional separation in three layers. More details about IFMIF-DONES Diagnostics and Control Systems can be found in [90].

There are some proposals about the technologies to be used for each of these systems, even though it is not a final decision and the tendencies could change. For the MPS the latest proposal is based on WINCC OA on top of Siemens PLCs. The SCS requires fastest reaction times, so will use CompactRIO and custom FPGA solutions. For CODAC, the proposal is to implement a soft real-time distributed control system based on EPICS (Experimental Physics and Industrial Control System) framework (for more details go to 2.3.1).

3.2.2 RH Local Instrumentation and Contol System

As a starting point for the logical design of the RH control system, the IFMIF-DONES project defined in [91] a base architecture inspired by similar installations.

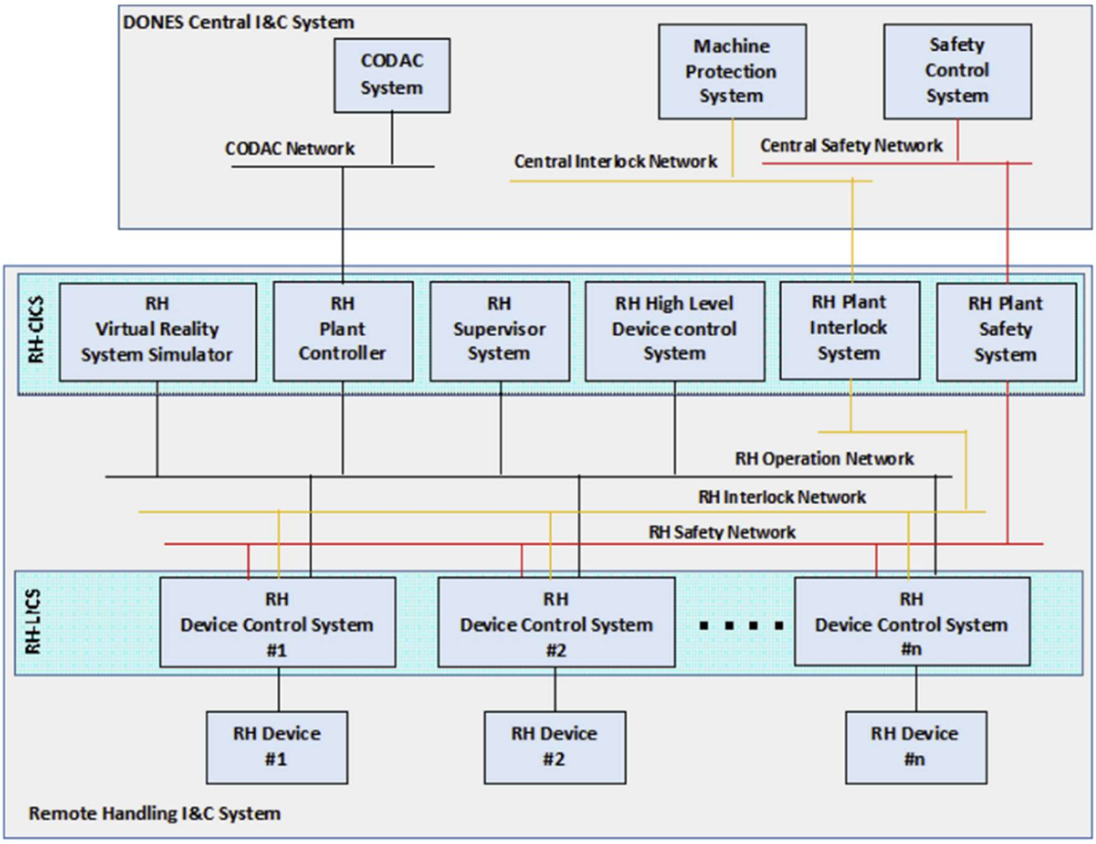


Figure 35: Preliminary definition of DONES RHCS Architecture [91]. Defines 3 vertical layers to match Central I&C, and 2 horizontal layers to implement a set of common RH functions (RH CICS) and local control of the devices (RH LICS).

The design established a separation into three vertical layers (Operation, Interlocks, and Safety) and three horizontal layers (DONES Central I&C, RH Central I&C, RH Local I&C). Three networks were also established to provide support to each of the aforementioned vertical layers, with each network corresponding to a respective vertical layer as previously delineated by CICS, as illustrated in Figure 35. The architectural approach employed in this design features six logical blocks (which serve to map the principal functionalities of the RH system): Virtual Reality, Plant Controller, Supervisor, High Level Device control System, Plant Interlock and Plant Safety.

However, this preliminary design was presented years ago and there are many updates on the design that were not foreseen at that time. The following chapters provide an updated and improved design of the Remote Handling Control System, which is the main contribution of this thesis.

Chapter 4
Reference Architecture for the Remote Handling Control System at IFMIF-DONES

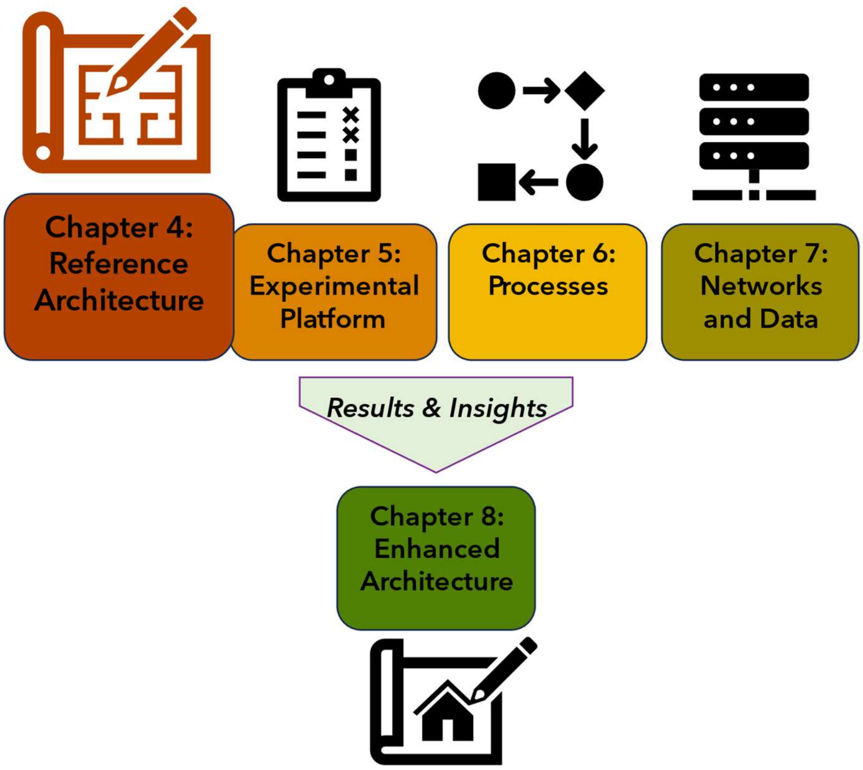
The work presented in this chapter represents the core of my **contributions to the WPENS** project over the past years and forms a pivotal part of this thesis. This chapter undertakes a detailed analysis and review, elucidating the unique challenges associated with designing a RH Control System for a fusion-related facility and introducing an enhanced modular architecture tailored to meet these requirements.

The **logical architecture** defined herein introduces specialized **modules, networks, and candidate technologies** to allow seamless integration of **heterogeneous RH devices into a common control framework** operated from a **dedicated control room**. These innovations ensure semantic interoperability, robust planning capabilities, and advanced operator interfaces, setting a new **industrial-based approach for RH systems in radiation environments**. Building on the foundational concepts and top-level requirements gathered from previous chapters, this chapter translates theoretical frameworks into feasible design solutions.

The proposed architecture defines two distinct levels within the RH control framework: the **High-Level Control System (HLCS)** and the **Low-Level Control System (LLCS)**. This logical separation enables clear distinctions between the functionalities managed at the device level and those overseen by central control. Core elements, such as OPC UA for standardized communication, advanced human-machine interfaces for operator interaction, and specialized modules ensure seamless interoperability and operational efficiency.

By outlining a detailed structure for the RHCS, including control room layouts and network configurations, this chapter lays the foundation for scalable and resource-efficient systems, addressing both current requirements and future adaptability.

4 Reference Architecture for the Remote Handling Control System at IFMIF-DONES



From this point onward, the chapter presents ideas and conclusions that constitute key contributions of this thesis. These insights build on the previous analysis of project needs, providing a deeper understanding of the challenges and proposing adequate solutions that ensure the suitability of the control architecture.

4.1 CICS and RHCS, two different control systems

The differences between CICS and RHCS have been analyzed as part of the work associated with this PhD on [62]. Mechatronic systems designed for remote manipulation tasks exhibit significant differences in control requirements compared to the other subsystems managed by the Central Instrumentation and Control Systems (CICS). In the context of CICS, the devices being controlled primarily consist of scientific instrumentation intended to gather data in a coordinated manner, along with industrial systems (typically programmable logic controllers, or PLCs) that execute automated control strategies. In this framework, control system engineers define system behavior based on events that trigger actions in a predetermined sequence, while operators engage by setting parameters and initiating specific events. As a result, operator interaction with the system occurs through discrete events that activate automated sequences, requiring operators primarily to configure setup points and parameters, with most actions being fully automated.

In contrast, the operation of RH devices necessitates that the operator is an integral part of the control loop. These devices function as remote tools that are either controlled or supervised by operators. This "man-in-the-loop" approach means that operators may assume real-time control of devices through haptic devices, or at the very least, actively supervise automated tasks due to the critical nature of the operating environment. The implementation of robotic systems necessitates additional features not addressed by CICS, which is based on the Experimental Physics and Industrial Control System (EPICS) framework for scientific instrumentation. These features include visual guidance, virtual reality environments, haptic feedback, motion planning, and the ability to teach poses. Consequently, this leads to the development of a control framework tailored for mechatronic systems that are closely integrated with human interaction. In this setup, CICS will manage coarse-grained control tasks (such as system coordination at the plant level), while the LICS for remote handling will focus on fine-grained control (the operation of RH devices).

4.2 A special LICS

The core of the DONES CICS is the CODAC system, which oversees and coordinates the various plant systems. Currently, this system is based on the EPICS control framework. According to the general approach outlined for DONES subsystems in [90], CODAC is responsible for several key functions:

- Overall monitoring of the LICS.
- Downloading configuration parameters to the LICS.
- Performing manual operations.
- Conducting diagnostics.
- Executing automated sequences.

However, the RH LICS will be an exception to this general approach due to the limitations of EPICS in controlling such specialized devices. The RH LICS must be considered a semi-autonomous system with a high degree of independence from the rest of the DONES facility. The primary reasons for this include:

- Remote Handling devices are complex mechatronic systems.
- Tasks in RH operations are not always repetitive, making it challenging to apply fully automated sequences due to the continuous need for human interaction and supervision.
- RH operations refers a broader process composed of different RH tasks.

- These mechatronic systems require advanced control strategies, including kinematics, pose estimation, and collision avoidance.
- RH equipment must be specifically designed for recoverability.
- The mechatronic systems used in RH tasks often require specialized interfaces, such as 3D joysticks, master arms, and haptic devices, to enable real-time control by the operator.
- RH operations will be conducted from a dedicated control room, where the coordination of various subsystems will be organized into work cells, facilitating operator interaction for complex tasks.
- Visual interaction is crucial for manipulation and maintenance tasks.

Given these requirements, it is proposed to design an RH LICS with the specific functionalities necessary to meet these unique challenges [62].

4.3 RHCS Requirements

Considering all the previously discussed considerations, a set of top-level requirements for the RH Control System has been collected in Table 7. This is an ongoing work, since much of the RH equipment and procedures are not completely defined yet. Therefore, we have tried to collect those requirements that apply to functionalities and concepts without going into specific technological proposals.

Req. ID	Description
RHCS1	RHCS shall be operated from a dedicated RH Control Room (RHCR)
RHCS2	RHCS shall follow the human-in-the-loop (HITL) approach for all RH devices, never allowing total automation for safety.
RHCS3	RHCS shall provide adequate HMI to all devices. The use of special input devices such as 3D joysticks, master arms, or haptic controllers must be considered when possible and needed.
RHCS4	RHCS must be flexible enough to perform scheduled and unscheduled RH operations.
RHCS5	RHCS shall integrate a wide range of controllers from RH equipment (PLCs, motion controllers, robotic controllers…).
RHCS6	RHCS shall be responsible for providing the necessary resources to operate remote tools/equipment and follow maintenance procedures, contribuying to maintenance planning and providing the needed logics and tools to successfully proceed.
RHCS7	RHCS logical structure shall be divided into two internal levels: HLCS and LLCS.
RHCS8	The LLCS shall contain all the device cubicles with the electronics dedicated to control RH devices and tooling.

Req. ID	Description
RHCS9	The HLCS shall contain servers and software tools to provide all the required functionalities required from the RH Control Room.
RHCS10	The standard interface and data format used to connect the HLCS and the LLCS shall be OPC UA.
RHCS11	The RHCS shall make use of four internal networks: RH User Network, RH Operational Network, RH Real-Time Network and the RH Video Network.
RHCS12	The RH User Network shall connect to HLCS modules and RHCR workstations.
RHCS13	The RH Operational Network shall be used by HLCS modules to communicate with LLCS modules using OPC UA interfaces.
RHCS14	The RH Real-Time Network shall connect haptic/master/hardware devices used by RH Operators with the specific RH devices and tools.
RHCS15	The RH Video Network shall connect HLCS "Viewing System" with the RH User Network and with the Central Video Network.
RHCS16	The RH HLCS shall include nine modules: Plant Controller, Supervision System, Command and Control, VR System, Condition Engine, Viewing System, Engineering Tools, RH Safety and RH Interlock.
RHCS17	The "Supervision System" shall be responsible for managing RH maintenance campaigns, RH user accounts, parallel/secuencial operations, teaching/executing automated sequences, RH inventory, as well as gathering feedback from the RH Operators and offering planning-related GUI.
RHCS18	The "Viewing System" shall be responsible for controlling the RH video streams, the PTZ operations on the video cameras, and converting video analog signals into video digital signals.
RHCS19	The "Command and Control" shall be responsible for recording relevant variable values, storing and offering RH devices' GUI control panels, and running the SCADA engine.
RHCS20	All RHCR workstations shall have access to video streams.
RHCS21	The "VR System" shall be responsible for storing and offering 3D virtual environments, as well as for generating synthetic data when it is needed (offline simulations).

Req. ID	Description
RHCS22	The "Condition Engine" shall oversee controlling all conditions required to perform a RH operation and reporting RH status to the CICS.
RHCS23	The "Plant Controller " shall be the gateway between the CICS and the RH LICS, for operational data and for timing.
RHCS24	The "Engineering Tools" shall host centralised engineering tools for programming, diagnose and maintain devices.
RHCS25	Inside each RH device cubicle (LLCS) there shall be several modules/drivers to fulfil de following functionalities: Cubicle Monitorization, Device Controller, Protection Module, Sensor Drivers, Actuator drivers, Tools Controllers and a Power Distribution.
RHCS26	The Protection Module shall enable device actuators only if Emergency Stop, MPS and SCS signals are correct.
RHCS27	Communications inside cubicles (module to module) shall use standard industrial fieldbuses (ProfiNET, EtherCAT...)
RHCS28	The cubicles that cannot implement an OPC UA server shall be connected to the "OPC UA Aggregation Server" to be properly interfaced from HLCS using the standard data format.
RHCS29	The RHCS "OPC UA Aggregation Server" shall be the interface between LLCS and HLCS, managing all LLCS signals introducing a maximum delay of X ms [TBD]
RHCS30	The RHCS shall have a module to connect all the RH cubicles with the MPS Network: the "RH Interlock System (Header PLC)".
RHCS31	The "RH Interlock System (Header PLC)" shall be connected with all the RH devices cubicles through the "Protection System" module.
RHCS32	The "RH Interlock System (Header PLC)" shall coordinate the machine protection actions at LICS level.
RHCS33	The RHCS shall have a module to connect all the RH cubicles with the SCS Network: the "RH Safety System (Header PLC)".
RHCS34	The "RH Safety System (Header PLC)" shall be connected with all the RH devices cubicles through the "Protection System" module.

Req. ID	Description
RHCS35	The "RH Safety System (Header PLC)" shall coordinate the workers/environment protective actions at LICS level.
RHCS36	RHCS must interface with CICS and its architecture must conform to the three-tier I&C system (CODAC System, Interlock Control System, Safety Control System).
RHCS37	RHCS must support the parallel operation of different devices in different areas to optimize time consumption.
RHCS38	The RH System is a system of systems and should be flexible enough to deal with reasonable upgrades to the facility.
RHCS39	The RH network infrastructure must allow multiple traffic profiles.
RHCS40	The RH network infrastructure must provide real-time capabilities to haptic controlled devices.
RHCS41	The RH network infrastructure must provide high-bandwith to stream video signals from the Viewing System.
RHCS42	The RH network infrastructure must ensure deterministic behavior, guaranteeing that all time-critical data is delivered within predefined latency bounds regardless of network load.

Table 7: RH Control System top-level requirements

4.4 Reference architecture and modules of the RHCS

The RHCS architecture shall follow the reference of the considered reference facility ITER as described in [59], given the similar functional requirements of both facilities in terms of RH capabilities. However, there are important differences in scale that impact not only the facility itself but also the overall project strategy:

- Complexity of the Machine: ITER is a more intricate installation compared to DONES , as can be observe on the analysis of both projects done in [64] and [92]. ITER requires a larger number of RH devices, many of which have been custom-designed. In contrast, most of the devices for DONES have been adapted from existing industrial solutions for use in radiation-activated environments. This simplifies the development of control logic for DONES by relying on Commercial Off-The-Shelf (COTS) controllers and leveraging familiar, agile commercial tools for control strategy development.

- Resource Availability: The ITER Organization possesses substantial financial resources and a large workforce capable of developing new technologies. DONES, however, operates with more limited resources. Consequently, the design of the DONES RHCS shall prioritize minimizing integration and development efforts by utilizing standard industrial technologies.
- In-Kind Contributions: RH devices for DONES will be contributed by various countries involved in the project as in-kind contributions. While ITER's approach involves the adoption of cutting-edge technologies and tools, which are currently known by only a limited number of experts, this approach could introduce additional challenges. Adapting these technologies before commissioning would require either a specialized in-house engineering team or outsourcing to external companies.

Given these considerations extracted from [62], the decision has been made to adapt the ITER control architecture to provide similar functionality and structure, but with a focus on using industrial standard technologies and components, allowing to reduce complexity and development efforts. This approach is more cost-effective and better suited to the available resources for IFMIF-DONES project.

4.4.1 Control framework selection

In the current phase of this work, two control frameworks have been identified from the candidates analyzed in Section 2.3 and summarized in Table 8 as the most suitable for application in IFMIF-DONES: OPC UA and ROS2. Both frameworks originate from open-source communities, are integrated into commercial solutions, and have reached a medium-high level of maturity. Given the estimated timeline of five to ten years between the writing of this thesis and the commissioning of the control system, these technologies are expected to continue evolving. At this stage, OPC UA is considered crucial to provide a standardized interface for RH devices, offering reliable interoperability and integration with the broader system. However, the potential incorporation of ROS2 has not yet been fully explored in detail. The possibility of leveraging ROS2 within the "Condition Engine" module, or elsewhere in the RH system, remains open for future consideration. This topic will be discussed further in Chapter 8, where the suitability of ROS2 for specific RH operations and its potential benefits will be examined.Although options such as GENROBOT and CORTEX are clearly focused on the specific use case for RH control systems, it is to be expected that their development will be slower due to the limited scope of their application and their proprietary development philosophy.

CONTROL FRAMEWORK	OPEN SOURCE	DEV. LANGUAGE	REAL-TIME	MATURITY	COTS
EPICS	*Yes*	*C, C++, Python, Java*	*Yes*	*Medium*	*No*
GENROBOT	*No*	*C, C++, Python*	*Yes*	*Low*	*No*
SIEMENS	*No*	*LAD, ST, FBD, STL, SCL*	*Yes*	*High*	*Yes*
ROS2	*Yes*	*C++, Python*	*Yes*	*Medium*	*Yes*
OPC UA	*Yes*	*C, C++, Python, Java, C#*	*Yes*	*High*	*Yes*
CORTEX	*No*	*C++*	*Yes*	*Low*	*No*

Table 8: Candidate control frameworks summary

4.4.2 Remote Handling Control System Architecture

Taking this design as a baseline, and according to the specifications outlined in Table 7 and all the previously discussed topics, the reference architecture depicted in Figure 36 has been developed.

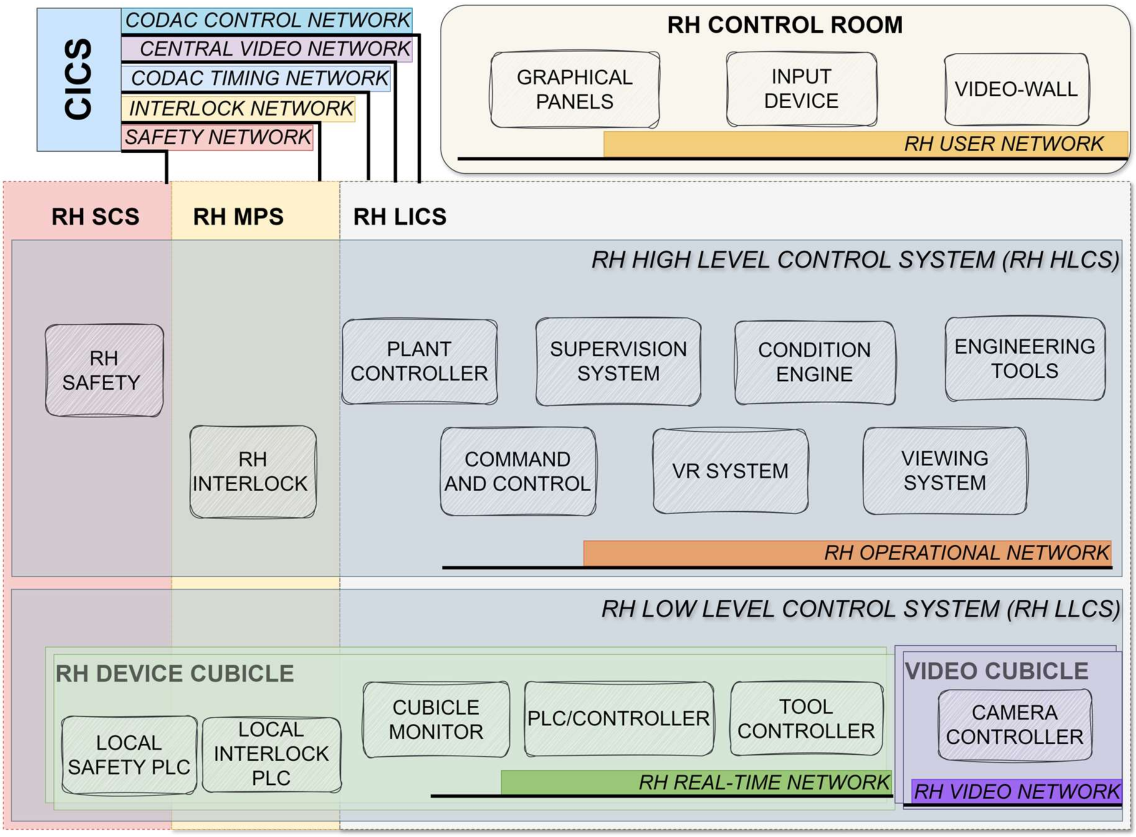


Figure 36: DONES RHCS Architecture. The three vertical layers defined by CICS are maintained, but internally the LICS is sub-divided in two different levels (RH HLCS and RH LLCS).

In the proposed design, the 3 vertical and horizontal layers are maintained to respect the constraints imposed by CICS, but new functional blocks and networks are introduced to accommodate the specific functionalities of the RH control system. In addition, a more consistent nomenclature has been introduced in the horizontal layers for the different levels of control:

- The top level of the RH control system is now called the RH HLCS instead of RH-CICS (there is only one CICS for the entire plant).
- The lower level of the RH control system is now called the RH Low-Level Control System and groups together the cabinets or cubicles that contain the controllers for each RH device and the controllers for the chambers.
- Both levels form the RH LICS, since the RH system is a plant subsystem as defined in the PBS (Table 1).

4.4.3 RH HLCS Modules

In the RH HLCS, new functionalities have been added and some of the original modules have been redefined, thus increasing the number of modules from the original 6 to 9. The definition of each module in this new architecture is as follows:

- Plant Controller: serves as the gateway between CODAC (CICS) and RH LICS. It is responsible for facilitating communication between the two control systems and ensuring the appropriate data format translation (EPICS-OPC UA) is carried out. It will act to select the relevant data for each of the parties and to filter the information that should not be exchanged. Additionally, it is responsible for synchronizing the clocks of all RH equipment with the rest of the plant systems.
- Command and Control: is responsible for the monitoring, control, and automation of processes and actions associated with the RH devices. The system collects data in real time from sensors and actuators, and provides operators with the ability to interact with the system through the use of graphic displays or control panels. Furthermore, it is also responsible for the management of alarms, diagnostics, condition monitoring, and the storage of historical data.
- Supervision System: oversees the management of RH processes. It is an expert system that is responsible for planning, coordinating, and recording maintenance campaigns and RH interventions. In order to achieve this, the maintenance campaigns must be decomposed into actions that can be carried out by the operators in a coordinated manner, and as many actions as possible must be parallelized in order to reduce the amount of downtime experienced by the plant. A more detailed discussion of this module can be found in Section 6.4 .
- VR System: offers a virtual representation of the areas where RH interventions are performed. The system allows operators to visualize in real time the location and pose of the RH devices inside the plant, thereby enhancing situational awareness and offering an unlimited points of view. This enables the avoidance of possible occlusions, the detection of collisions, and the improvement of spatial perception. It provides also offline simulation for operator training and procedure validation.
- Condition Engine: is responsible for ensuring that the necessary plant conditions are in place to enable the safe execution of RH interventions. Moreover, it is required to communicate to the CICS the status of the RH LICS as a single entity. More details about plant and subsystems status will be given in Section 6.3
- Viewing System: provides a real-time video transmission of the rooms where the RH interventions are conducted. In addition to displaying the video captured by the cameras, the system allows for the control of pan, tilt, and zoom, as well as other relevant image parameters.
- Engineering Tools: group all the required tools which are used for programming, configuration, and maintenance of the PLCs and controllers of the RH Devices. These tools will be utilized outside of the scope of routine RH activity, and never during the course of an intervention.
- RH Safety: this subsystem is an extension of the Central SCS, and is responsible for coordinating actions pertaining to radiological and personnel protection,

exclusively within the RH subsystem. Additionally, it will be responsible for the reception and transmission of safety events to the Central SCS.

- RH Interlock: this subsystem is an extension of the Central MPS, and is responsible for the management of protection functions involving different RH Devices. It is also responsible for the reception and transmission of interlock signals to/from the Central MPS related to the interaction of RH Devices with other plant subsystems.

4.4.4 RH Networks

The proposed architecture identifies five external networks connecting the RH LICS with the CICS and four internal networks. Table 9 provides a description of each of the networks.

Network	External (CICS)/Internal(RH)	Description
CODAC	External	Supervision and control of RH LICS
TIMING	External	Time sincronization services for all plant equipment
SAFETY	External	Environment and personnel protection events
INTERLOCK	External	Investment protection events
CENTRAL VIDEO	External	Video streaming and commands from standard cameras
RH USER	Internal	Operator interaction from RHCR with HLCS modules
RH OPERATIONAL	Internal	Supervision and control of RH Devices from RH HLCS
RH REAL-TIME	Internal	High frequency and real-time communication between haptic/hardware input devices placed at the RHCR and RH cubicles
RH VIDEO	Internal	Video streaming and commmands from rad-hard cameras

Table 9: DONES RHCS networks

4.4.5 OPC UA as standard interface

The DONES organization has the capacity to completely define the HLCS from scratch, while for the LLCS it will only be able to define some recommendations or basic requirements. The agreements reached for the development of the main RH devices by the different contributors (both research institutes and industry) have been organized in the form of in-kind contributions. Within the agreements, it has been established that the local control systems will be developed by the contributors. This means that each contributor will use the vendors and tools of their choice, which is likely to result in a variety of protocols and interfaces for the RH Device Cubicles inside the LLCS. However, it is possible that the project will require the inclusion of a standard interface, such as OPC UA, to integrate the RH devices into the HLCS.

The majority of commercial off-the-shelf (COTS) PLCs and controllers now have embedded OPC UA servers, reflecting the widespread adoption of this standard for industry 4.0 digitalization [93]. OPC UA has become the solution of first choice for ensuring interoperability and data exchange between heterogeneous systems.

Moreover, the ongoing development of OPC UA FX (Field eXchange) aims to address the limitations of the existing OPC UA standard for real-time communication by using state-of-the-art technology like TSN. Once fully implemented, OPC UA FX will extend the capabilities of the standard and allow OPC UA to serve as a fieldbus, enabling precise and synchronized motion between RH devices directly over the operational network. More details about OPC UA Fx capabilities can be found in [94].

OPC UA's ability to structure and manage complex data is critical to achieving homogeneous integration of disparate RH devices within a single control room. By standardizing data management, OPC UA facilitates the use of common tools and functionality across all RH subsystems, simplifying the control architecture and improving maintainability. As new devices are added, the network can easily adapt without extensive reconfiguration, ensuring scalability.

In addition, OPC UA supports the latest commercial solutions in industrial control and automation, making it a future-proof choice for RH systems. Its platform-independent nature allows it to be implemented in a variety of hardware and software environments, providing the flexibility needed to meet evolving technology requirements.

4.4.6 Definition of Low Level Control System components

This level will be integrated by around 35 different local controllers, all of them near the RH devices (in the Main Building) and protected inside cubicles (RH Device cubicle), one per RH device. The additional tooling used by these devices could be included inside the same cubicle or have its own one.

As previously stated, it will be challenging to impose constraints on the contributors with regarding to the manufacturers or models of controllers, fieldbuses, or particular sensors/actuators. This will allow for a greater degree of flexibility in the design of local control, enabling it to be adapted to the specific requirements of the various devices and the capabilities and experience of each contributor. However, a generic design has been established that all cubicles must comply with, comprising seven fundamental internal components as illustrated in Figure 37.

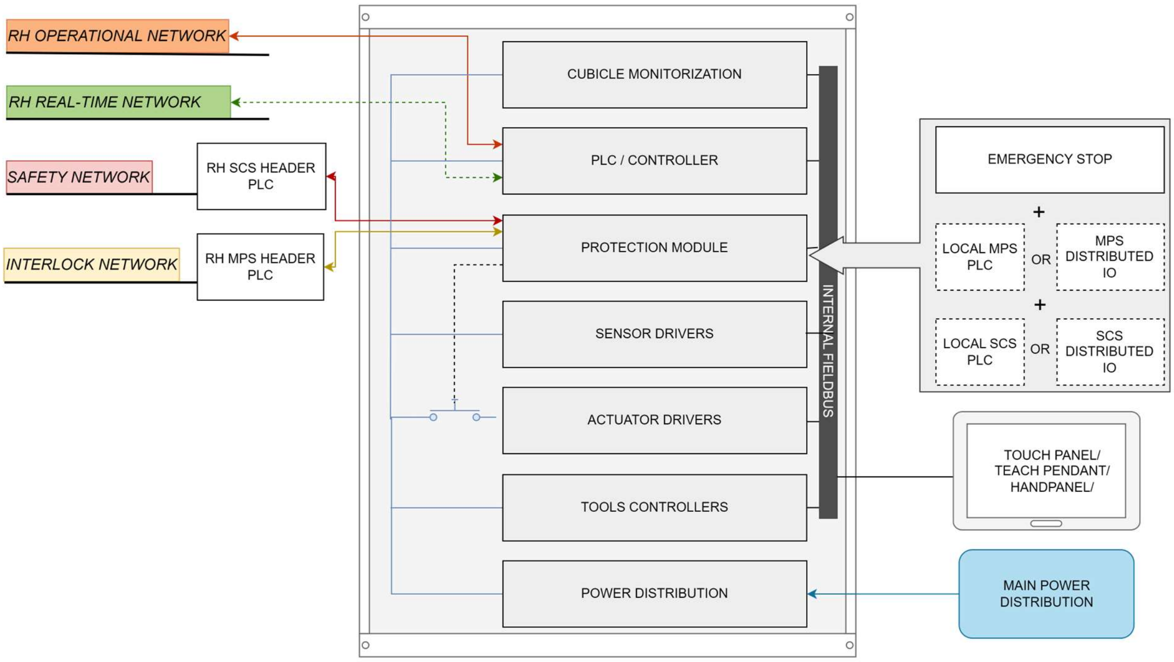


Figure 37: RH Device Cubicle components and interfaces. On the left side shows the three network interfaces that all cubicles must have (the green one will be present only for devices requiring high frequency commands).

- PLC/Controller Module: deals with all the low-level logic to control that specific RH device/tool. This module must be connected to the RH Operational Network and the RH Real Time Network (optional, since not all RH devices/tools may need it).
- Protection Module: is the responsible for protecting the RH device/tool in case of receiving any Interlock (MPS), Safety (SCS) or Emergency Stop (ES) signals. An emergency stop is a signal sent by from the RH Control Room or RH Device Cubicle to stop the movement of a specific RH device. It is triggered by pressing a red button. The activation of any of these 3 signals must trigger a Safe Stop procedure (see 4.4.6.1). Once the device is completely stopped, the module shall interrupt the electrical supply of the Actuator Drivers.
- Actuator Drivers Module: it has all the electronic to process output signals to actuators. Its electricity input supply can be interrupted by the Protection Module in case of protection event.
- Sensor Drivers Module: it has all the electronic to process input signals from sensors (temperature, distance, radiation, torque…) that may be necessary to operate that device/tool.

- Tool Controller Module: it manages a specific tool (bolting tool, grinding machine, cleaning tool…). It could be a simple module controlled by a PLC, or an independent controller.
- Cubicle Monitorization Module: allow to control and monitor environmental parameters (temperature, cubicle's door state, ventilation speed, …) inside the cubicle.
- Power Distribution Module: is the responsible for supplying electricity to the previous modules. It will not make use of a UPS, since that responsibility depends on the facility electrical supply.

4.4.6.1 Safe stop sequence

Emergency Stops for RH devices should be performed in a controlled and safe manner to avoid dangerous situations. These situations to avoid could be the following:

a) Disabling control over a device that is moving a heavy load.
b) Abruptly stopping a device that is moving and has high inertia.
c) Stopping a device that is carrying a highly activated load or is near a radiation source.
d) Leaving a moving element obstructing the access path to a room.

To avoid these scenarios, RH Devices should implement a "safe stop sequence". Unlike an ordinary emergency stop, there is no need for "immediate" action to be taken on the device (considering relatively slow movements of RH devices). Depending on the specific device, this safe stop will be performed in one way or another. The stop order must be processed at the device level, and can be generated by:

- Emergency Stop button associated to the device, or from the general ES button of the RHCR.
- Local or central Interlock event
- Local or central Safety event

These inputs are subject to continuous monitoring in the cubicle of each device by means of its Protection Module. In order to ensure the safe stopping of the device, it is necessary to consider factors such as the current speed of movement of the device, whether it is handling a load, and whether it is situated in a critical zone.

4.4.7 Approaches to mitigate the problems of radiation

The working environment of the RH devices entails significant exposure to high-energy neutrons and gamma radiation. The radiation will affect the structural materials of the devices, causing increased brittleness or deformations. This will also impact the sensors and actuators, potentially leading to degraded accuracy or failures. Additionally, the electronics may experience transient failures and cumulative degradation in performance. The following is a series of basic recommendations for the protection of electronic components in areas with radiation within IFMIF-DONES. This is a particularly complex issue, and designers of RH devices are encouraged to consult with the neutronics and safety experts on the project to discuss the matter further. For those interested in learning more about radiation effects, the design of radiation-hardened (or rad-hard) components, or the estimation of accumulated doses, please refer to [95].

Of the radiation types, neutron radiation is the most damaging as it has the ability to penetrate the atomic structure of materials, causing nuclear shifts and transmutations. This is particularly problematic for semiconductors, which are susceptible to performance degradation and failure modes such as transients like Single Event Upset (SEU) or gradual accumulation of damage known as Total Ionizing Dose (TID), as described in [96]. Gamma rays have the potential to ionize matter in their path, leading to data corruption in memory units and temporary failures in electronic circuits.

Ideally all electronics could be placed inside protected control cubicles, where they are shielded from radiation. Sensors and actuators, however, are typically mounted directly on the RH device and thus exposed to high levels of radiation. This setup necessitates the use of an umbilical cable to link the control cubicle containing all the sensitive electronic (processing units, memory, drivers…) with the sensors and actuators. The design of this umbilical cable is crucial, particularly in relation to its flexibility and signal integrity. Increasing the number of analog signals transmitted through the cable will decrease its flexibility, complicating the cable management and potentially leading to signal degradation over long distances. Therefore, minimizing the use of analog signals and instead opting for digital signals where possible is recommended to maintain signal integrity and enhance the system's reliability. To do so, the RH Device cubicle can be split in two parts: Signal Conditioning Cubicle (SCC) to house the I/O interface dedicated to signal conditioning, and Local Control Cubicle (LCC) to house controllers and most sensitive electronics. Figure 38 shows four different configurations that can be adopted depending on the length of the umbilical, number and type of signals (digital/analog), levels of radiation or modularity of the components:

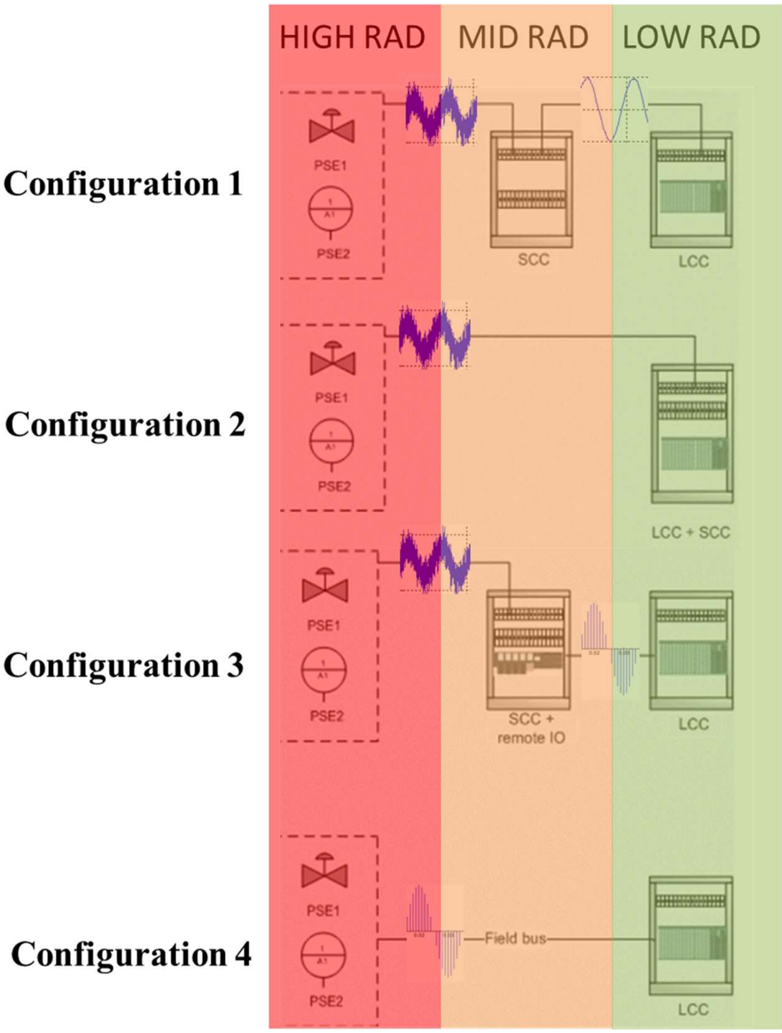


Figure 38: Signal conditioning on radiation environments. Left side represent highly activated area , the right side is totally safe area.

- Configuration1: sensors/actuators works with analog signals. The SCC must be placed close to the device due to the low signal levels with some protection to reduce radiation levels on I/O devices. The LCC is located outside the radiation area or totally protected from radiation. The length of LCC – SCC and SCC – RHE cables have to be compliant with signal levels for EMI (ElectroMagnetic Interference) issues.
- Configuration2: This configuration is similar to configuration 1, but LCC and SCC are merged in order to optimise the space allocation. The levels of the analog signals are stronger than previous case, so the SCC can be moved farther from RHE.
- Configuration3: the control unit of LCC is configured with a remote I/O rack installed in the SCC. The difference with the first approach is that here the signals between SCC and LCC are digital. It allows that link between the LCC controller

and the remote I/O rack may be fiber optic in the case of a long distance connection, strong EMI issues or any voltage isolation issue.

- Configuration4: RHE is connected directly to LLC and all signals are digital. The medium may be fibre optic. In this configuration, there is no need for signal conditioning and the distance for the umbilical can be longer.

In scenarios where electronics inevitably have to be on board of RHE, two approaches can be considered: shielding most sensitive components and transmitting analog/digital signals (preferably when it is possible to include on-board digital converters), or using rad-hard electronics capable of withstanding the radiation levels without additional shielding.

When the failure of an electronic component does not imply a system failure and its replacement is straightforward, a third alternative of “monitor and replace” can be considered. In some cases it is more cost-effective to use standard components and replace them periodically than to use the rad-hard alternative. An example of this might be cameras, which gradually degrade in image quality as the dose received increases (allows monitoring of the sensor status) and are relatively easy to replace. While a standard PTZ camera can cost hundreds of euros, rad-hard versions are in the tens of thousands range. When failure occurs, components must be replaced, leading to downtime and increased maintenance complexity.

Conversely, preemptive upgrading to radiation-hardened versions of electronics ensures the longevity and reliability of the system but at a higher initial cost. This option should be considered for those systems that are permanently deployed in AREAS with higher radiation, such as those electronic components located inside the Test Cell. The signals from the thermocouples that control the temperature inside the capsules containing the samples will have very low signal levels, so it would be very interesting to be able to amplify and digitalize these signals as close as possible to the sensors by means of rad-hard chips such as those offered by manufacturers like Microchip or MAGICS.

4.4.8 Proposal for the RH Control Room

The RH operations in DONES will be directed from a dedicated RH Control Room, separated from the Main Control Room. One of the reference facilities in terms of RH capabilities due to the experience accumulated during more than 40 years of experience is JET, which also count with a dedicated control room for RH operations. It has been upgraded recently to support the decommissioning of the machine, that will start on the next years and will take about 800.000 person hours of work. RH operations are executed only inside the torus using mainly MASCOT as described in [51].

Figure 39: JET RH Control Room upgraded. The MASCOT master device is placed on the center.

The operations in JET are conducted in a sequential manner within the torus, given that there is a single point of entry for RH equipment into the interior of the reactor. Consequently, the control room is configured to facilitate these operations through the MASCOT master device, which occupies a central position within the room.

Another reference to consider for the design of the RH control room is ITER. In this case, as in DONES, it is necessary to perform RH operations in parallel. For this purpose, it is planned to divide the control room into "independent" workspaces, called work-cell. The work-cell concept is commonly employed for the control room of larger plants. Figure 40 shows the arrangement of the work-cell envisaged for the ITER RH Control Room.

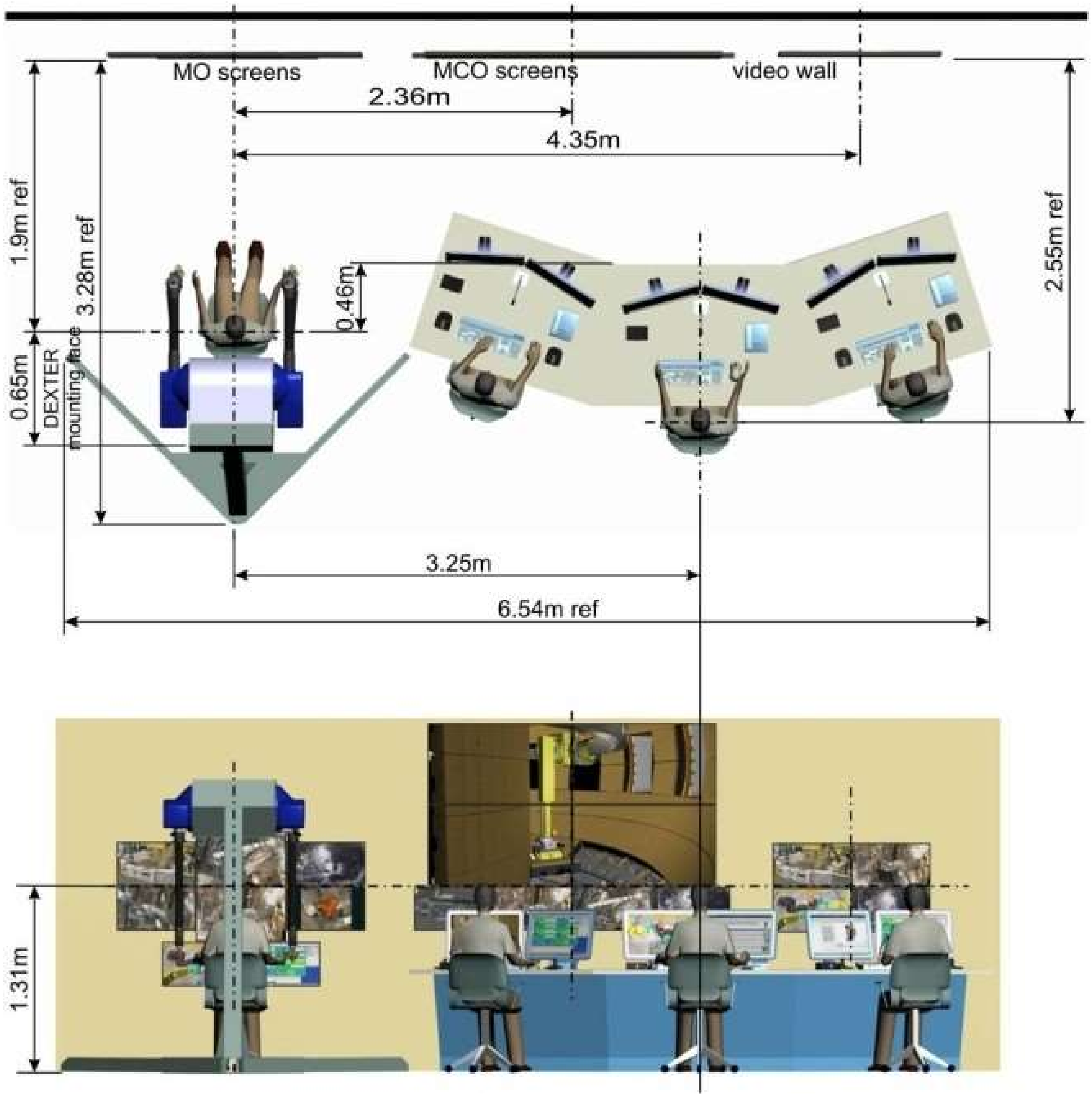


Figure 40: Work-cell layout for the ITER RH Control Room [58]

This layout is based on a team of four operators: three are in charge of the execution of the RH tasks through the control panels, for the control and monitoring of RH equipment; the fourth position is reserved for the master-slave servo-manipulator operator. Each work-cell will be equipped with a set of monitors, which provides operators with the visual perception of the remote environment [58].

In DONES, RH maintenance campaign will consist of a number of maintenance tasks to be carried out in limited maintenance period. The volume of RH tasks to be undertaken in a campaign is such that, in order to respect the time constraints, several tasks will need to be carried out in parallel. To meet this requirement, the RH Control Room must be organized as a set of autonomous work-cells. The RHCR will be placed in the Main Access Building, which is close to the Main building as shown in Figure 41.

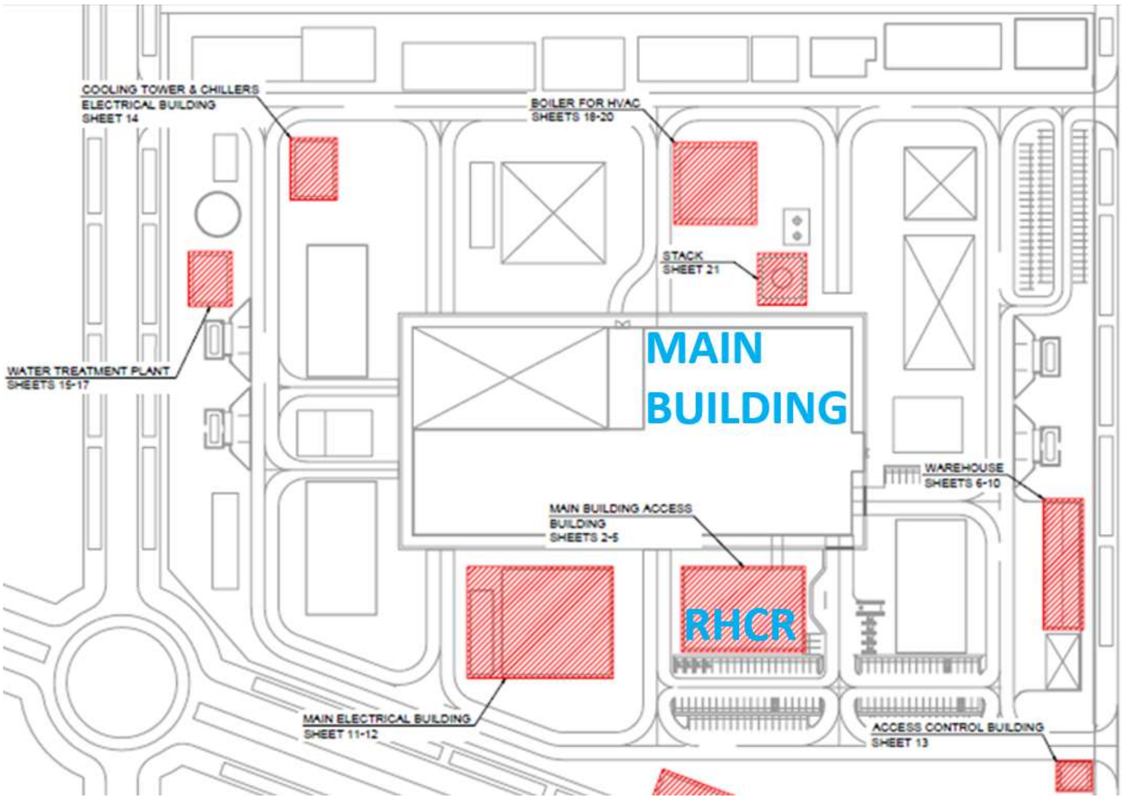


Figure 41: Location of Main Building and RHCR on IFMIF-DONES facility layout.

Inside this building there will be also the Central Control Room, allowing all plant operators to share common spaces like meeting rooms, changing rooms, lockers, kitchen…Both rooms will share a large space of around 1100m2, which will facilitate the coordination of RH with the rest of the plant's systems. However, the space dedicated to the RHCR will have to be kept isolated to provide a calm and quiet environment to facilitate the concentration of the operators during the interventions.

In order to estimate the necessary space to be allocated for the RHCR, two proposals have been developed. The first one considers three working areas: one for the Accelerator systems, one for the Lithium systems, and one for the Access Cell systems. The second one takes into account the introduction of the second particle accelerator, which would be located in a different space from the first one. The final RHCR design shall consider norms such as UNE-EN ISO 11064 "Ergonomic design of control centres", ISO 11226 "Ergonomics - Evaluation of static working postures" and IEC 60964 "Nuclear power plants - Control rooms – Design".

Proposal 1

• There will be 16 RH workers, distributed around three work cells and one supervision work cell. Each work cell will have four RH Operators and a RH Local Supervisor.

• Each work cell will be four meters by eight meters (32 square meters). In total, 96 square meters and 15 RH workers (RH Operators + RH Local Supervisors). The individual work cell for the RH Central Supervisor will be three meters by three meters (9 square meters). As an error margin for additional tables and walkways space, a 25% is considered. Therefore, the RHCR would need 131 square meters.

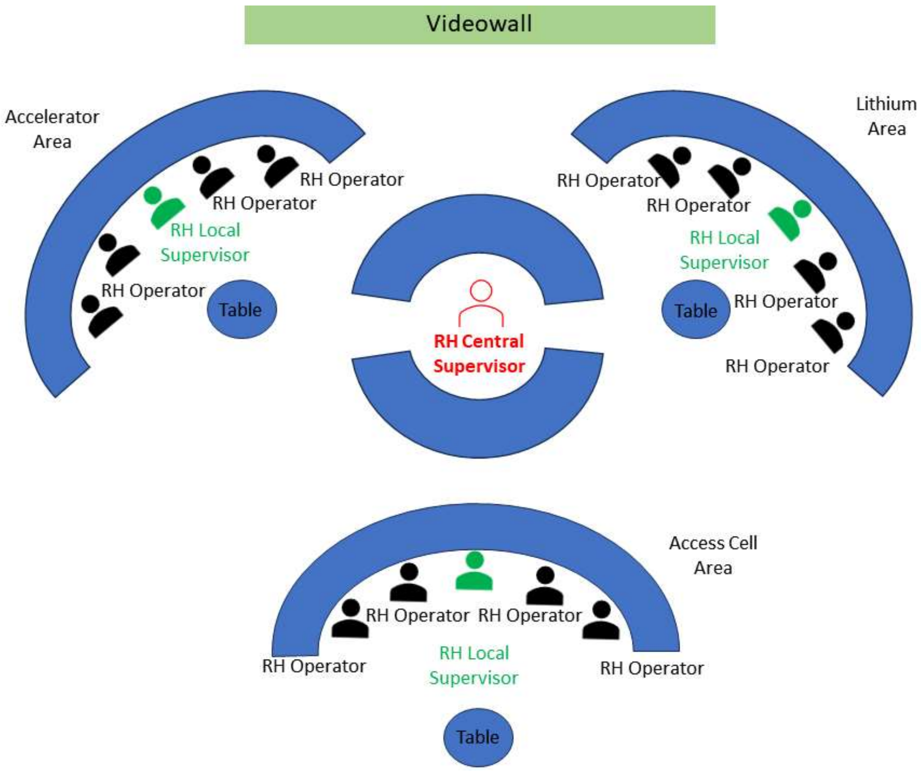


Figure 42: RHCR distribution proposal 1. Not in scale.

Proposal 2

• There will be 17 RH workers, distributed around four work cells and one supervision work cell. Each work cell will have tree RH Operators and an RH Local Supervisor.

• Each work cell will be four meters by six meters (24 square meters). In total, 96 square meters and 16 workers (RH Operators + RH Local Supervisors). The individual work cell for the RH Central Supervisor will be three meters by three meters (9 square meters). As an error margin for additional tables and walkways space, a 25% is considered. Therefore, the RHCR would need 131 square meters.

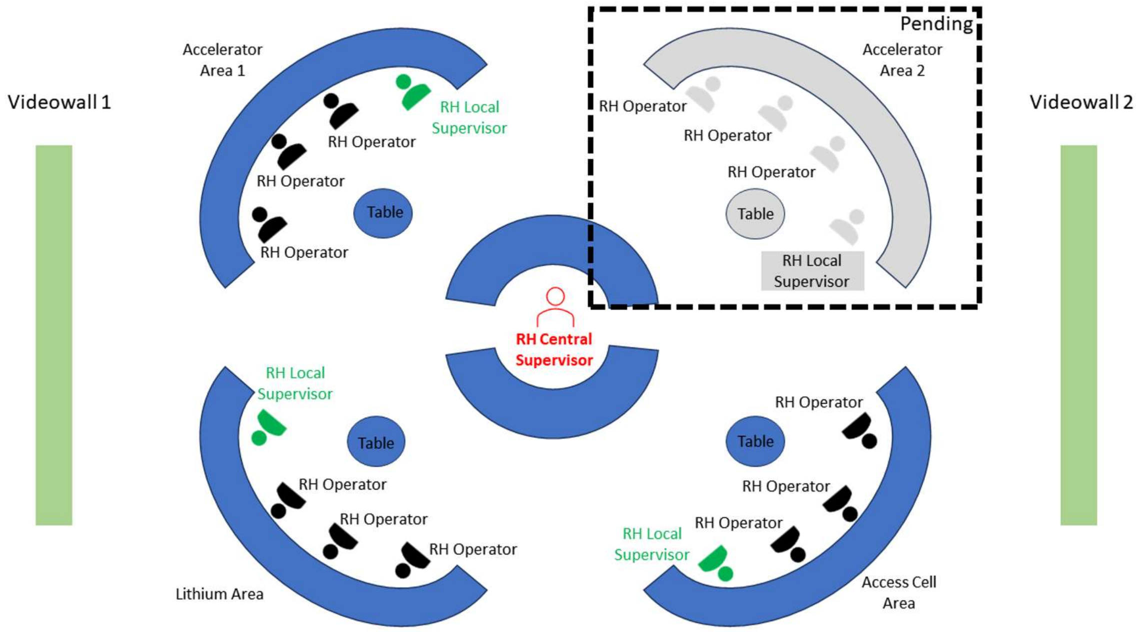


Figure 43: RHCR distribution proposal 2. Not in scale.

4.5 Conclusions of Chapter 4

In this chapter, two of the five main tasks of this thesis are addressed, providing the following results:

- T1. Identification of Requirements: The needs of the IFMIF-DONES project were analyzed in Sections 4.1, 4.2, and 4.3, followed by the summary of requirements summarized in Table 7.
- T2. Development of a Control Framework: In Section 4.4, a detailed analysis of control frameworks applicable to the RH system of IFMIF-DONES was conducted, leading to the definition of a reference control architecture. The control system's functionality was described through functional blocks, and a standard data interface was proposed to standardize the variety of RH devices required.

Through a thorough analysis of operational and technical demands, a structured framework of requirements was defined, reflecting both the immediate needs and the anticipated challenges of the facility. These requirements emphasized the importance of modularity, scalability, and the integration of a human-in-the-loop (HITL) strategy to ensure the safety and efficiency of operations. Key considerations also included the design of advanced interfaces for operator interaction, such as haptic feedback systems and tools for pose teaching, and the use of a tiered architecture divided into HLCS and LLCS. This hierarchical structure ensures that specific responsibilities and functionalities are clearly delineated and efficiently executed.

Drawing inspiration from the architecture of ITER while tailoring it to the unique scale and resource constraints of IFMIF-DONES, the proposed framework strikes a balance between technological innovation and practical feasibility. The use of OPC UA as a standard interface ensures compatibility and seamless data exchange among the heterogeneous components of the system, while leveraging commercial off-the-shelf (COTS) technologies to simplify development and integration. The inclusion of ROS2 as a potential tool for future modules, underscores the system's forward-looking approach, integrating current needs with adaptability for emerging technologies like TSN and OPC UA FX.

The chapter also introduced design principles for the RH Control Room, emphasizing the importance of efficient space utilization and operator-centric layouts. Inspired by established references like ITER and JET, the proposed control room adopts a work-cell concept that facilitates parallel operations and minimizes downtime during maintenance campaigns. This practical design aligns with the broader architectural goals of scalability and modularity, ensuring both the current and future applicability of the RHCS.

Overall, Chapter 4 lays a solid foundation for the RHCS, combining requirement definition with an innovative control framework that bridges the gap between industrial standards and the cutting-edge needs of remote handling in fusion-related facilities. This work not only addresses the immediate goals of IFMIF-DONES but also sets the stage for future advancements in the field of control systems for remote operations.

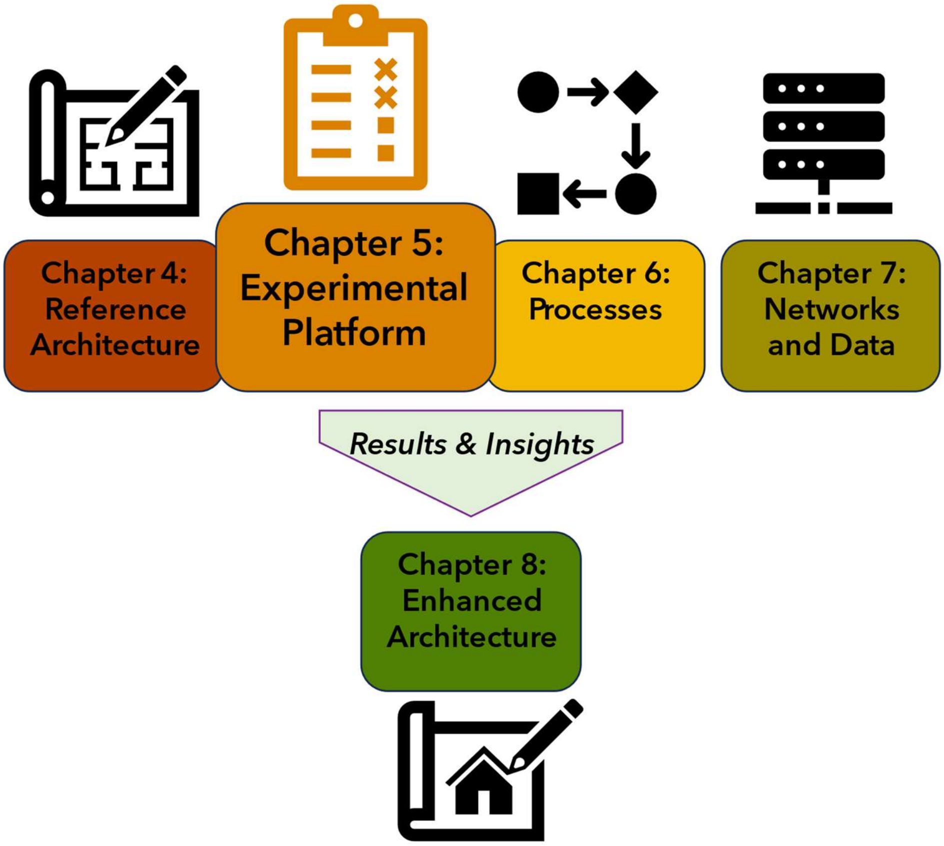
Chapter 5
Experimental Platform: UGR-DONES Control Laboratory

This chapter focuses on the development, configuration, and validation of the experimental setup at the **UGR-DONES control laboratory**. Serving as a testbed for RH systems, the lab **replicates representative operations and control scenarios** to evaluate the feasibility and performance of the proposed RHCS.

The lab integrates various components, including a 6-DOF robotic arm, a lifting platform, and a conveyor belt, which collectively enable complex manipulations while addressing the heterogeneity and precision demands of RH devices. Advanced tools, such as a **VR-based scene** for enhanced operator interaction and **haptic feedback** systems, provide immersive and efficient user control.

The chapter describes the hardware, controllers, and software tools employed, as well as the **experimental procedures** carried out to validate the system. These procedures simulate real-world RH tasks, enabling a detailed study of execution times, operator learning curves, and performance optimization strategies. This experimental setup forms the foundation for validating the proposed RHCS architecture, bridging the gap between theoretical design and practical implementation.

5 Experimental setup: UGR-DONES control laboratory



In order to validate the concepts and technologies proposed in the reference design, a testbed has been developed with robotic devices representative of RH tasks. Within the UGR-DONES control laboratory, a robotic cell has been created where remote manipulation tasks can be executed. The following sections will describe the mechatronic components, controllers, networks, and software tools used, as well as a overview of the functionality offered and the control strategies implemented.

Figure 44: Robotic cell at UGR-DONES control laboratory.

5.1 Test bench for representative telemanipulation tasks

The test bench developed within the UGR-DONES Control Lab aims to emulate one of the key RH devices within the DONES facility. If we consider the Test Cell as the central element of the facility, the RH devices responsible for carrying out operations inside it can be considered the most critical. Operations such as connecting/disconnecting connectors, inspection, screwing, or cleaning inside the Test Cell will be performed using a robotic arm mounted at the end of the ACMC boom. This combination results in a system with 7 degrees of freedom (DOF) for the robotic arm (RA) and 4 DOF for the ACMC, blending high-precision robotic control systems with industrial PLC-based crane control systems. This difference in the type of controllers makes it an interesting setup for studying control systems and provides a representative example of the heterogeneity already mentioned in RH controllers.

The devices chosen for the test bench aim to mimic this combination. As the central component, a 6-DOF robotic arm was selected. To add additional degrees of freedom within the constrained space of the laboratory, a lift platform and a conveyor belt have been included, providing 2 more DOF to the system. The robotic arm is suspended from the ceiling inside a cage, with the lift platform positioned directly below it to allow movement in the Z-axis of the workspace. This configuration replicates the working conditions inside the Test Cell, where the RA is suspended from the boom of the ACMC. To simulate the movement of the crane trolley, the conveyor belt attached to the lift platform provides X-axis movement for the objects to be manipulated. Although the RA itself is not moved, from the perspective of the manipulable objects, 2 of the 4 DOF offered by the crane are represented. The layout of the elements in the lab is shown in Figure 45.

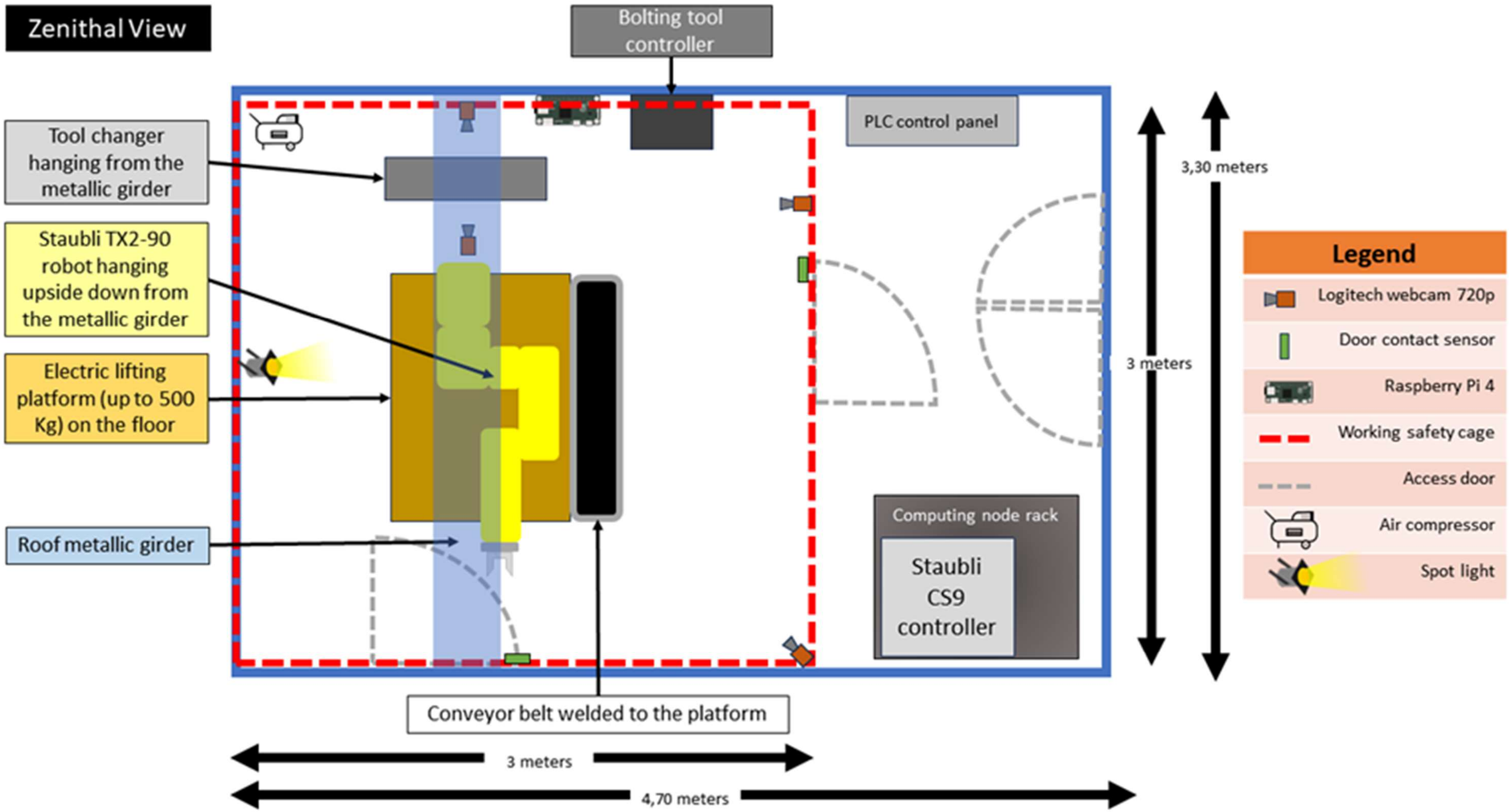
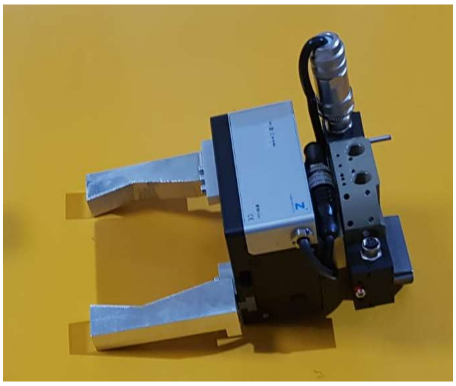


Figure 45: UGR-DONES Control Lab distribution. The operator is sitting on the bottom part, separated by a glass that can be covered to eliminate direct view of the robotic cell.

5.2 List of components

This section gathers in Table 10 the main components of the robotic cell, accompanied by a description where the component references and other relevant information can be found.

ID	Component	Description
1	Robotic arm  	***(RH Devices and sensors)*** Staübli Tx2-90 6DOF industrial robotic arm. Payload: 14kg Reach: 1000mm Repeatability: ±0.03 mm Controller: CS9 (ID 17)
2	Lifting platform 	***(RH Devices and sensors)*** Tymbia 500 Lifting platform electrically actuated. Payload: 500kg Max height: mm Controller: ET200SP (ID 15)

3	Conveyor belt 	***(RH Devices and sensors)*** Custom design + SIMOTICS 1P Linear conveyor belt attached to the lifting platform. Payload: 14kg Length: mm Controller: SINAMICS 210 (ID 16)
4	Bolting tool 	***(RH Devices and sensors)*** Rexroth Tightening System 350 Programmable hand-held nutrunner. Max torque force: 400Nm Controller: (ID 18)
5	Parallel Gripper 	***(RH Devices and sensors)*** Zimmer GEH6040IL-03B1 Two finger parallel gripper electrically actuated. Max gripping force: Controller: IO-Link Master Module (ID 19)
6	Tool changer 	***(RH Devices and sensors)*** Staübli MPS 035 Tool changer with one robot plate and two tools plates. Actuation: pneumatic Controller (sensor reading): ET200SP (ID 15)

		Controller (pneumatic valves): CS9 (ID 17)
7	Webcams 720p  	***(RH Devices and sensors)*** Logitech C505 USB Webcam (4 units) Resolution: 720p Controller: Camera controller (ID 22)
8	Webcams 1080p  	***(RH Devices and sensors)*** Trust TW-200 USB webcam with autofocus (3 units) Resolution: 1080p fullHD Controller: Computer vision server (ID 21)
9	Safety limit switch 	***(RH Devices and sensors)*** Schneider XCS-PA791 Safety limit switch with external actuator Controller: CS9 (ID 17)

10	Force/Torque sensor 	***(RH Devices and sensors)*** Onrobot HEX-E Sensor 2.0 Force and torque sensor attached to robot flange. Controller: Compute Box (ID 14)
11	OCR Detector 	***(RH Devices and sensors)*** Jetson Nano 4GB RAM 16G eMMC OCR detector attached to lifting platform. Controller: PLC S7-1500 (ID 22)
12	Air compressor 	***(Building services)*** Pneumatic supply for the tool changer.
13	Air conditioning system 	***(Building services)*** Two splits to maintain control electronics in temperature range

<table>
<tr><td>14</td><td>Compute Box (OnRobot)
</td><td>(RH Low Level Control)

Controller to interface F/T sensor and robot.

Drives: F/T Sensor (ID 14)

Configuration interface: Web</td></tr>
<tr><td>15</td><td>ET200SP (Siemens)
</td><td>(RH Low Level Control)

Distributed IO module to manage sensor/actuators digital and analog signals

Drives: Lifting platform (ID 2), MPS (ID 6)

Engineering tool: TIA Portal V17</td></tr>
<tr><td>16</td><td>SINAMICS S210 (Siemens)
</td><td>(RH Low Level Control)

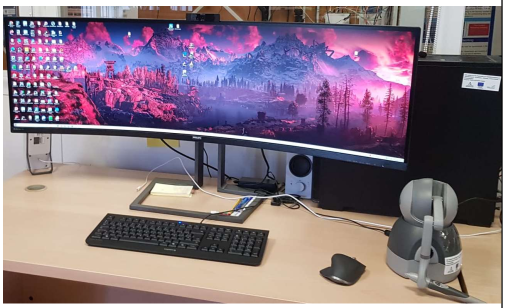
Motor driver for conveyor belt.

Drives: Conveyor belt (ID 3)

Engineering tool: TIA Portal V17</td></tr>
</table>

17	CS9 (Staübli)  	***(RH Low Level Control)*** Robotic controller for the robotic arm. Drives: Staübli Tx2-90 (ID 1) Engineering tool: Staübli Robotics Suite 2022.7
18	CS351 (Rexroth)  	***(RH Low Level Control)*** Controller for the tightening system Drives: Rexroth Bolting Tool (ID 4) Engineering tool: BS350
19	TBEN-S2-4IOL (Turck) 	***(RH Low Level Control)*** IO-Link Master Module. Gateway to connect the gripper and the PLC Drives: Zimmer Parallel Gripper (ID 5) Configuration interface: Web
20	Asus RS500-E9 	***(RH High Level Control)*** Server with Red Hat OS and virtual machines running EPICS modules Controlling: Virtual plant status (simulation)

21	Computer vision server 	***(RH High Level Control)*** Raspberry 4B running CV algorithms Controlling: Webcams Autofocus (ID 8)
22	PLC S7-1500 	***(RH High Level Control)*** Controller to manage sensors and actuators, communications and tooling Controlling: ET200SP (ID 15), SINAMICS S210 (ID 16), TBEN-S2-4IOL (ID 19), CS351 (ID 18) Engineering tool: TIA Portal V17
23	Camera controller 	***(RH High Level Control)*** PC with Ubuntu running the video server Controlling: Webcams Logitech (ID 7)

24	Operator workstation 	***(RH High Level Control + User interface)*** PC running Windows10. It runs the SCADA engine, VR scene and the Engineering tools. Also provides control panels to the operator. Controlling: all RH devices (main user interface)
25	Touch (3D Systems) 	***(RH High Level Control + User interface)*** Haptic controller. User interface for manual control of the robotic arm. Controlling: CS9 (ID 17)
26	Ethernet switches (Mikrotik) 	***(Network)*** Standard ethernet switch (2 units)

27	Industrial managed switch (SIEMENS) 	***(Network)*** Industrial ethernet switch supporting PROFINET

Table 10: UGR-DONES Control Lab components

5.3 Simplified RH Control Architecture at UGR-DONES Control Lab

Using only the components described in the previous section, a simplified version of the control system proposed in 4.4.2 has been implemented. For the development of this test bench, we started with a stand-alone RH system capable of providing basic control functions over the RH devices. This design will be expanded in Chapter 6, with a focus on processes by adding components such as a virtual mock-up of the CICS. The complete design of the network will be addressed in Chapter 7, which is now simplified to a single network without traffic distinction.

Focusing on the functional aspect, only 4 of the HLCS modules are strictly required to execute a telemanipulation task in the proposed laboratory environment:

- Engineering Tools: Enables configuration and setup of the devices.
- Command and Control: Provides user interfaces for interacting with the devices.
- VR System: Offers a real-time virtual scene of the workspace.
- Viewing System: Provides real-time video feeds from the laboratory cameras.

The architecture proposed in Figure 46 provides the basic functions necessary for a complete remote handling system in a laboratory setting. Equipment protection and safety functions have not been considered (beyond those implemented internally by the devices themselves), as such limitations would constrain the experimental nature of the proposed environment. This proposal was presented in SOFT 22 (Symposium On Fusion Technology) congress and the related results were published in Fusion Engineering and Desing special issue [62].

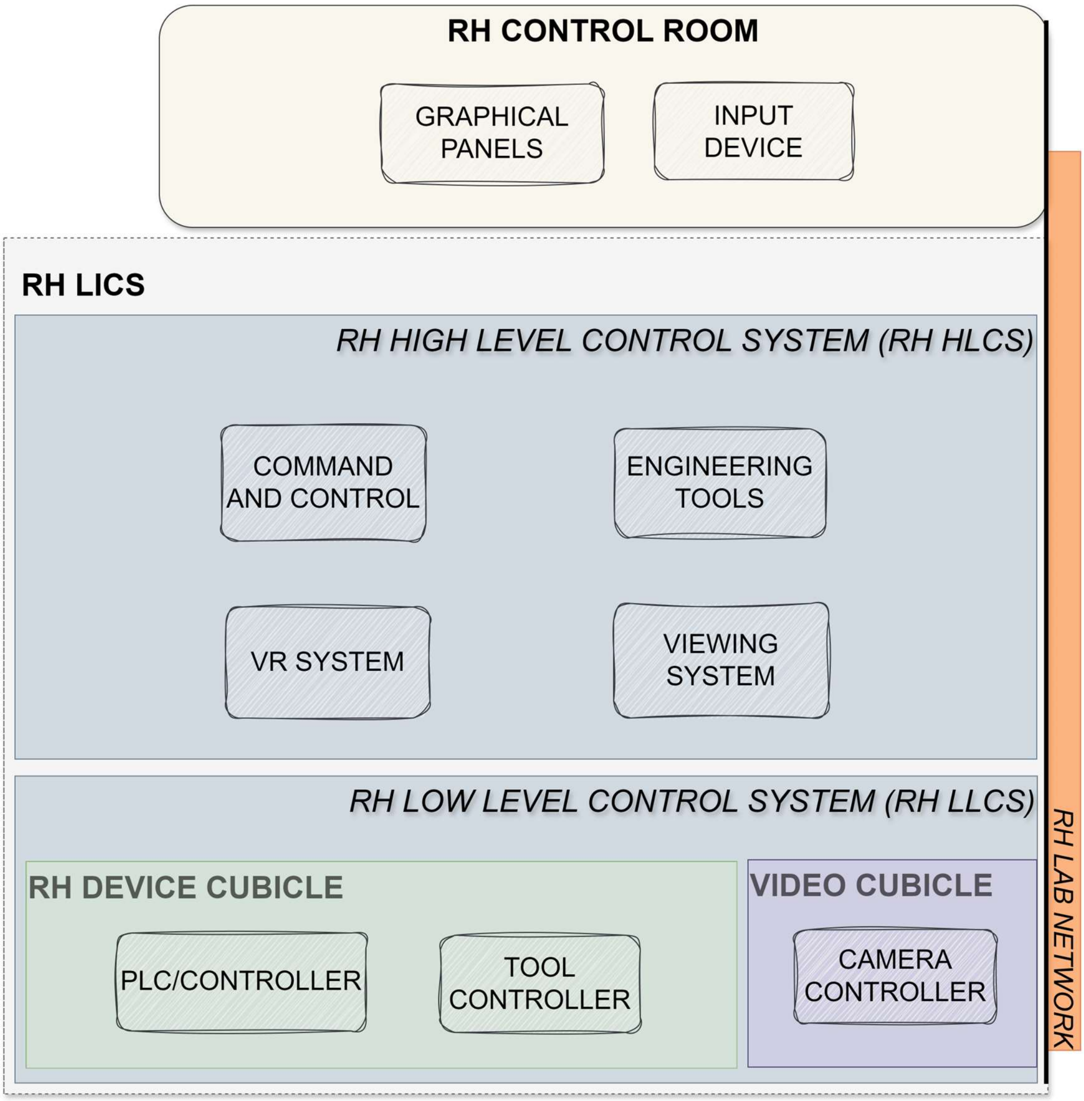


Figure 46: Simplified control architecture for the test bench. RH HLCS contain 4 modules to provide basic functionality, and a single network is used to connect all the components.

5.4 Functionality overview

This section describes the main functionalities implemented in the test bench, detailing the available user interfaces for each device and the operating modes.

5.4.1 Conveyor Belt control

The control of the conveyor belt is managed using the technological functions provided by the SINAMICS S210 driver. This device offers predefined functional blocks from SIEMENS that enable precise and easily parameterized motion control. These are referred to as "technological objects," which are libraries that provide functions for object counting, kinematic calculations, tool handling, and, in this case, motion control. For controlling the conveyor belt, JOG motion and relative motion have been utilized, as illustrated in Figure 47.

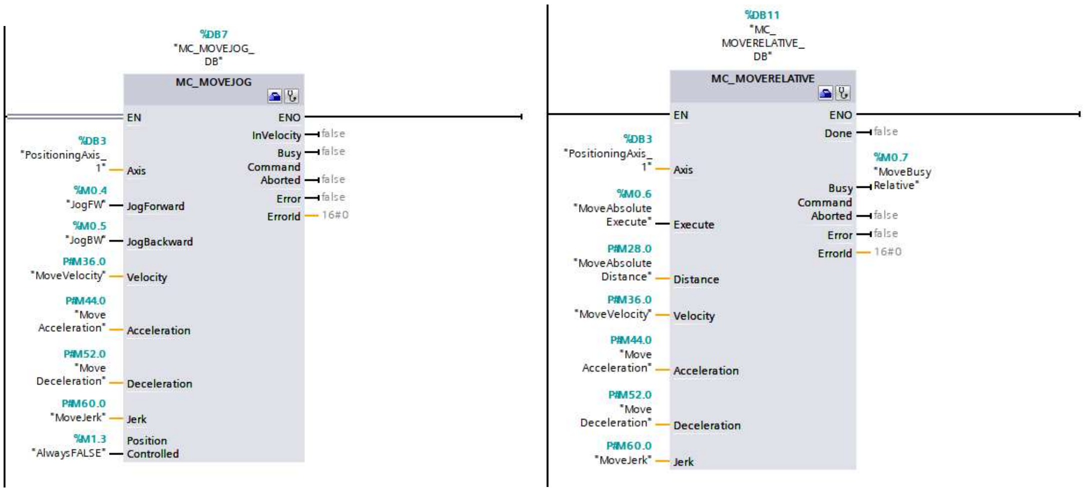


Figure 47: SIEMENS technological objects for motion control.

This device operates as a module connected to the S7 1500 PLC (ID 22), communicating in real-time via PROFINET. All control logic (including the technological objects), as well as communication management with other systems, is executed on this device.

The control panel shown in Figure 48 provides a section where movement parameters used by the technological objects can be defined via display bars, and buttons are available to send commands. For JOG mode movement, two buttons are used to control forward and backward motion. For relative motion, an input dialog allows the user to enter the desired displacement distance (in mm), and a button is provided to send the motion command.

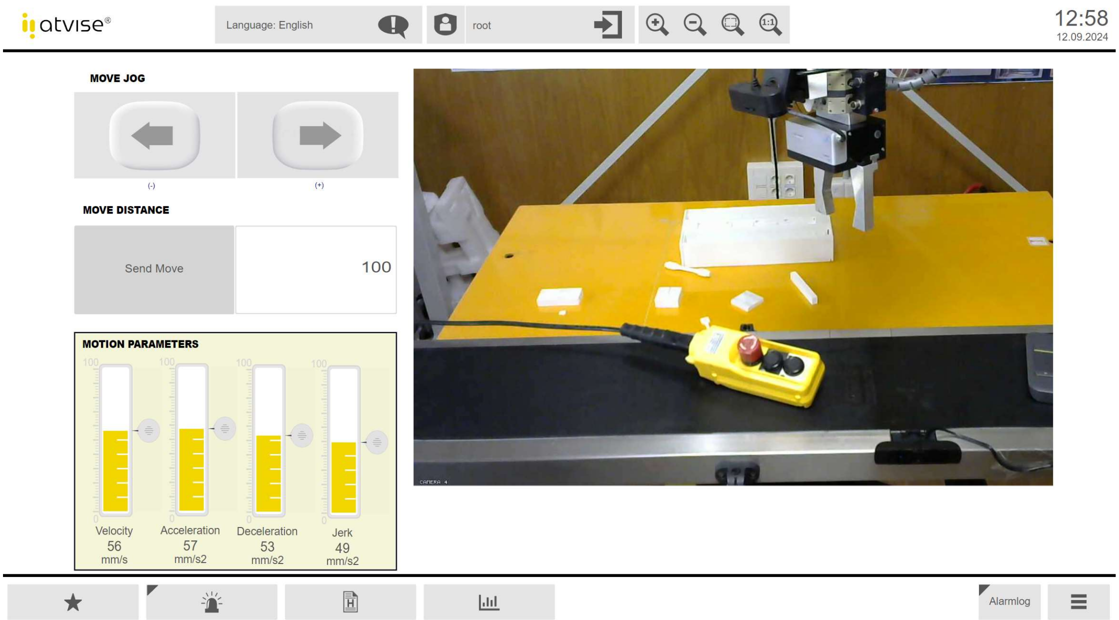


Figure 48: Conveyor belt control panel with the embedded live streaming from the camera system.

5.4.2 Lifting Platform control

The lifting platform did not have any built-in interface for remote control, only a manual control panel with three buttons for raising, lowering, and emergency stop. To enable remote control, it was necessary to manually wire the connections of the control panel and connect them to relays controlled by the ET200SP I/O module (ID 15), as the signals exceed 24V. This module is operated by the S7 1500 PLC CPU (ID 22), which ensures that the two signals (raise/lower) are never activated simultaneously and manages communication with the rest of the system.

The platform lacks an encoder or any sensor that would provide information on its current height. To estimate the height, a computer vision application based on OCR has been developed, running on a JETSON Nano (ID 11) attached to the conveyor belt and lifting platform setup. The camera reads the height (marked in centimeters) displayed directly in front of it. The value obtained is then sent to the S7 1500, which processes the data and shares it with other systems on the network in a standardized format.

The control panel (Figure 49) is simple, featuring two buttons for raising or lowering the platform, and a display bar that indicates the current height of the platform.

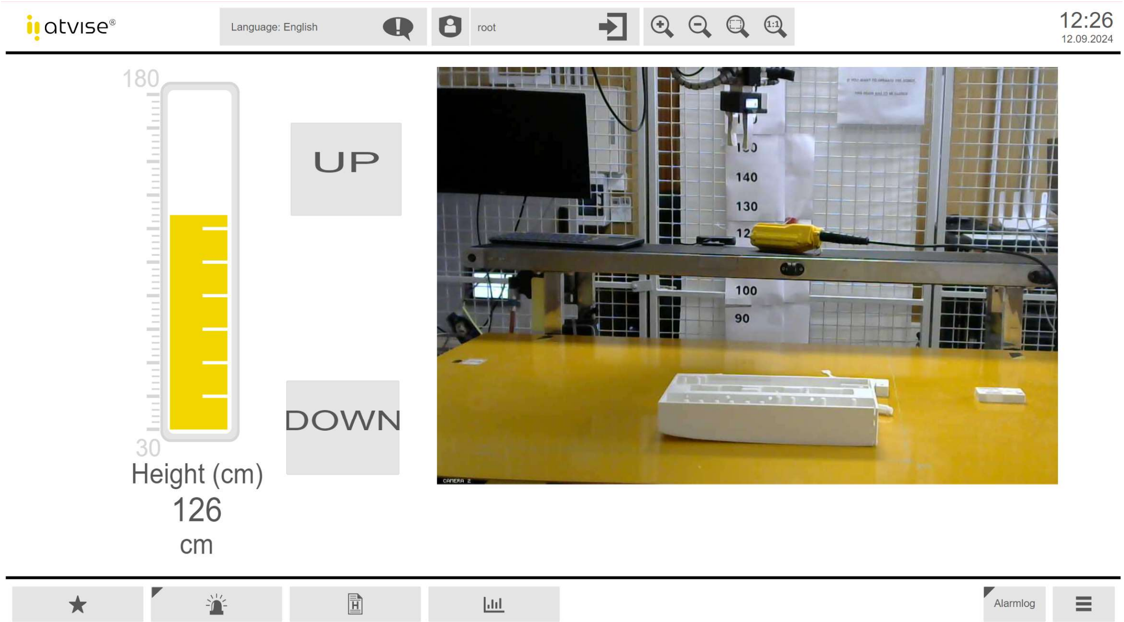


Figure 49: Lifting platform control panel with the embedded live streaming from the camera system.

5.4.3 Viewing System

This system provides an interface for viewing video streams from multiple webcams positioned within the robotic cell. A Linux-based PC runs Motion software, responsible for collecting the different video feeds and serving them via an Apache web server. To access the main interface, any computer connected to the laboratory network simply needs to access the IP address of the Viewing System.

The interface shown in Figure 50 has been developed using Javascript and CSS, allowing users to select different cameras and adjust basic parameters such as brightness, contrast, and saturation. The video streams are transmitted over the network using MPEG encoding, encapsulated over TCP. Additionally, it is possible to access each video stream individually by appending the specific port number to the server's IP address (8081, 8082, 8083, etc.).

Figure 50: Viewing system web interface. Lateral left view (top left), lateral right view (top right), cenital view (left bottom) and robot flange view (bottom right). Two more cameras can be selected using the interactive web interface.

5.4.4 VR Scene

To support the Viewing System, a virtual scene based on Unity3D has been developed by the VALERIA lab with the 3D models of the devices present in the robotic cell. Our contribution to this module focuses on the control of the virtual model, by configuring the OPC UA interfaces to control the movement of the virtual objects and defining the control strategies to translate the movement of the user into the 3D space of the scene that will guide real robot movements.

The virtual scene will allow having unlimited points of view from which to follow the operation inside the cell, improving its situation awareness and avoiding possible occlusions that may appear in the cameras. The movement of the devices is represented in the virtual scene in real-time, providing a refresh rate higher than 60 FPS to obtain a fluid movement. This scene can be executed as an executable file from any computer connected to the network, or from Unity3D Editor installed to develop the application in the Operator Workstation (ID 24).

Unity3D also manages the haptic device (ID 25) that allows to have a manual control of the TCP of the robotic arm, and to obtain feedback of the forces sensed by the F/T sensor (ID 10). Ideally this functionality should be implemented in a separate dedicated system, but the manufacturer of the haptic device offers most of the functionalities through software packages for Unity3D. For this reason, we have chosen to include this haptic control functionality within the virtual scene, as it simplifies the development of control strategies and allows us to take full advantage of the haptic functionalities.

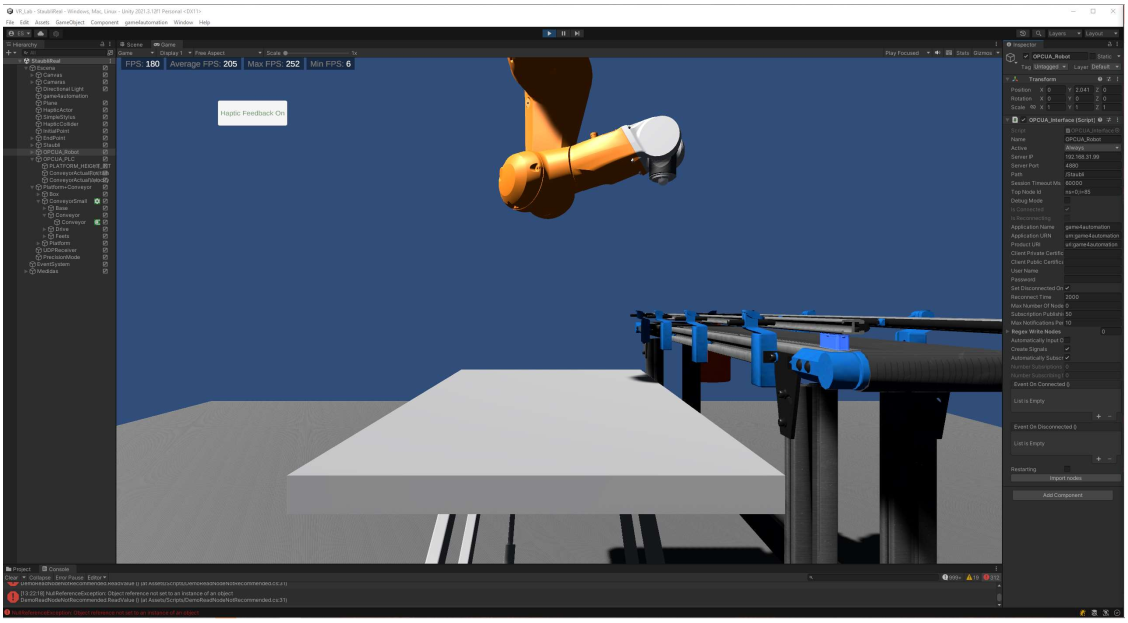


Figure 51: Virtual reality scene of the test bench on Unity3D Editor.

The interface displays in the upper left corner debug information such as the scene refresh rate, as well as a button to enable or disable force feedback on the haptic device. The position commanded by the haptic device is represented by a white sphere indicating the position in three-dimensional space (X, Y, Z) which is sent using UDP to the CS9 robot controller (ID 17) to make the corresponding kinematic calculations in real time and track the trajectory described by the operator. More details can be found on 5.4.6.

5.4.5 Tools control

To control the gripper (ID 5) it is necessary to use an IOLink Gateway (ID 19) that allows communication with the PLC S7 1500 (ID 22), which is responsible for managing the associated state machine. To implement this state machine in the PLC, the Siemens graph programming (or GRAFCET) has been used, which is a control diagram with stages and transitions that allows the creation of state machines by means of blocks and transitions based on conditions. The resulting finite state machine (FSM) will be instantiated by means of a functional block in the main PLC program. To start the state machine, it must be verified that the gripper is attached to the robot by reading the proximity sensors equipped on the tool changer (ID 6).

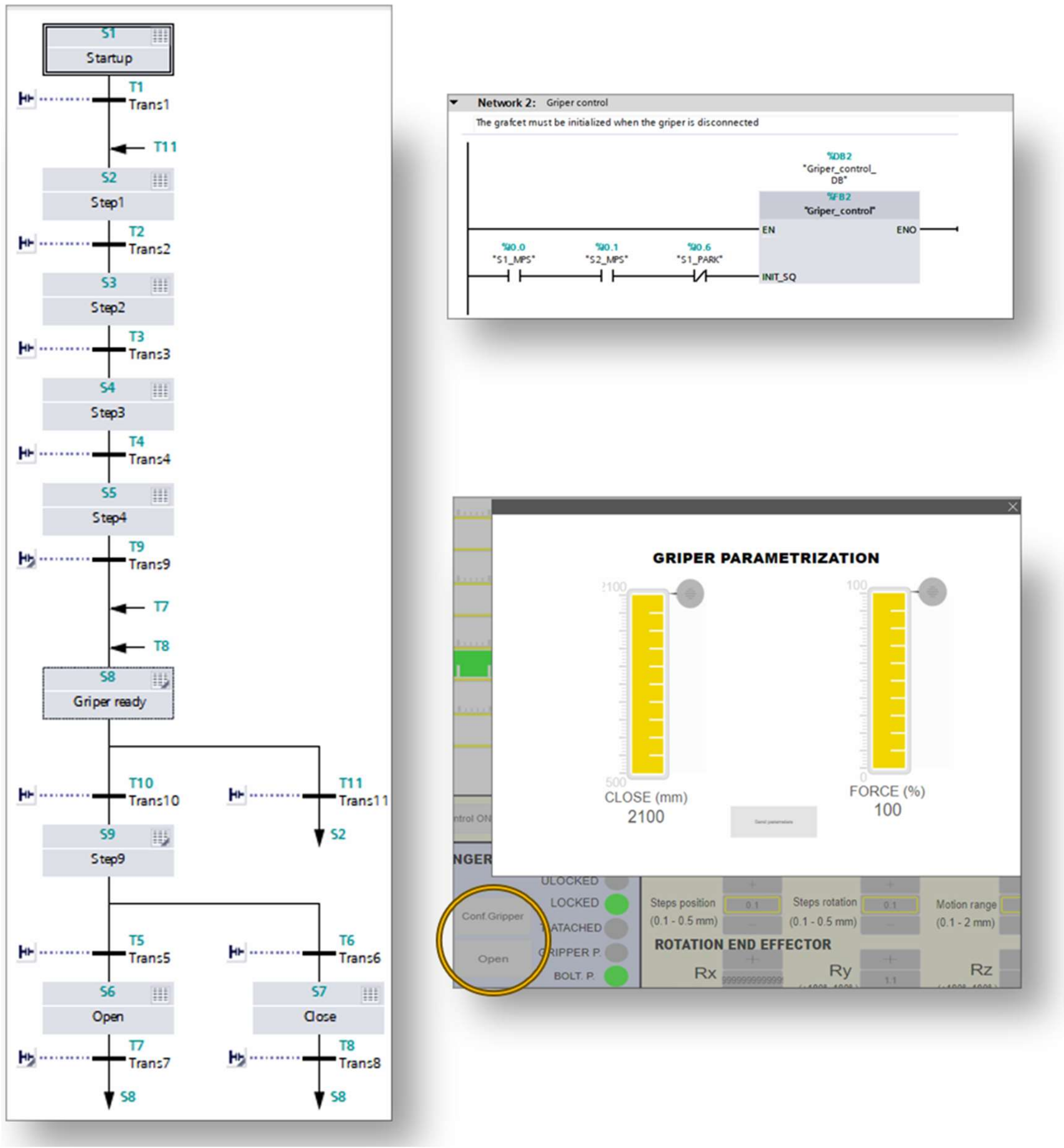


Figure 52: Grafcet FSM for gripper control (left side), function block instance of FSM (top right) and gripper parametrization panel popup (bottom right)

The control panel offers two main buttons, one for opening/closing the fingers, and one for launching a pop-up window with the gripper configuration parameters. The operator configurable parameters are finger travel (stroke) and maximum force to be applied. In this way it is possible to grip objects with known dimensions by defining the opening distance between the fingers, or to define a maximum force to be applied and close the fingers completely. In the second case, when the gripper reaches the maximum force percentage value indicated, it will stop and the object will be gripped (if the defined force is sufficient).

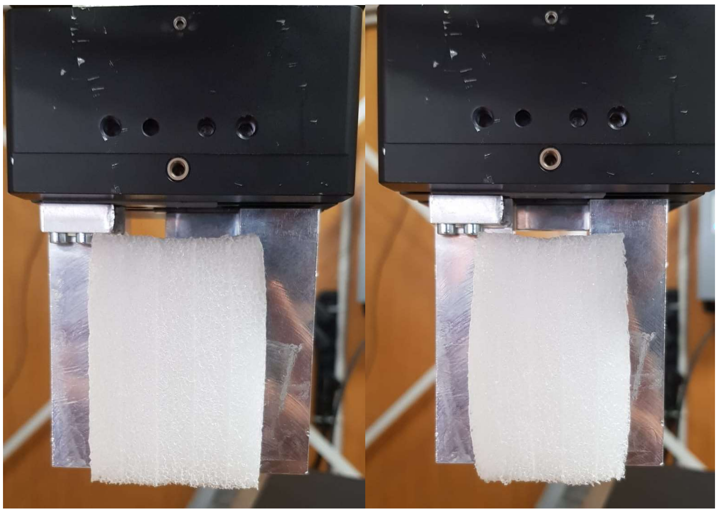


Figure 53: Foam grip (force = 5% on left side, force = 100% right side)

The bolting tool is programmed by means of a proprietary software tool (BS350), which allows the definition of precise tightening sequences and profiles (so-called tightening programs) where tightening torques, number of turns, tightening time and other advanced parameters can be specified.

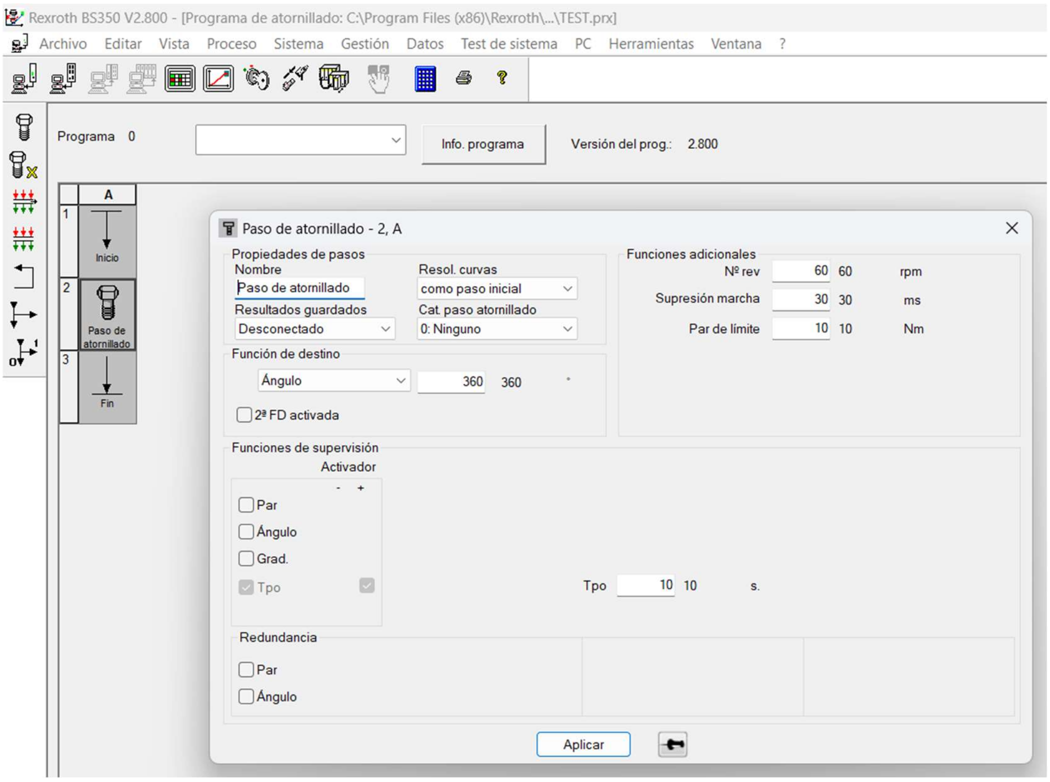


Figure 54: BS350 tool to define tightening programs for the bolting tool

To execute these programs stored in the memory of the CS351 controller (ID 18) it is necessary to follow a series of steps defined by means of another graphcet. The state machine will allow the execution of a clockwise (CW) or counterclockwise (CCW) screwdriving sequence depending on the activation of the associated PLC signals.

However, this tool won't be attached to the robot because it could damage the robot's joints.To solve this problem, a solution is presented in [97] by offering external anchor points.The authors show how high screwing torques can be achieved with low torques in the robot's joints when the tool is designed to fit the bolting components and an efficient combination of position and force control modes is used on the robot.

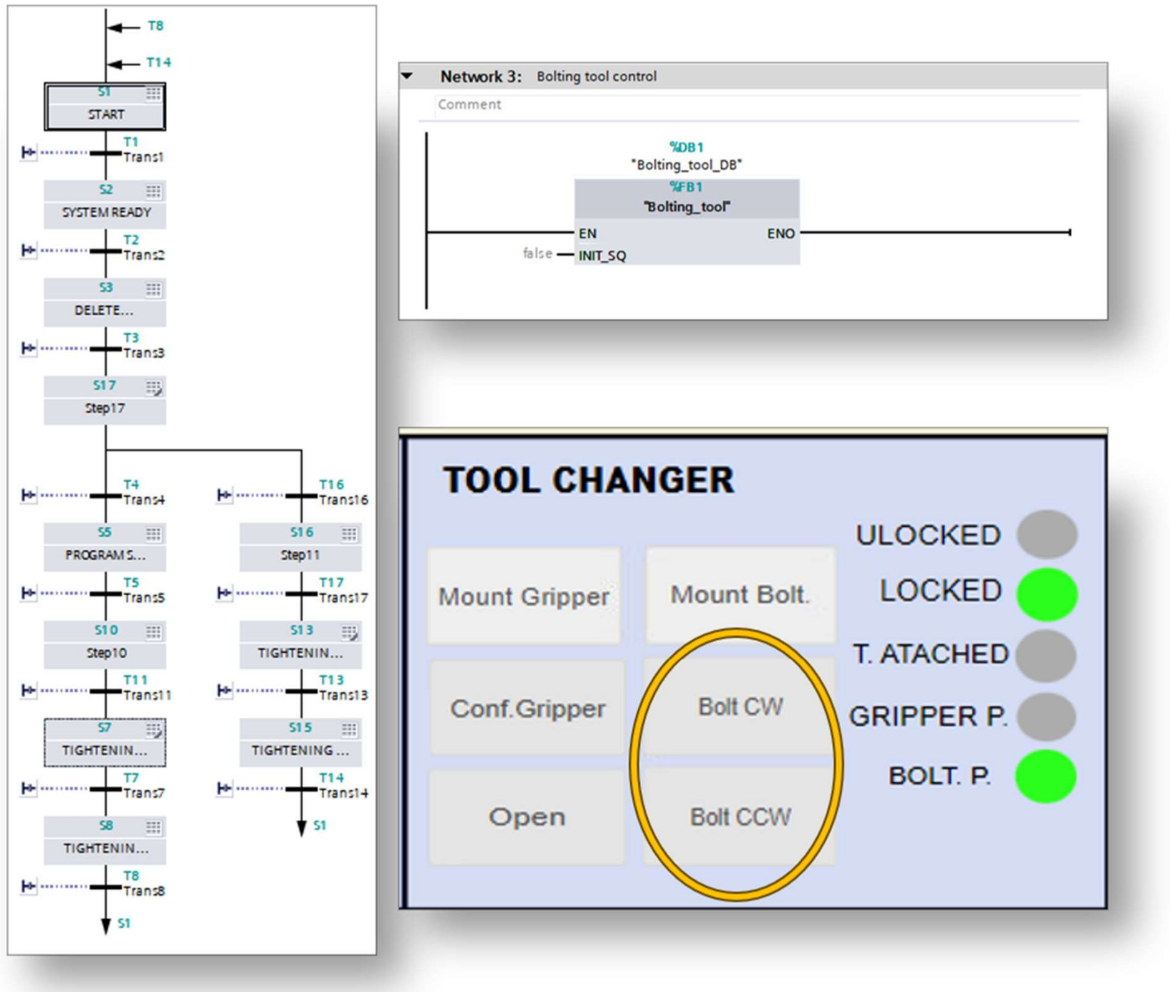


Figure 55: Grafcet FSM for bolting tool control (left side), function block instance of FSM (top right) and tigthening program selection buttons (bottom right)

5.4.6 Robotic arm control

The control of this device is the most challenging due to its complexity. It is divided into two main components: the first is responsible for inverse kinematics and managing the robot's internal functions, while the second handles the trajectories described by the operator through the haptic device, which is part of the VR system executed in Unity3D.

Figure 56: Diagram for the telemanipulation system, showing the inputs and outputs of each component.

The first component is in charge of the low level control. It runs on the robot's CS9 controller (ID 17), and is in charge of controlling actuators and sensors, calculation of inverse kinematics, monitorization of basic parameters, and basic protection functions. This implementation uses the manufacturer's software, Staübli Robotics Suite (SRS 2022.7.0), which allows the development of applications through a proprietary language called VAL3. This software also facilitates the configuration of various robot parameters, communication management, and real-time or simulation-mode visualization of the robot's 3D model.

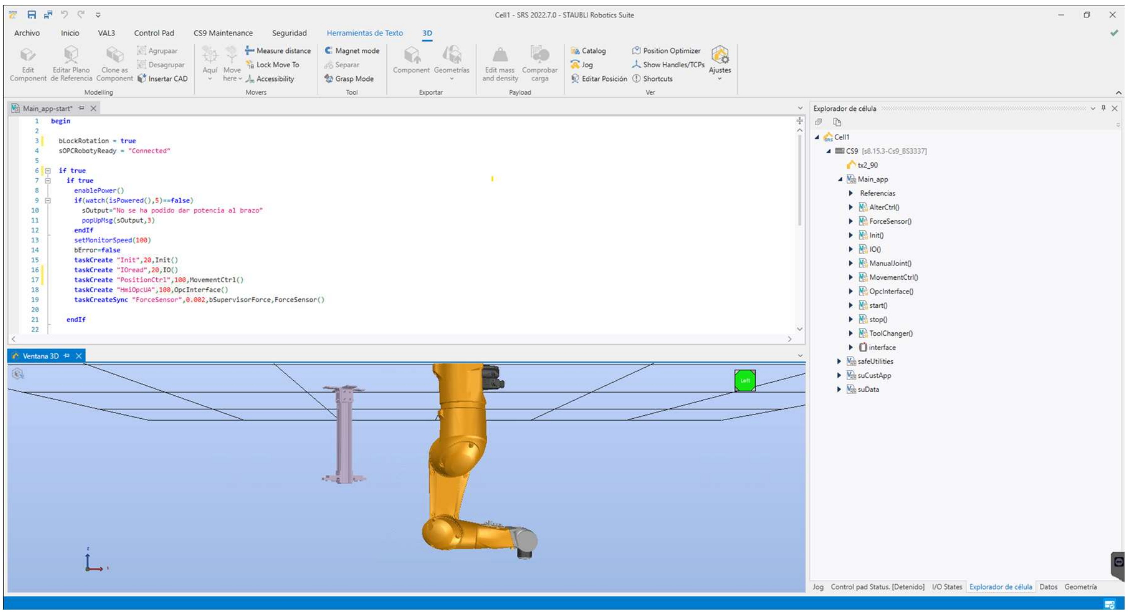


Figure 57: SRS 2022.7.0 main view. Top left windows shows a VAL3 program, bottom left window shows the 3D view and right windows shows the programs used by the robotic application.

The application is divided into different tasks, each of them in charge of a different functionality. The most important are described below:

- IO(): manages input/output signals associated with the robot's external sensors (doors, tool changer, emergency stop).
- OpcInterface(): initializes the variables communicated to the outside from the robot and updates their values in each execution.
- ForceSensor(): manages communication with the force sensor, initializing it and decoding the messages received. It checks that the forces sensed in each axis do not exceed the established threshold, and in positive case it activates a collision flag that inhibits the movement in the corresponding direction.
- MovementCtrl(): manages the three programs in charge of robot movement (AlterCtrl, ToolChanger, ManualJoint). The movements of the robot can only be commanded from a single program simultaneously. This program is in charge of launching or killing each of these three tasks depending on the mode selected by the user.
- ManualJoint(): allows the individual control of each joint of the robot.
- AlterCtrl(): allows manual real-time control of the robot's TCP. This task controls the real-time position of the TCP by applying a transform (x,y,z,rx,ry,rz) with respect to a starting point. It first decodes the position received via UDP, checks that the resulting displacement does not exceed configurable maximum values and performs the kinematic calculations to obtain the desired TCP displacement. Displacement will not occur in an axis if a force above the set threshold has been detected. It also allows the “Follow human” mode and change the movement ratio with respect to the haptic device input (so called “Precise mode”).
- ToolChanger(): manages the tool exchanger. It collects sensor signals and user commands, checks that the conditions are correct, and executes the appropriate sequence of pre-programmed movements for the tool exchange.

There are three main operating modes defined for the robot. The first one is the "Manual control", which allows to select the position of each of the six joints in degrees.

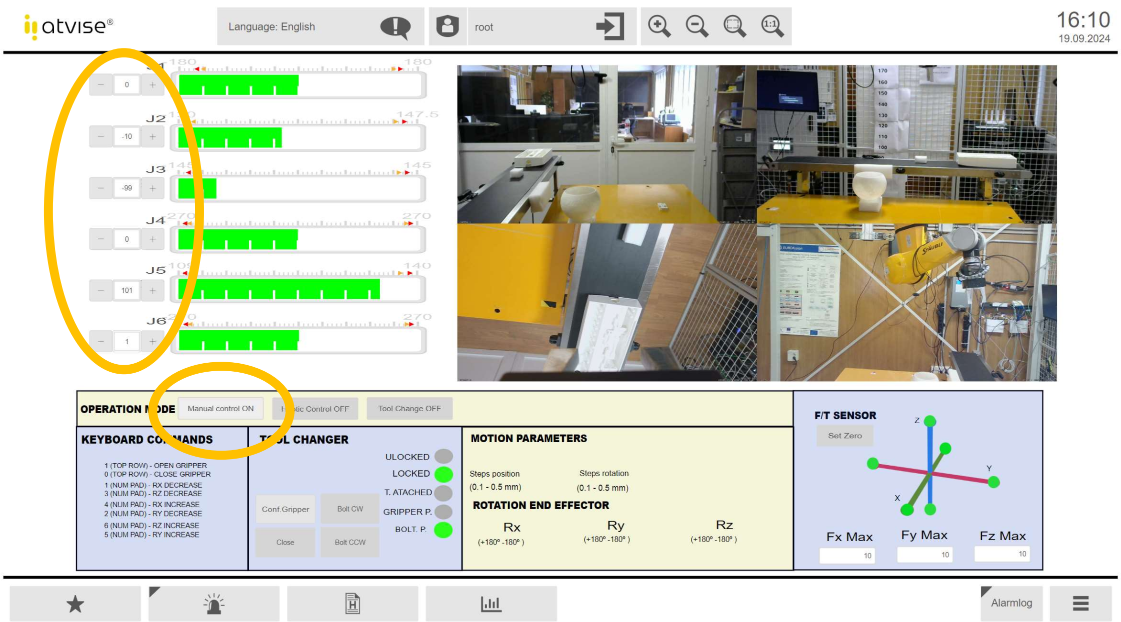


Figure 58: Manual mode controls. Enables joint control buttons and disables motion parameters and tool change buttons.

The second is the "Tool change" mode, which allows to perform the tool exchange by executing preprogrammed sequences for the approach to the rest station, the search of the contact point with the tool plate, and the safe coupling by means of the pneumatic system.

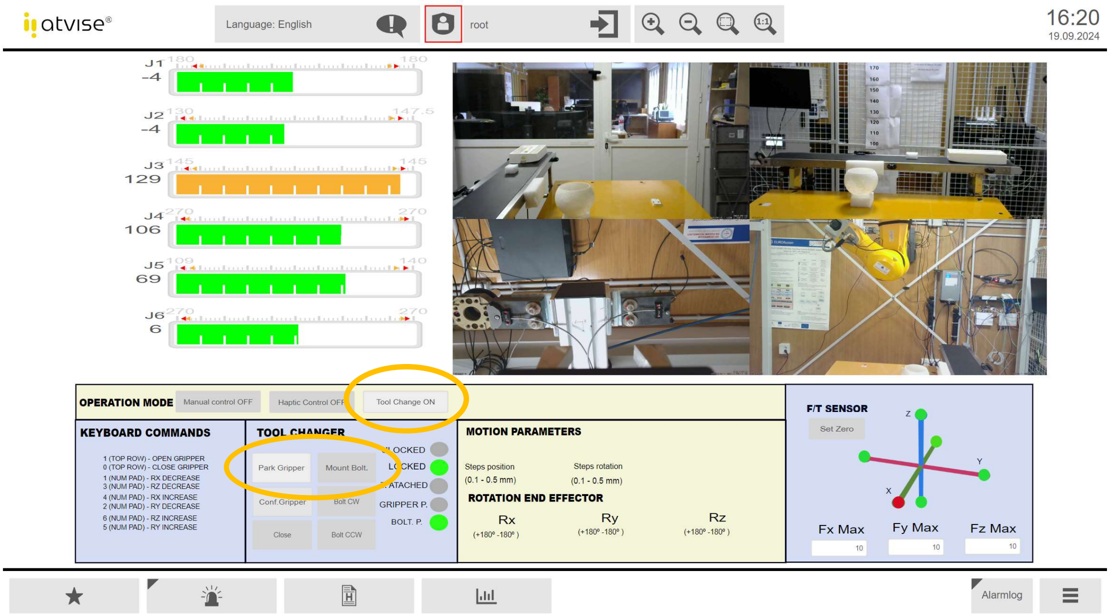


Figure 59: Tool Change mode. Enables Park/Mount buttons for the gripper and bolting tool, and disables motion parameters.

The third mode is the “Haptic mode”, which enables real-time position control of the robot's TCP from an external system, and in turn enables two additional sub-modes. The first sub-mode enables precise control of the TCP (“Precise mode”), adjusting the motion ratios between haptic device and robot to perform a smaller movements. Figure 60 illustrates the Fast mode, with a robot TCP displacement of about 20 cm for the haptic device travel shown. Figure 61 illustrates the Precise mode, showing a robot TCP displacement of about 2cm for the same haptic device travel.

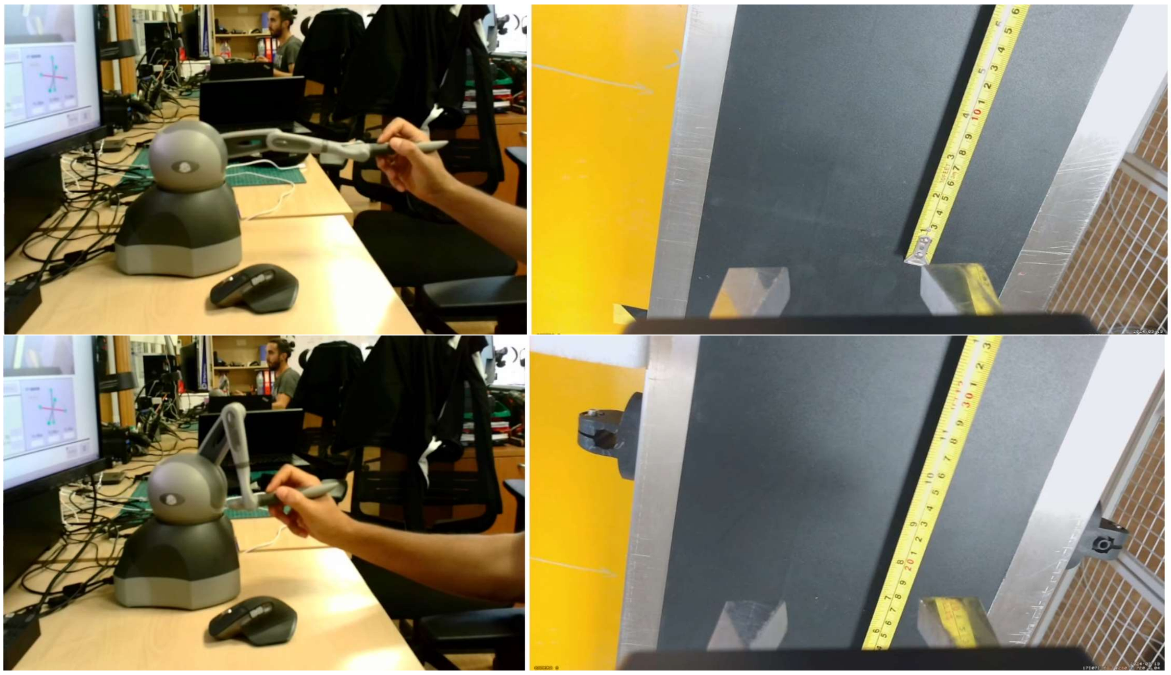


Figure 60: Haptic control in Fast mode. The maximum travel with a single stylus displacement is 20 cm.

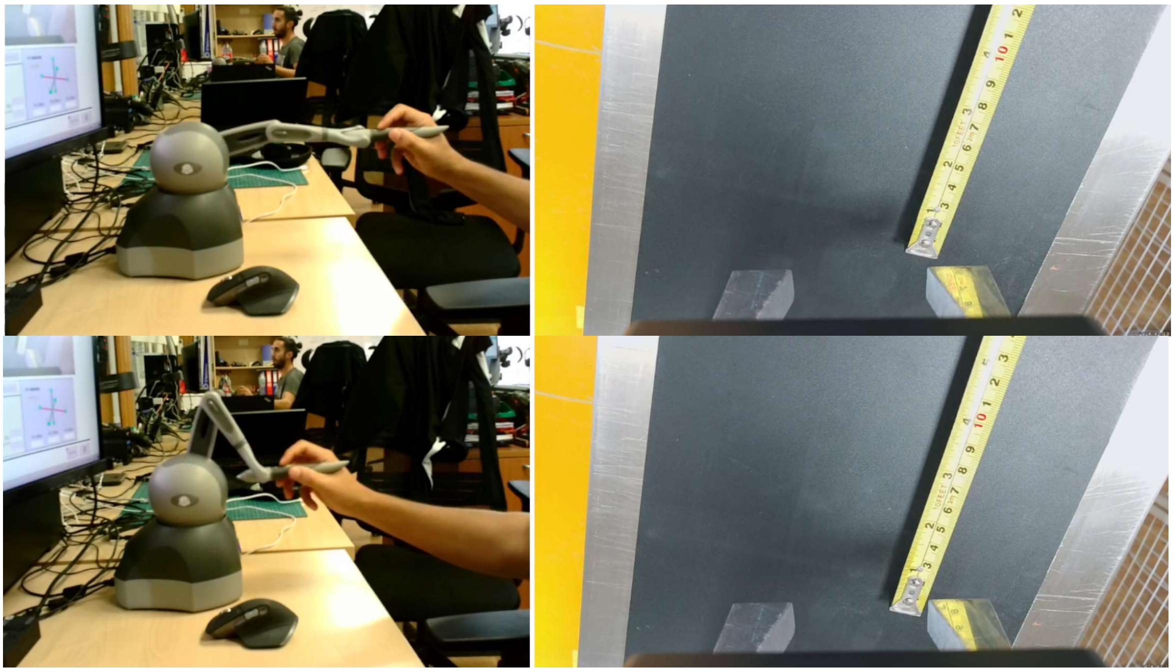


Figure 61: Haptic control in Precise mode. The maximum travel with a single stylus displacement is 2 cm.

The second sub-mode within the "Haptic mode" allows the user to pull the robot's wrist to guide it to the desired position by means of the forces detected by the F/T sensor. This feature is useful to teach robot positions and check robot range.

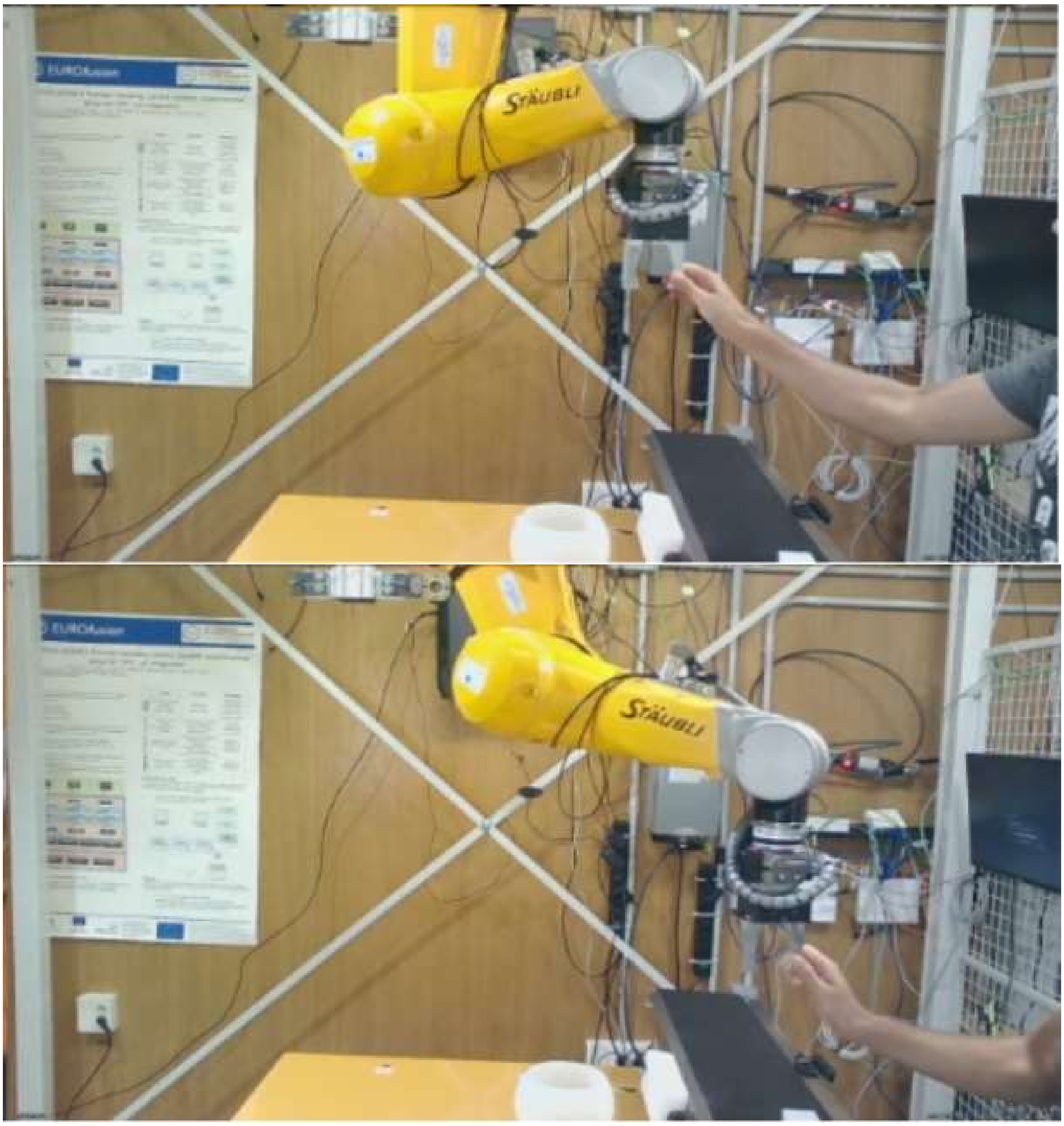


Figure 62: Manually guiding the robot using the F/T sensor. It moves by pulling the tool equipped by the robot, and stays in place as soon as the force is released.

The second control component for the robotic arm has been developed in Unity3D, primarily focusing on managing the haptic device. Unity3D programming involves two main aspects: a graphical component and a scripting component. The graphical part is centered on using components or objects that are hierarchically organized and configurable via the Inspector, which provides customizable parameters for each object. The scripting part allows the implementation of control strategies using C# and libraries such as OpenHaptics, which enables advanced control of the haptic device.

The communication between the haptic device (managed through the virtual scene) and the robot controller is bidirectional and operates in near real-time. From the haptic device to the robot, the position of the "end point" (corresponding to the tip of the stylus) is transmitted whenever the user presses the button on the stylus. In the opposite direction, force sensor data is sent to provide basic force feedback on the haptic device, allowing the user to detect contact between the robot's TCP or whether a load is being held.

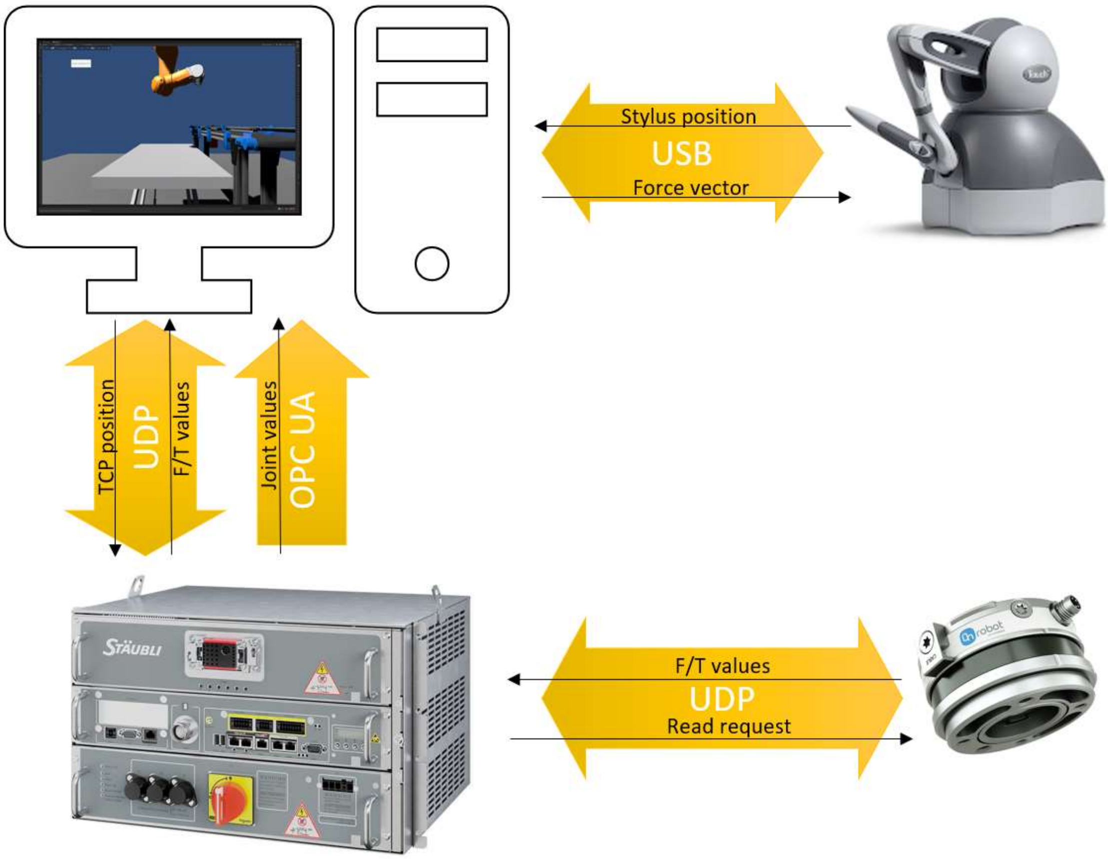


Figure 63: Data flow and components used to implement haptic control with force feedback.

Achieving high precision and real-time force feedback, crucial for bilateral teleoperation systems, typically requires a control loop frequency of 1KHz or higher, as indicated in [98]. While the industry standard for ensuring responsiveness and stability is a minimum frequency of 500Hz, our system currently operates at approximately 100Hz. Despite this, and the inherent limitations posed by using a non-real-time operating system (Windows 10) and Unity3D (which limits the control loop to the frame rate on the running scene), our solution successfully delivers a haptic feedback experience that significantly enhances user interaction with the remote environment. This allows operators to perceive critical events, such as tool collisions, and respond effectively, thereby maintaining a high level of situational awareness. While there is room for improvement in terms of loop frequency, the current system provides a valuable and functional feedback mechanism within these constraints.

This feedback is subject to a slight delay, making it essential for the robot controller to handle collisions internally, ensuring that no excessive force values are exceeded that might cause damage. When attempting to touch a surface or slide while maintaining constant pressure, the feedback exhibits a "bumpy" behavior, so the force values presented to the user are limited. In certain situations, it may be preferable to disable the feedback entirely to prevent unreliable force responses.

5.5 Results and discussion

The following section describes the RH operation defined to evaluate the test bench. Subsequently, the results obtained will be analyzed, and the conclusions drawn will be discussed.

5.5.1 Experimental setup

To evaluate the previously described functionalities, a representative RH operation has been designed based on the extraction procedure of the irradiated material samples. This operation is of interest for the DONES project, since it will be a key procedure that will allow a second irradiation period to be performed. The capsules (and the sensors inside them) have a lifetime equivalent to one irradiation campaign. Therefore, those samples of materials to be irradiated in a second or successive irradiation campaign will have to be removed from the irradiated capsules and reinserted in new capsules.

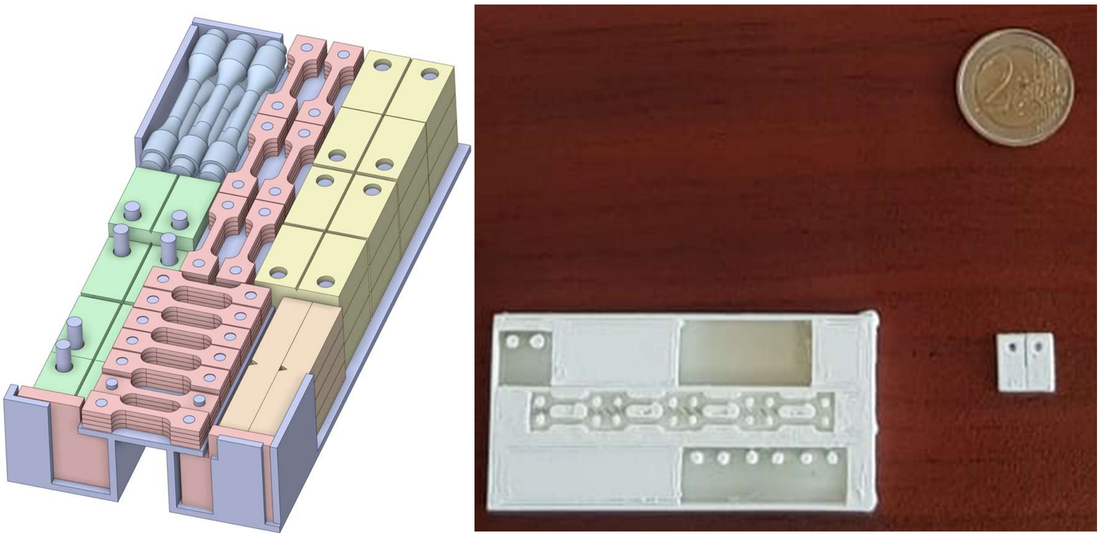


Figure 64: CAD design of the capsule containing the material samples (left) and 3D printed mockup (right)

This operation would not be part of the RH maintenance campaigns at DONES, since it would be performed in a hotcell inside the facility not related to the RH Control Room. However, it was chosen as requested by the project to evaluate its feasibility. Due to its high complexity and required accuracy, we will be able to ensure that the developed system is suitable to perform other simpler RH operations such as those expected to be performed during maintenance campaigns.

The procedure has been redefined to adapt it to the capabilities of the laboratory and to use the tools available in the laboratory. To handle such a small sample size, a custom-designed manipulator is required, capable of equipping different suction cups to handle the different sample formats. In the report [99] a set of tools and supports designed for the handling of the original capsules and samples is presented as shown in Figure 65.

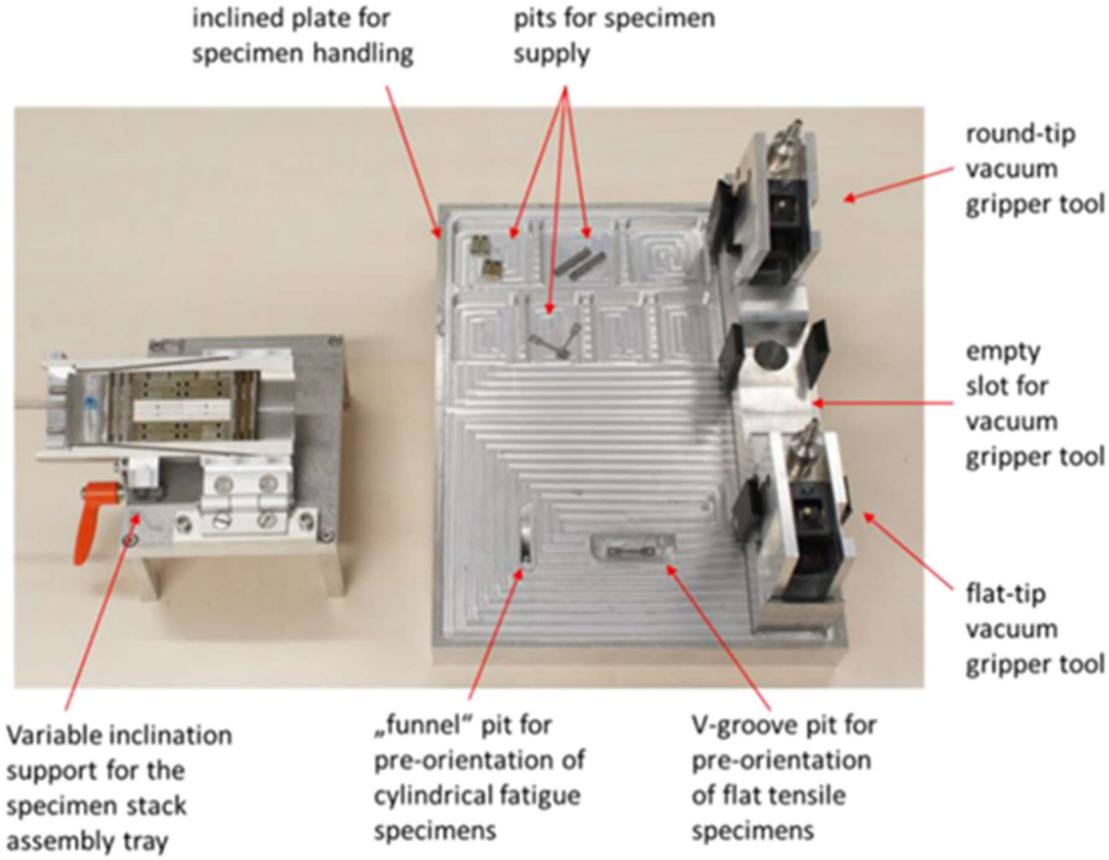


Figure 65: Tooling and supports to perform sample extraction from irradiated capsules [99]

In our case, the capsule and samples used for the procedure have been 3D printed at 4:1 scale, so that they can be manipulated with the two-finger manipulator.

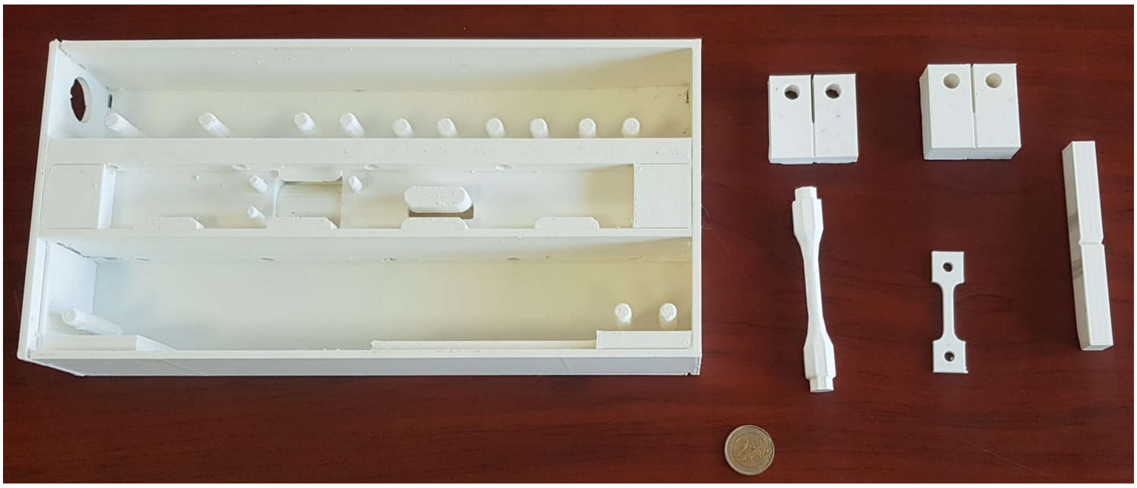


Figure 66: Capsule and samples 3D mockup scaled up to 4:1

Initially, the samples are inserted into the capsule and it is welded to ensure tightness. The actual procedure will involve the use of a cutting tool to create an opening in the top face of the capsule. Once the irradiated samples have been introduced into the new capsules, they must also be welded. As these cutting and welding operations cannot be carried out in the laboratory, a pointer with a marker will be used to perform a "simulated cut/weld" over the surfaces. This will replace the screwdriving tool, which will not be necessary in this procedure.

Figure 67: Pointer used to simulate cutting and welding by marking the edges on the part.

The operating conditions and procedures must respect the RH concept. It is not permitted any manual intervention within the work area, except for setup preparation before the start of each test and later for data collection. The operator will not have direct view to the work area and will be guided solely by the camera system and the virtual scene.

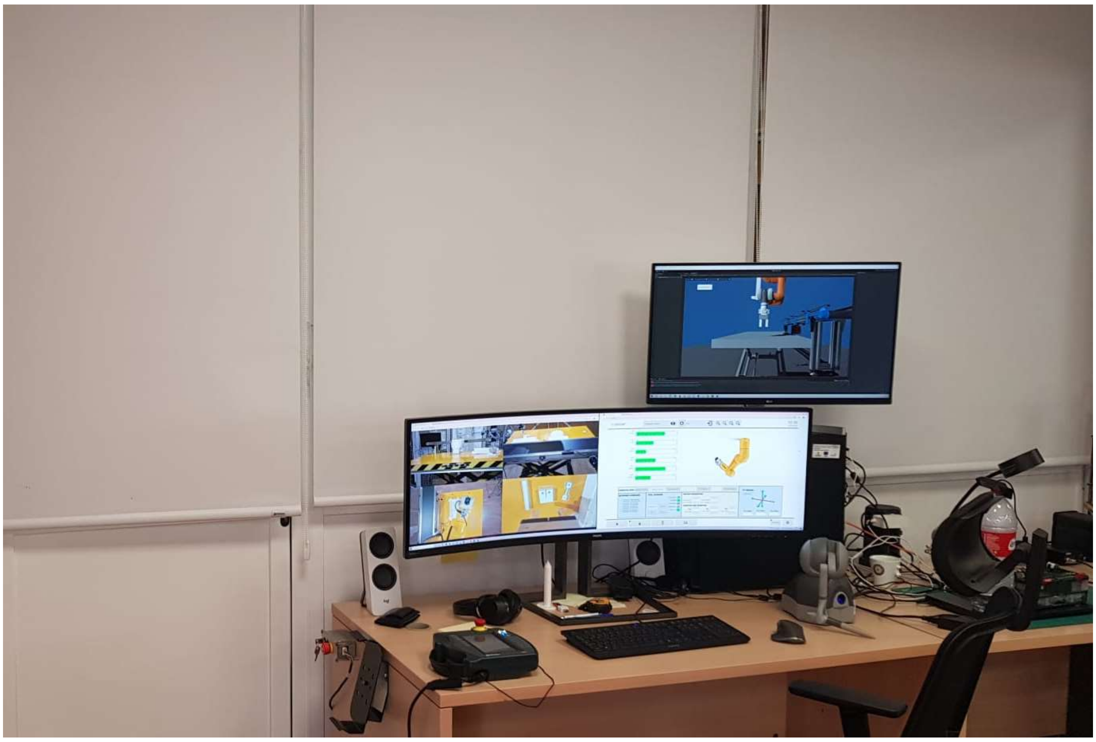


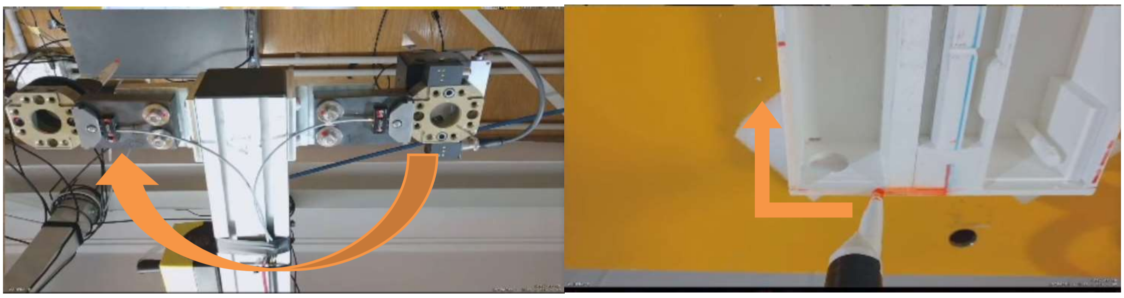
Figure 68: Operator Workstation without direct view to the robotic cell. The roller-blinds allow to cover the direct view of the robotic cell.

The procedure has been described through a series of actions or steps that are understandable by the operator using natural language. Since this is a novel procedure that has not yet been thoroughly studied, the actions are described at a high level without specifying concrete actions or values. It is expected that these details will be identified by the operator through experimental and iterative processes. Therefore, the procedure will gain more detail as each of the four high-level steps outlined below is completed:

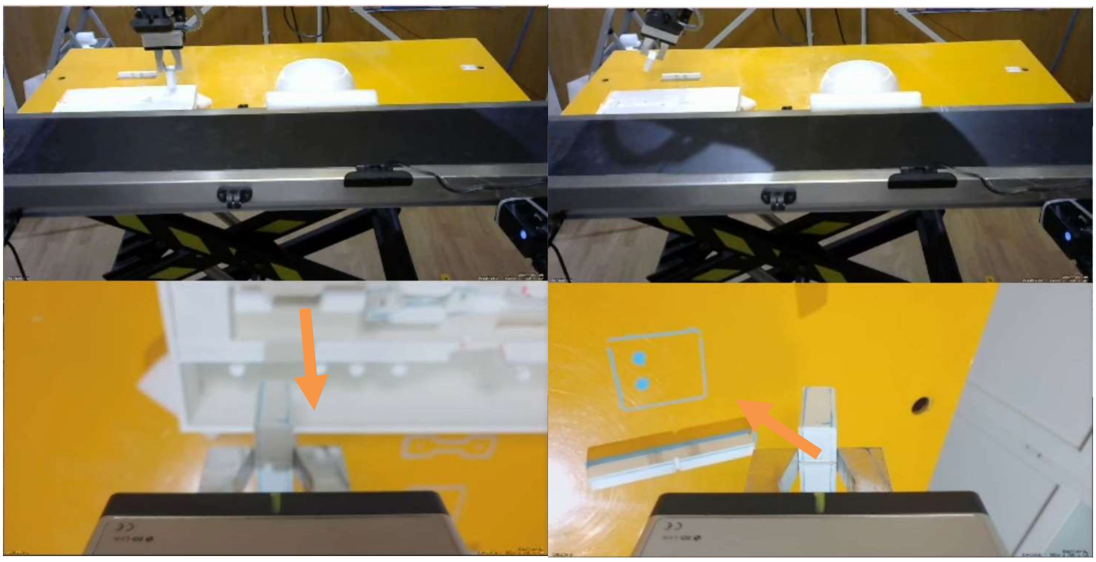
- Step 1: Capsule Introduction. Move the capsule into the work area, positioning it within the reach of the telemanipulator. To do this, the capsule should be placed at an appropriate height using the lifting platform and at a suitable distance using the conveyor belt.

- Step 2: Place Capsule on the Lifting Platform's work surface. Use the gripper to pick up the capsule from the conveyor belt and place it in the designated area on the lifting platform.

- Step 3: Partial Cut of the Capsule's upper face. Perform a tool change using an automatic sequence. Use the pointer tool to trace the marked edge of the upper face, simulating a cutting operation. The tool must remain in contact with the capsule's edge throughout the entire cutting path.



- Step 4: Extraction and Placement of Samples. Remove three samples of different formats from inside the capsule. Place each sample in the designated area, ensuring they fit within their corresponding silhouettes.



5.5.2 Results of task execution

For each attempt, the entire sequence was recorded from perspectives that include the two monitors used at the operator's station, as well as a view of the haptic device as shown in Figure 69. Table 11 summarizes the results of the first 15 attempts, indicating PASS or FAIL, the reason for failure, a mitigation measure, and the time taken for each attempt. The mitigation measure shall be used to include actions or modify the procedure to avoid the cause of failure.

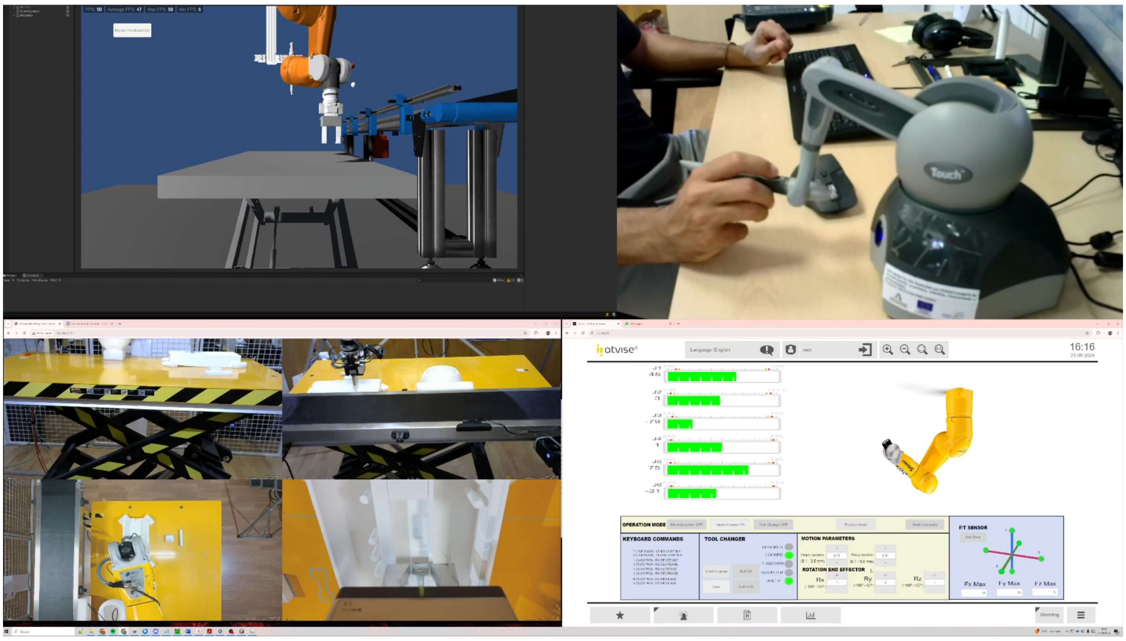


Figure 69: Recording of the task execution. Shows the virtual scene (top left), the haptic device and user manipulation (top right), the viewing system (bottom left) and the control panel (bottom right).

Trial	Result	Fault	Mitigation	Execution time
1	Fail (step2)	The gripper's closing position is insufficient to grasp the capsule by its side walls.	Manually modify the OPC UA variable that defines the gripper's closing position to reduce the gap between the fingers.	2:06
2	Fail (step2)	Overspeed in joint 3 due to a complex arm pose.	Avoid lifting the capsule too high when transferring it from the	3:38

			conveyor belt to the platform.	
3	Fail (step 3)	Unable to perform the cut as the capsule slides on the platform.	Add a support to secure the capsule to the work surface.	9:24
4	Fail (step 2)	Unable to place the capsule in the support due to poor grip on its side walls.	Create a gripping point at the center of the capsule for more stable handling.	8:18
5	Fail (step 3)	Overspeed in joint 3.	Perform smoother movements and identify whether the failure occurs in Fast or Precise mode.	8:30
6	Fail (step 2)	Overspeed in joint 3 due to the commanded TCP position being out of range.	Raise the platform to a height of at least 1.20m to prevent the TCP from going out of range.	4:31
7	Fail (step 3)	Collision with the platform during the tool change.	Lower the platform below 80cm before each tool change.	4:58
8	Fail (step 3)	The return path after the tool change encounters a singularity that cannot be crossed.	Adjust the robot control strategy to avoid passing through the singularity.	5:37
9	Fail (step 4)	Overspeed in joint 1 when applying rotations in X and Y.	Avoid abrupt rotations in X, Y; use the control panel's +/- indicators for gradual adjustments.	24:30
10	Fail (step 4)	Overspeed in joint 1 due to the arm pose needed to place the samples.	Change the sample position to ensure better arm posture.	18:56
11	Fail (step 4)	The third sample jumped while being extracted and fell into a	Modify the sample's initial position to facilitate easier extraction.	42:23

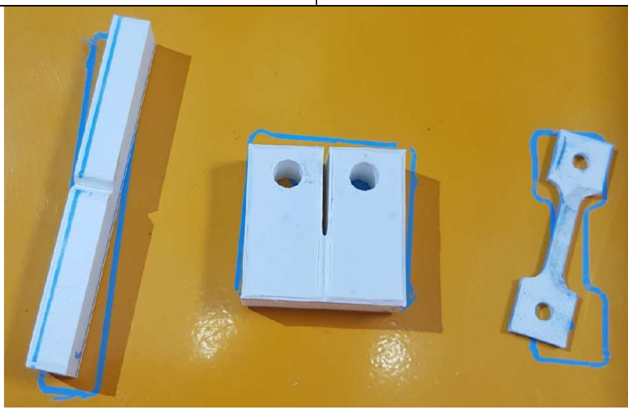
		difficult-to-retrieve position.		
12	Fail (step 1)	Overspeed in joint 3; the arm pose at the start of the sequence was not the intended start position.	Start the operation with the robot's program freshly restarted.	1:39
13	Pass			21:22
14	Fail (step 4)	The third sample jumped while being transported to its destination due to snagging on the capsule.	Lift the sample at least a couple of centimeters after extraction to avoid contact with the capsule and prevent it from falling.	24:04
15	Pass			23:40

Table 11: Results of RH procedure execution

The results of the fifteen trials made have been collected in the Figure 70 where the result (including the step in which the sequence failed) and the execution time of each trial are shown. A key observation from the graph is that Step 4 occupies most of the execution time across attempts, consuming more than half of the total time. Many failed attempts were caused by joint overspeed, typically occurring when trying to position the TCP outside the robot's reachable range. This issue stems from the fact that the trajectory is described within Unity3D, while the robot's kinematics are computed on its controller. The system does not validate whether the user-defined target position is reachable by the robot since motion planning and kinematic calculations are executed independently. By integrating both motion planning and kinematics within a single control node, 6 out of 13 errors could have been avoided, specifically those related to joint overspeed.

Trial 11 demonstrates how execution time can dramatically increase when encountering unforeseen scenarios, such as the falling of a piece into a hard-to-reach area that could not be recovered.

For the successful attempts, there is a notable trade-off between precision and execution time. Once critical points and failure conditions were identified in trial 13, the user was able to learn and adapt the procedures, completing trial 15 in a similar amount of time while almost completing trial 14 as well.

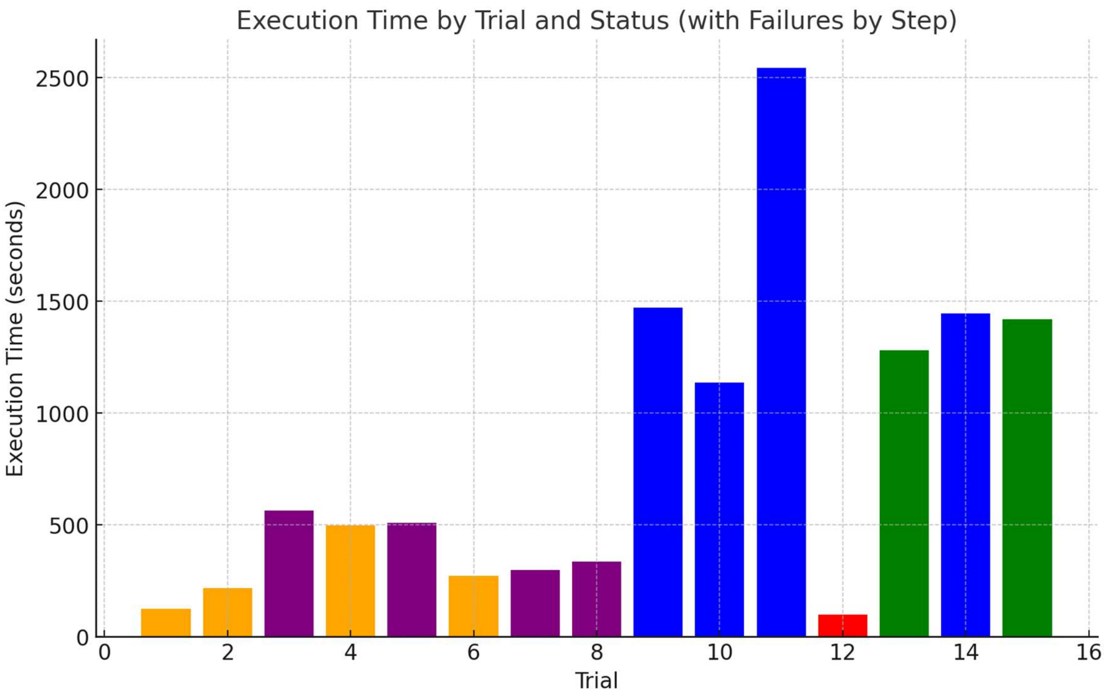


Figure 70: Execution time per trial. The color indicates the step in which the error occurred: Red: Step 1, Orange: Step 2, Purple: Step 3, Blue: Step 4, Green: PASS.

5.5.3 Conclusions of Chapter 5

In this chapter, two of the five main tasks of this thesis are addressed, providing the following results:

- T5. Experimental Validation: A specific RH operation will be described on this section to evaluate the functionality and performance of the test bench developed in Section 5.1.
- T4. Intervention Time Improvement: The execution times for the described RH operation was studied in Section 5.5.2, identifying operations that require the most time and proposing improvements to reduce these times.

The test bench has been successfully validated through the execution of a remote manipulation task in a semi-structured environment, with a human operator integrated into the control loop. The task was performed under controlled conditions, such as predefined initial positions for the capsules and fixed locations for both the capsules and the samples, enabling an evaluation of execution times over multiple trials. These controlled conditions would allow for potential automation of most actions, but any deviation from these conditions would cause the process to fail without the ability to adapt. The flexibility and capabilities of the test bench are primarily driven by the operator's ability to assess the situation, respond to unforeseen scenarios and cover many different operations without any modifications on the control strategies or programming needed.

The use of industrial tools and standards has also proven valuable, significantly reducing development time and leveraging the functionalities provided by device manufacturers. The test bench demonstrated its capacity to handle components of various sizes with dexterity, ensuring the integrity of equipment, tools, and manipulated objects.

The results from the fifteen trials underscore the importance of thoroughly studying the procedures to be followed (ideally through simulations on a first approach and later in the physical setup) to minimize failed trials that could lead to situations that cannot be remotely managed. The training and learning process of the operator also plays a critical role, along with the integration of functions that help reduce cognitive load and provide guidance or assistance during operations.

Finally, the need to include motion planning functionality has been identified as a key factor in reducing execution times and minimizing the number of errors once the RH procedure is clearly defined. Combining this with the migration of kinematic calculations from the robot controller to one of the RH HLCS modules would help eliminate most of the errors encountered. By having trajectory planning and kinematics handled within a single module, it would be possible to discard positions known to induce singularities or joint over-speed conditions.

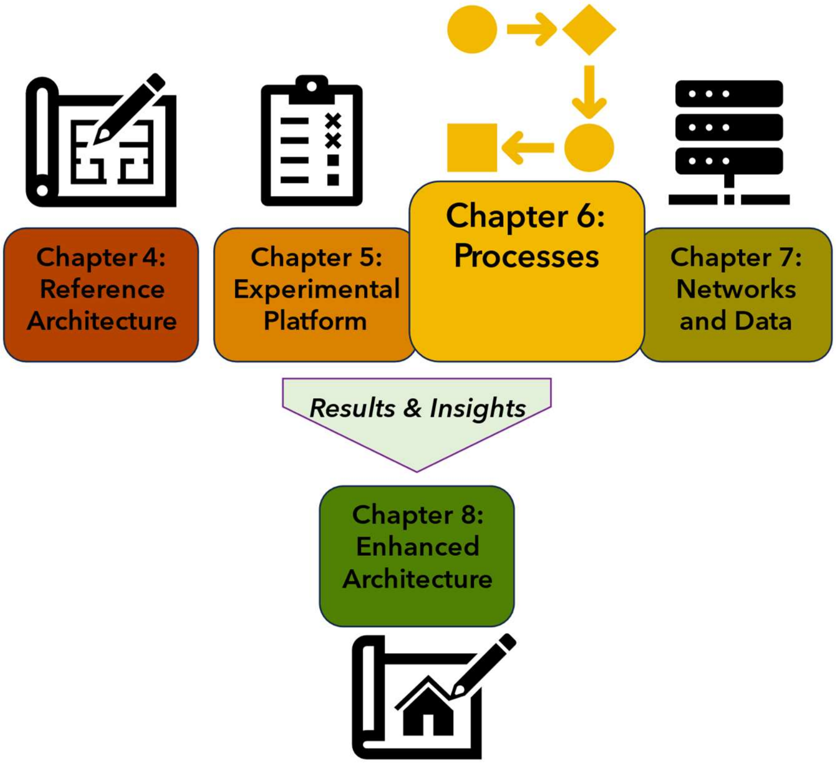
Chapter 6
RH processes at IFMIF-DONES

The chapter outlines significant advancements in defining the **roles, workflows, and tools** necessary for the **coordination and management of RH operations** and maintenance campaigns within the IFMIF-DONES facility. It integrates both theoretical and experimental contributions, emphasizing the use of **structured languages** for task definitions, the development of an **expert Supervision System**, and the evaluation of practical **workflows** specifically tailored to RH requirements.

A key focus of the chapter is the critical role of **process management** in the efficient operation of RH systems. Topics such as role assignments for RH users, the adoption of human and machine interpretable semantics, and the definition of **coordination mechanisms between the CICS and the LICS** are thoroughly explored. These elements are crucial for understanding the functioning of RH systems in IFMIF-DONES and have a direct impact on the design and implementation of the control architecture.

Furthermore, the chapter evaluates open process management tools for their suitability in the RH Supervision System. It presents an in-depth analysis of task parallelization strategies and workflow visualization tools, offering insights into their practical application. Experimental results are discussed, particularly those involving **bridging technologies like OPC UA and EPICS**, which were tested for seamless integration between the CICS and the RH LICS. By combining these methodologies and technologies, the chapter lays a solid foundation for increased automation in RH campaigns, while underscoring the importance of human oversight and expert intervention to maintain operational safety and adaptability.

6 .RH processes at IFMIF-DONES



From an organizational perspective, understanding the processes and procedures associated with RH is essential to ensure the system's effectiveness and safety. Processes define the broader workflow and objectives of RH operations, while procedures specify the detailed steps needed to accomplish each task. These aspects influence not only the structure of the control system but also its interfaces, decision-making capabilities, and error management strategies. However, this aspect has not yet been addressed in the IFMIF-DONES project, which leaves empty gaps on the RH System specifications, and consequently its control systems.

In this chapter, our contribution focuses on analyzing the RH system from an organizational viewpoint, focusing on the definition of user roles, the use of structured languages for task descriptions, the coordination with the CICS, and the creation of workflows. We also propose the design of an expert supervisory system to manage RH operations more efficiently, aligning the control system's capabilities with operational demands and improving overall system performance.

6.1 RH Users

For the successful execution of RH maintenance campaigns, the coordinated participation of personnel located in both the Central Control Room (CCR) and the RHCR is essential. Each person involved plays a distinct role, defined by their responsibilities and the actions they are authorized to perform. These roles ensure that the complexity of RH operations is efficiently managed and that the control system architecture is properly aligned with organizational needs. Below are the four primary roles identified within the RH system.

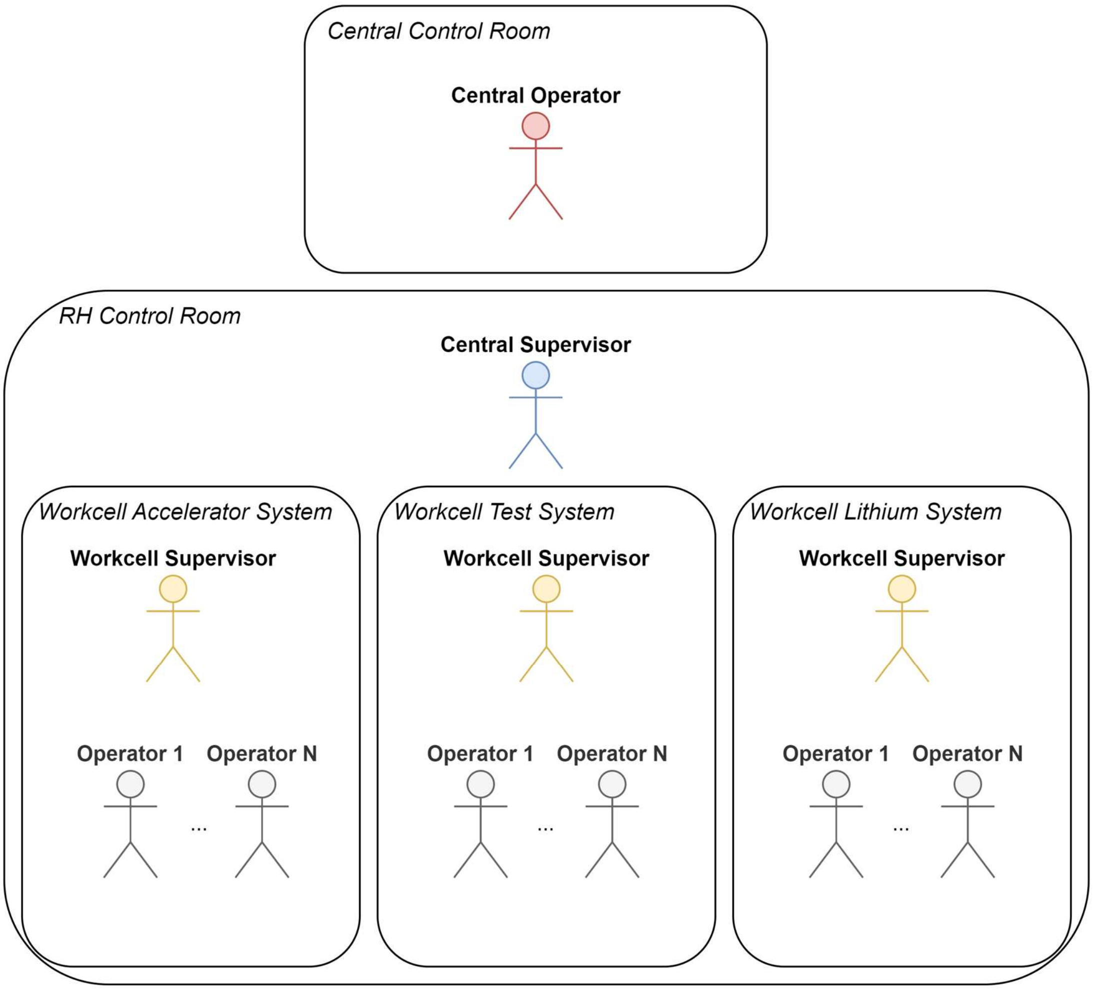


Table 12: Hierarchy of RH roles

6.1.1 RH Central CICS Operator (Central Operator)

The Central Operator is stationed in the CCR and possesses a deep understanding of the systems requiring remote intervention. In this role, the operator has access to LICS OPIs (Operator Interface Panels) for the systems that are being maintained and is familiar with both the RH procedures and RH devices. Its main responsibility is to support the RH team by facilitating interactions with other LICS. These interactions include tasks such as checking plant preconditions for RH intervention, obtaining sensor readings, and executing acceptance tests. The Central Operator acts as the interface between the plant systems (which are controlled and monitored only from CCR) and RH team in the RHCR, ensuring proper synchronization during maintenance operations, and providing real-time feedback on system status.

6.1.2 RH Central Supervisor (Central Supervisor)

The Central Supervisor works from the RHCR and has an extensive knowledge of the RH procedures and devices. Their primary responsibility is to organize and manage operations within the RHCR, including the assignment of tasks to various workcells. This role is crucial in ensuring that the right people and resources are directed to the appropriate tasks and that safety protocols are strictly followed. The Central Supervisor is the highest authority in the RHCR during maintenance campaigns, responsible for overall coordination and decision-making. They also act as a liaison between the operators and the Central Operator, ensuring that work progresses smoothly. This individual must always be present when the RH system is operating, as they oversee the entire maintenance operation and handle any emergencies or unexpected issues.

6.1.3 RH Workcell Supervisor (Workcell Supervisor)

The Workcell Supervisor is responsible for managing specific maintenance areas or workcells within the RHCR. Each workcell will have its own supervisor who is an expert in the RH procedures and devices related to that particular facility systems. The Workcell Supervisor's main goal is to support the operators within their workcell and ensure that tasks are executed according to the established procedures and within the designated timelines. This role involves direct management of up to three or four operators per workcell, ensuring that communication and coordination remain fluid. They also report to the Central Supervisor, relaying critical information on task progress, safety issues, or equipment malfunctions.

6.1.4 RH Device Operator (Operator)

The RH Device Operator works directly with the RH devices, controlling them from the RHCR to perform remote interventions. Their main responsibility is to execute tasks assigned by the Workcell Supervisor, following detailed instructions and using the software and hardware interfaces of the RH system. Operators require strong technical skills to handle RH devices and respond effectively to unexpected challenges. In addition to performing remote tasks, the operator must provide continuous feedback on the status of the interventions, ensuring that any issues are communicated quickly to supervisors for resolution.

6.1.5 Implications for the RH Control System

The distinction between these four roles ensures a clear chain of command and structured flow of information. Each role has a specific focus, but all must work in close coordination to ensure the safety and efficiency of RH operations. The Central Supervisor manages high-level organization, while the Workcell Supervisors ensure that operators can execute their tasks smoothly within their specialized domains. The integration of the Central Operator guarantees that any interactions with other plant systems are handled efficiently. This coordination reduces the likelihood of errors and maximizes the efficiency of maintenance campaigns.

The definition of these roles has significant implications for the design and operation of the RH Control System. A well-structured control architecture must account for the hierarchical structure of decision-making and task execution. By designing the system around these user roles, we ensure that automation and human intervention are optimally balanced, providing both flexibility and control over RH operations.

In addition to these defined roles, the use of a structured language for RH task definitions will further enhance communication between the human operators and the control system. This will be essential for the definition of workflows and a supervisory expert system to improve automation and decision-making, reducing the maintenance periods.

6.2 Applicability of RH Structured language

Remote maintenance operations in the IFMIF-DONES facility will rely on structured, predefined procedures to ensure consistency, accuracy, and safety. The use of SL for defining these procedures is a widely accepted practice in facilities with complex remote maintenance needs. These languages combined with flowcharts allow for the clear definition and management of RH operations and offer opportunities for automation of the processes.

The importance of structured languages can be seen throughout the entire life cycle of a maintenance campaign:

- Definition: SL enable the RH procedures to be described using a standardized syntax and ruleset. This standardization ensures consistency and provides a common understanding between different stakeholders. The syntax of the language allows for accurate documentation of each task and step involved in RH operations, ensuring that procedures are clearly communicated to all operators.
- Simulation: Once defined, RH procedures can be simulated in virtual environments, allowing for the identification of potential issues such as collisions, inconsistencies, or unreachable poses. This process enhances the accuracy and reliability of the maintenance task by allowing it to be validated before actual implementation. The structured nature of the language makes it possible to automate parts of the simulation process, such as kinematics validation and path planning.
- Training: A key advantage of using SL is its ability to train operators who may not be familiar with specific procedures. The human-readable aspect of the language allows trainees to follow and execute procedures without needing prior knowledge of the operation. This simulation-based training helps reduce errors during live operations, as operators can familiarize themselves with the tasks in a controlled environment.
- Operation: During actual maintenance campaigns, SL allows for real-time monitoring and progress tracking. Operators can mark tasks as complete, and the system can automatically calculate the total percentage of the campaign completed, as well as update the estimated remaining time. This provides greater transparency and helps supervisors optimize resource allocation, ensuring the campaign progresses smoothly.

The VALERIA lab (Virtual reAlity Lab for sciEntific and industRIal fAcilities) has developed a structured language specifically tailored for RH procedures, known as VTDs (Virtual Task Descriptions) [100], and create virtual simulations of it to identify possible issues in advance. These VTDs, presented in an Excel-based format, break down each maintenance task into four levels of increasing detail. This hierarchical structure ensures that each task can be described at varying levels of complexity. The upper levels provide a broad overview of the process, while the lower levels delve into precise operational details.

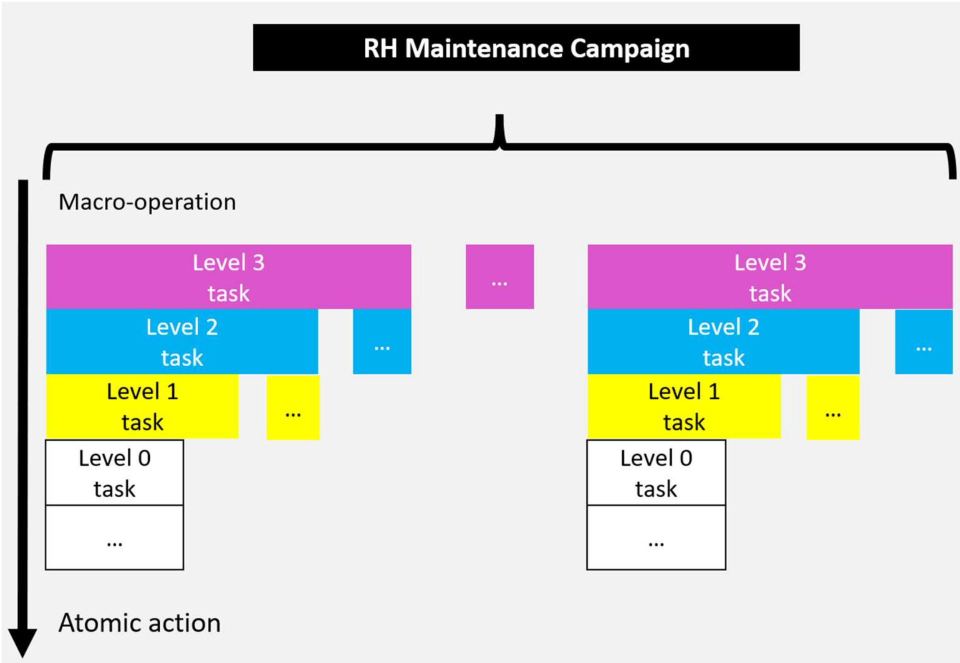


Figure 71: Decomposition of RH procedure in 4 levels. Campaign is composed by operations, which are divided in 4 levels starting from generic description down to atomic actions.

In addition to hierarchical definition of tasks by complexity, it is essential to establish temporal dependencies between them. Task parallelization (the ability to perform tasks simultaneously) plays a significant role in reducing the overall duration of maintenance campaigns. However, task parallelization is not straightforward, as it is constrained by factors such as the availability of RH devices and tooling, operator skill levels, or the presence of required spare parts. Each of these factors must be carefully considered to minimize plant downtime.

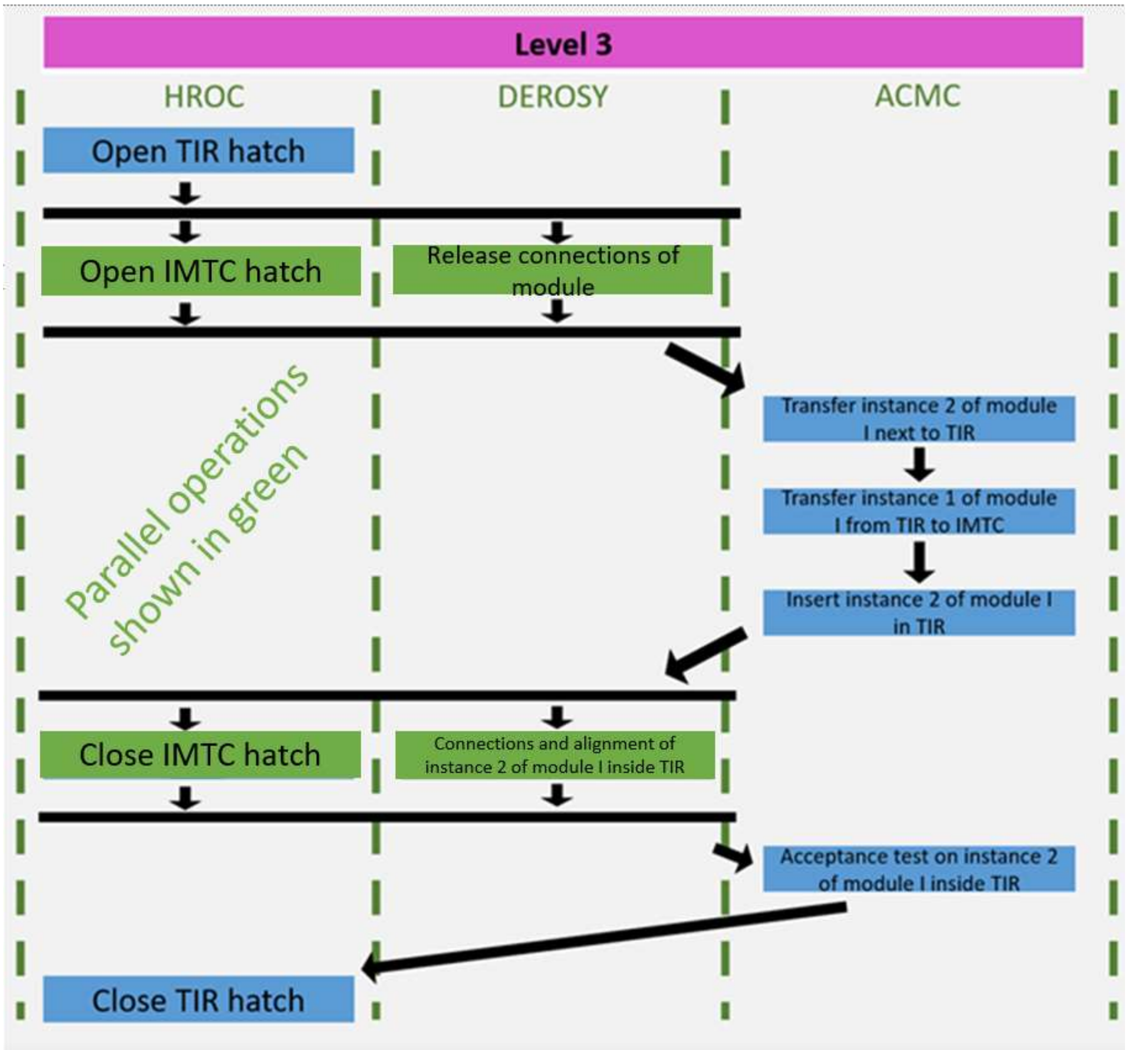


Figure 72: Example of task parallelization from TIR replacement VTD. Each column represents a RH device. It shows dependencies on different steps. Parallelization of steps at the same horizontal level is possible.

For example, in the TIR replacement procedure, parallelization is crucial to optimizing the workflow. Certain tasks can be performed concurrently if resources (such as RH devices or operators) are available, but these dependencies must be identified in advance to avoid delays. Diagrammatic representations of these workflows, as shown in Figure 72, allow for an at-a-glance understanding of which tasks can be performed in parallel and which must follow a sequential order.

To further enhance the management of RH procedures, studies such as [101] propose the development of an ontology for maintenance management. Ontology, in the context of computer science and systems engineering, refers to a formal and structured representation of knowledge within a specific domain. It establishes a shared vocabulary, outlines relationships between concepts, and defines the rules governing their interactions. In RH systems, the application of ontology addresses the critical need for semantic interoperability and structured knowledge representation, ensuring streamlined operations and efficient management. Ontologies have been proposed for similar applications and fields, such as [102] which focuses on generic maintenance activities or [101] that deals with industrial maintenance.

Although the creation of such an ontology requires significant development effort, it holds the potential to drastically improve the efficiency of RH systems, not just in DONES but in similar facilities across the field. By leveraging this approach, maintenance operations could be optimized, allowing for better resource management, reduced errors, and increased automation.

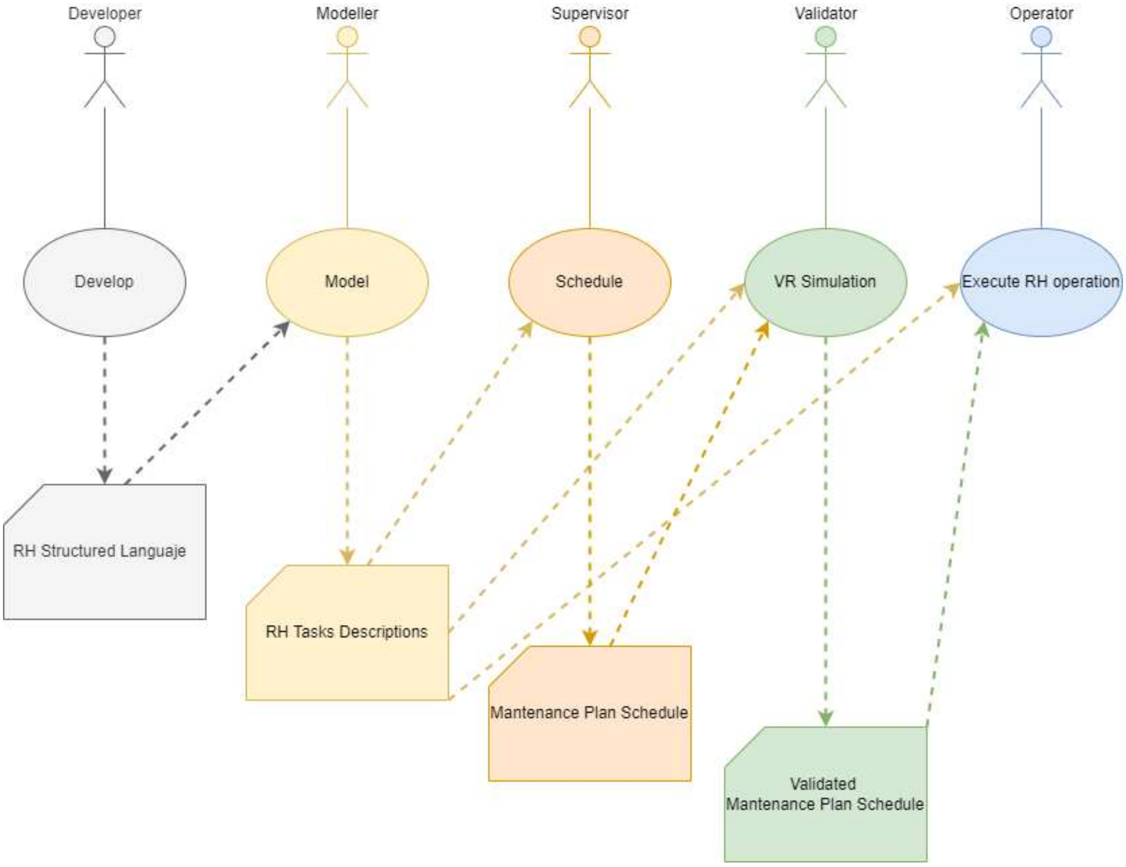


Figure 73: Roles, actions and outputs to develop and deploy RH ontology.

This effort will require a detailed and collaborative approach, involving experts from various fields to establish a comprehensive framework. The diagram presented in Figure 73 outlines the process for deploying such an ontology in the DONES environment, highlighting the steps needed to achieve that goal.

6.3 Coordination RH LICS-CICS

The coordination of maintenance campaigns, particularly those involving RH, will require the participation of numerous actors: the roles defined in Section 6.1, system managers of the components to be maintained, logistics personnel, safety officers, and more. Each individual involved will have a specific task and objective assigned. Similarly, the control systems in use will need to manage specific actions and automatisms in a coordinated manner. To facilitate this coordination, state machines will be implemented, abstracting the various plant states to ensure smooth operations.

In Section 3.1.3, we introduced the concepts of COS and GOS, along with the different maintenance states of the plant. These states play a crucial role in coordinating the interaction between the CICS and LICS. The COS is defined by a state machine that illustrates the possible states, sub-states, and transitions between them. For the COS of the RH system, there are specific considerations that must be addressed:

- The RH system will report only one COS, despite being a LICS composed of various complex devices. This COS is designed to be a summary of the overall status of the RH system, providing a high-level overview for the CICS.
- The RH COS must take into account the statuses of various RH devices, RH HLCS modules, and the RH Control Room. These different elements collectively define the system's operational state.
- The statuses of individual RH devices are reported to the CICS independently via diagnostic or control signals.
- The Plant Controller module will be responsible for reporting the COS to the CICS. This module acts as the primary interface between the CICS and RH LICS, ensuring accurate communication between the two systems.
- The module responsible for defining the COS is the Condition Engine, which determines the system's state based on various operational inputs.
- Each device's status within the RH system will be managed internally. The PLC/Controller will implement a finite state machine (FSM) that allows transitions between states, based on GOS and control signals from both the CICS and RH LICS.

To successfully carry out a remote maintenance campaign, certain preconditions must be met at the plant level to ensure its safe execution. These preconditions, which are external to the RH system, should be verified at the CICS level to ensure that the facility is correctly configured before beginning RH operations.

Conceptually, these preconditions can be viewed as a checklist that must be reviewed and approved, most likely by the RH Central Operator from the CCR, before the GOS can be switched to the appropriate maintenance state. This means that before transitioning the GOS to any maintenance mode, a manual (or automated, where possible) check needs to confirm that all items on the checklist are in order. This information is then input into the control system. All LICS that will be impacted by the RH operations, or that could potentially interfere with them, must be transitioned into a "safe COS".

Figure 74 represents the sequence of actions required to change the maintenance mode indicating below the expected level of automation of each stage of the sequence according to Table 22.

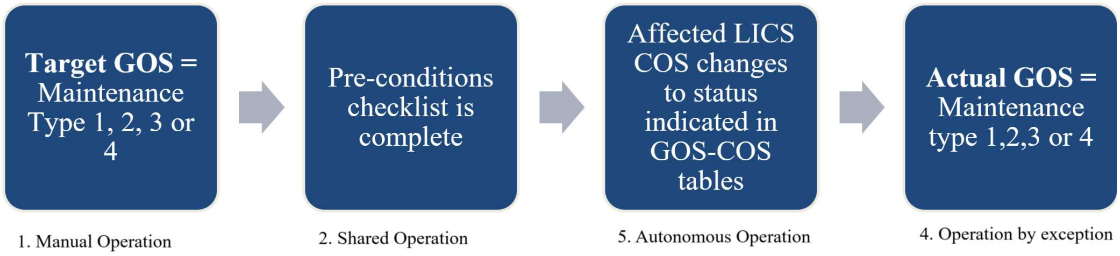


Figure 74: Sequence to change GOS. Once the target GOS is selected, the pre-conditions must be checked and the affected LICS must change their COS to be prepared for RH intervention. The expected automation level of each step is indicated below.

Each precondition checklist should include everything necessary for the RH system to perform the maintenance tasks associated with the selected mode. There will be at least four different checklists, one for each type of maintenance. These checklists may include both fixed and variable items, which should be completed by the RH team before each maintenance campaign or intervention. Some of the key checks to be included are:

- Availability of spare parts or components to be replaced.
- Logistics are ready to supply the components in the areas where they can be handled by RH systems.
- Electrical, pneumatic, gas, and other necessary facility supplies are activated for the RH devices that require them.

6.3.1 Activation sequence for RH devices

Before an RH Operator can take control of a device, several conditions must be met. These conditions will be imposed by different levels of the control system and will involve manual and automatic actions. To identify the order in which these conditions are checked, a flow diagram has been proposed based on the following assumptions:

- There must be a manual mechanism to enable devices individually for exceptional situations (rescue and recovery, commissioning, device maintenance…). Automation of RH processes are applied to the most frequent operations and incrementally as experience is gained.
- The RH system can only be active when the plant is in one of the 4 maintenance modes previously described.

- The procedures describing the maintenance, operation or rescue operations have been previously defined by means of a Structured Language and stored in a database. These descriptions indicate **how** to use the RH devices.
- The RH system shall respect the authority of the CICS as the highest control layer. It will oversee the activation RH devices, giving the green light to RH intervention to the different areas of the plant. Therefore, at the central level it will control **where** the RH system can operate.
- The RH High Level Control System will oversee managing the correct execution of the RH interventions. It will oversee authorizing the execution of RH operations. Therefore, at the RH HLCS level it will control **who** (assign task to operators), and **when** (schedule task execution) RH devices are operated.

Thus, the proposed flow considers activation by areas, by tasks, manual and automatic mechanisms. A more detailed definition on the specific automation level according to the definition from Table 22 will be required in the future. A total of 6 condition checks must be met to ensure that any RH device can be used. In summary, the device will be ENABLED when it receives the enabling signal from the Condition Engine, the Protection Module powers the device actuators, and the device FSM shows no internal errors. Figure 75 shows this sequence with more details:

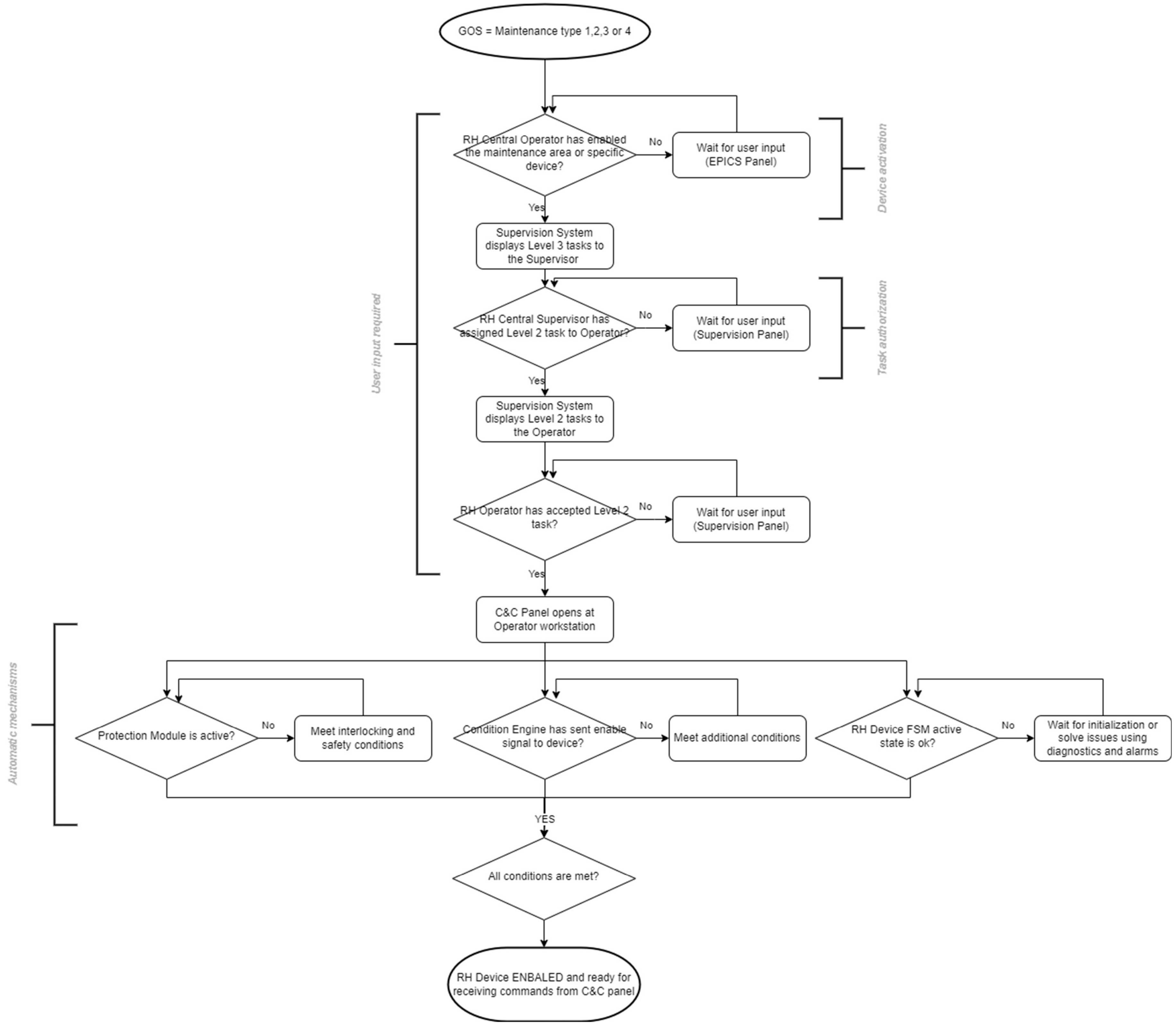


Figure 75: Flow diagram showing the conditions (rhombus shape) required to automatically enable RH devices. Manual authorization is required to enable areas (CICS) and assign task (RH LICS). Automatic checks of GOS and COS are performed after.

6.3.2 Safe stop sequence

One critical aspect to consider in RH systems is the need for controlled emergency stops. Unlike other systems where an emergency stop (ES) requires an immediate action, in RH operations, it is crucial to execute stops in a controlled manner to prevent additional hazards. Emergency stop commands can be triggered by several sources:

- The device-specific emergency stop button or the general ES button from the Remote Handling Control Room (RHCR).
- A local or central interlock event.
- A local or central safety event.
- The CCR supervision panel.

When an RH device is actively engaged in operations, receiving an emergency stop command can pose significant risks, particularly in dangerous environments like fusion facilities. The primary dangers to avoid during an emergency stop in RH systems include:

- Loss of control over a device that is handling a heavy load, which could result in the load falling or causing damage.
- Abrupt halting of a device with high inertia, which can lead to mechanical stress, damage, or even failure of the equipment.
- Stopping a device near hazardous environments, such as those carrying highly activated loads or operating near radiation sources, which could increase exposure risks or prevent proper containment.
- Blocking access paths to critical areas by leaving a moving element obstructing entry or exit points, potentially preventing safe access for personnel or maintenance operations.

Therefore, the controller of RH devices must implement strategies to handle emergency stop scenarios in a controlled way, ensuring that operations are paused safely and systematically. The process should involve slowing down movements rather than abruptly halting them, safeguarding the equipment, operators, and surrounding environments while maintaining compliance with safety protocols.

6.3.3 Data flow

To coordinate operations between the CCR and the RHCR, a number of software tools and interfaces are needed process the exchange of information. This information can be divided into 2 main categories: data about RH procedures, and control data. The former will be key to coordinate the management of maintenance campaigns between the two rooms. This information described using a SL is processed by the Supervision System. Control data will be managed mainly at LICS level (RHCS), and only a small set of relevant monitorization data and alarms will be sent to the CICS. Table 13 details the different types of data exanged between LICS and CICS for each of the five different networks connecting both levels as represented in Figure 36.

Data type	Traffic description	Network interface	Source node	<->	Destination node
Time reference	NTP protocol	CODAC timing - RH Operational, RH User	CODAC Time master server	->	RH HLCS Servers, RH Device Cubicles, RH workstations
RH procedures	Access to Supervision System. Information about procedures using SL. Task progress. Not EPICS based.	CODAC Control - RH User	RH Supervision System	<->	Central RH Operator workstation
RH control	Device status, device activation, COS and GOS information. EPICS based.	RH Operational - CODAC Control	RH Plant Controller	<->	CCR RH EPICS HMI
Video stream	Live video from maintenance areas. PTZ commands.	RH Video - Central Video	RH Viewing System	->	CCR video wall /workstations
Interlocks events	Machine protection events and monitorization data related to MPS	RH Interlock - MPS	RH Interlock Header PLC	<->	Central MPS
Safety events	Safety related signals and events.	RH Safety - SCS	RH Safety Header PLC	<->	Central SCS

Table 13: Network interfaces between CICS and RH LICS. Column <-> indicates the direction of communication

6.4 Supervision System for process control

The Supervision System is the HLCS module responsible for managing maintenance campaigns. It functions as an expert system that can be implemented in different ways, as introduced in 2.2, and its main objective is to manage and coordinate RH operations. The system is composed of two internal components: the RH Database and the Supervision Engine.

The RH Database stores all the necessary information for performing RH operations, including a four-level description of each task, embedded authorizations for RH operations, linked RH devices and tools, required spare parts, multimedia files and logs. The Supervision Engine is the core of the system, containing the logic required to manage RH procedures according to the SL. It controls workflows and manages the authorization process as described in 6.3. It also provides different Graphical User Interfaces (GUIs or panels) designed for the logged-in user.

Each role in the RH process will have access to a dedicated Supervision System control panel, which will present specific information and allow for the execution of actions. To describe how the system functions, this thesis uses mockups of the user interfaces. From a process perspective, this approach focuses on the system's functionalities for each RH role, highlighting the actions expected from each user and the necessary information they must access, rather than delving into the technical details of the system's operation (that will depend on the software tool selected by the project).

All Supervision System panels include basic information about the plant’s status and the progress of RH processes as shown in Figure 76. Additionally, they display the status of the backend system (Supervision Engine or SE) as well as the RH Database (DB), which stores procedure descriptions, automatic sequences (teach files), logs, multimedia files, and more.

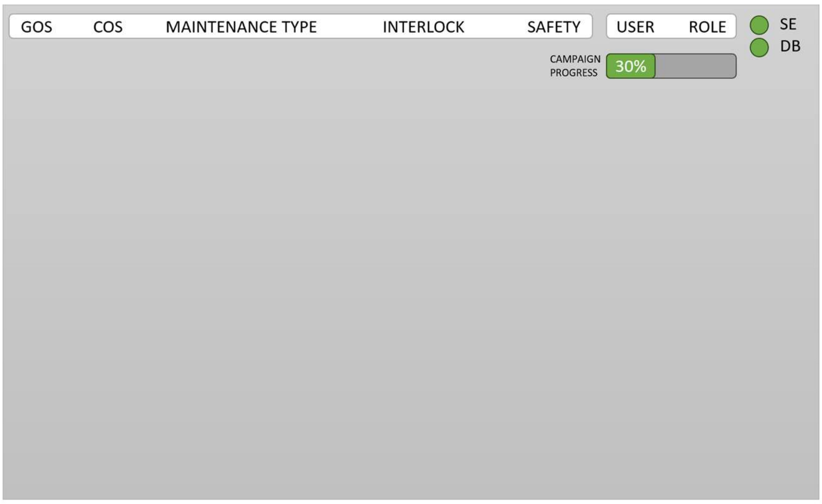


Figure 76: Supervision System Panel mockup with general information to all RH roles

6.4.1 Central Operator Panel (COP)

The Central Operator interacts with the Supervision System through a panel that provides high-level information on maintenance campaigns, enabling coordination and monitoring of RH operations from the CCR. The COP offers two main views: Operation Mode and Editing Mode.

In Operation Mode, the operator can authorize the use of RH devices either by maintenance area or individually. The panel also shows the status of each device and allows for the triggering of emergency stop sequences if a risk is detected. The Central Operator can initiate maintenance procedures once plant states are active, coordinating with subsystem managers to ensure that conditions are met before activating the procedure.

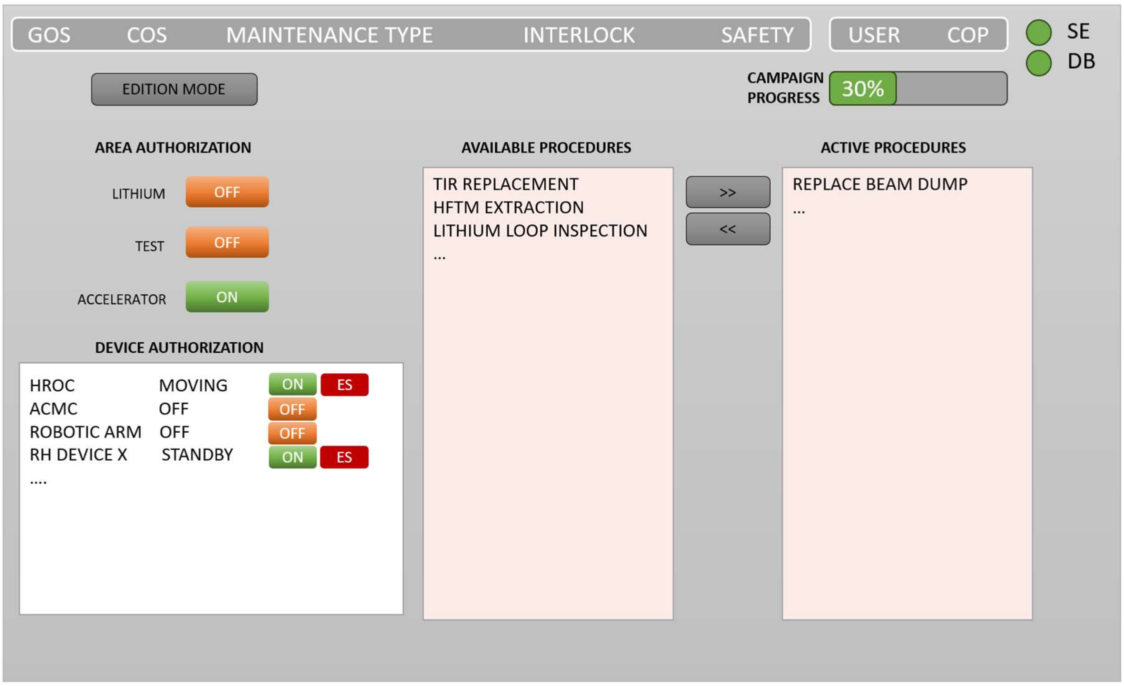


Figure 77: Central Operator Panel (COP) in Operation Mode.

In Editing Mode, the operator can select ongoing maintenance campaigns and add or modify procedures using a SL as shown in Figure 71 (color on the background areas of the panel refers to SL levels). The editor will verify that the steps of the procedure comply with the rules of the SL and offer a visual representation of the workflow through a flowchart. The editor also allows adding documents, multimedia files, and teach files stored in the RH DB. This mode is also accessible by the Central Supervisor.

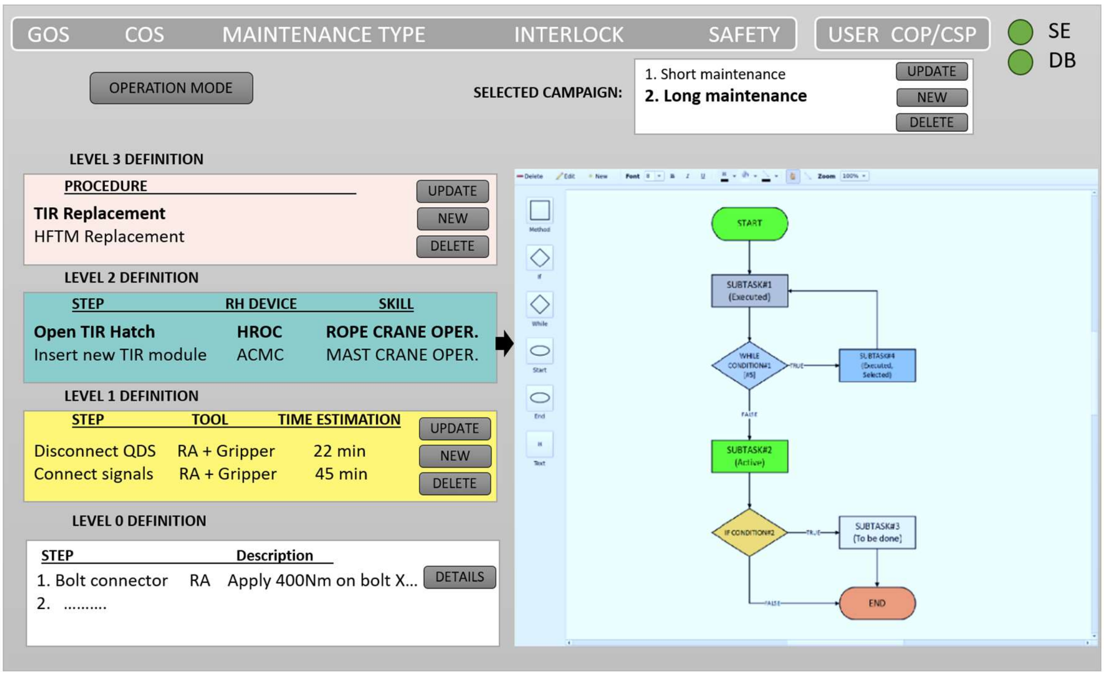


Figure 78: Central Operator Panel (COP) and Central Supervisor Panel (CSP) in Edition Mode.

6.4.2 Central Supervisor Panel (CSP)

The Central Supervisor is responsible for distributing work within the RHCR once authorized from the CCR from the COP. This role involves assigning active procedures to different workcells and planning their timing using a Gantt chart. The Supervision System shall assists in finding the optimal configuration to minimize intervention time by parallelizing procedures according to resource availability and operator schedules. The Central Supervisor can also monitor the activation status of RH devices and initiate emergency stops if necessary.

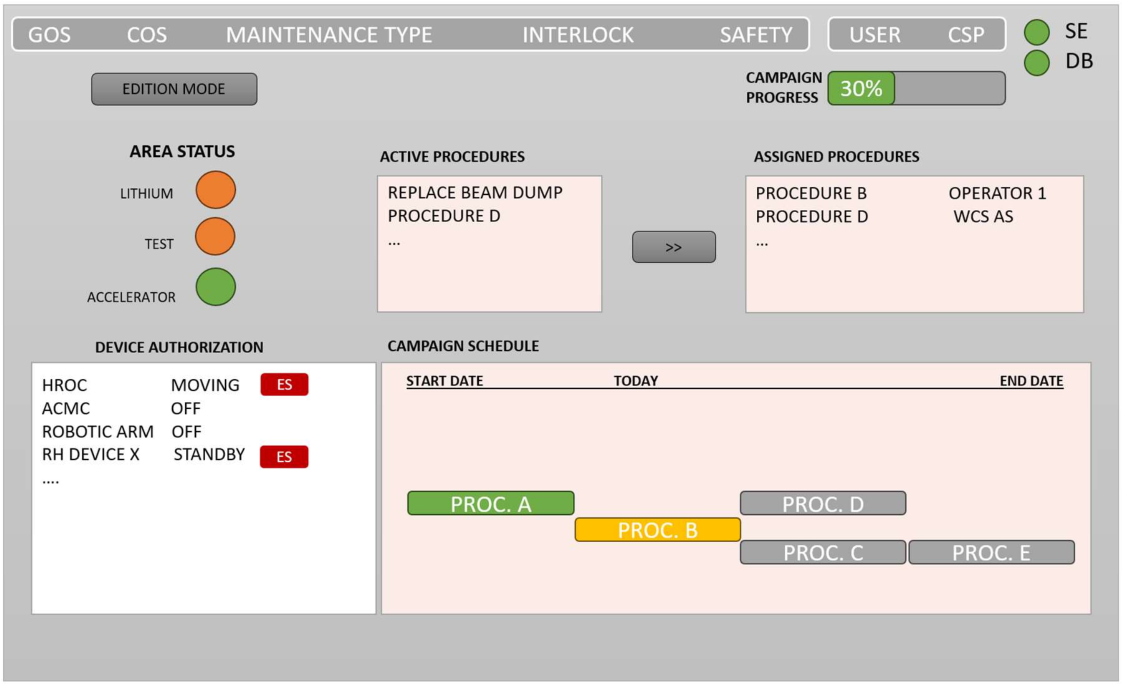


Figure 79: Central Supervisor Panel (CSP) in Operation Mode

6.4.3 Workcell Supervisor Panel (WSP)

The Workcell Supervisor distributes work orders among operators in their maintenance area. They will manage a window displaying the necessary actions (level 2 tasks, according to Figure 71) to complete the procedures assigned by the CSP. The Supervision System will only show operators who are available during the current shift and have the required skills for the task. After a level 2 task is completed, the Workcell Supervisor will review the evidence collected by the operator and validate the task. The supervisor also manages inventory and coordinates with logistics for the supply of required components up to the maintained area.

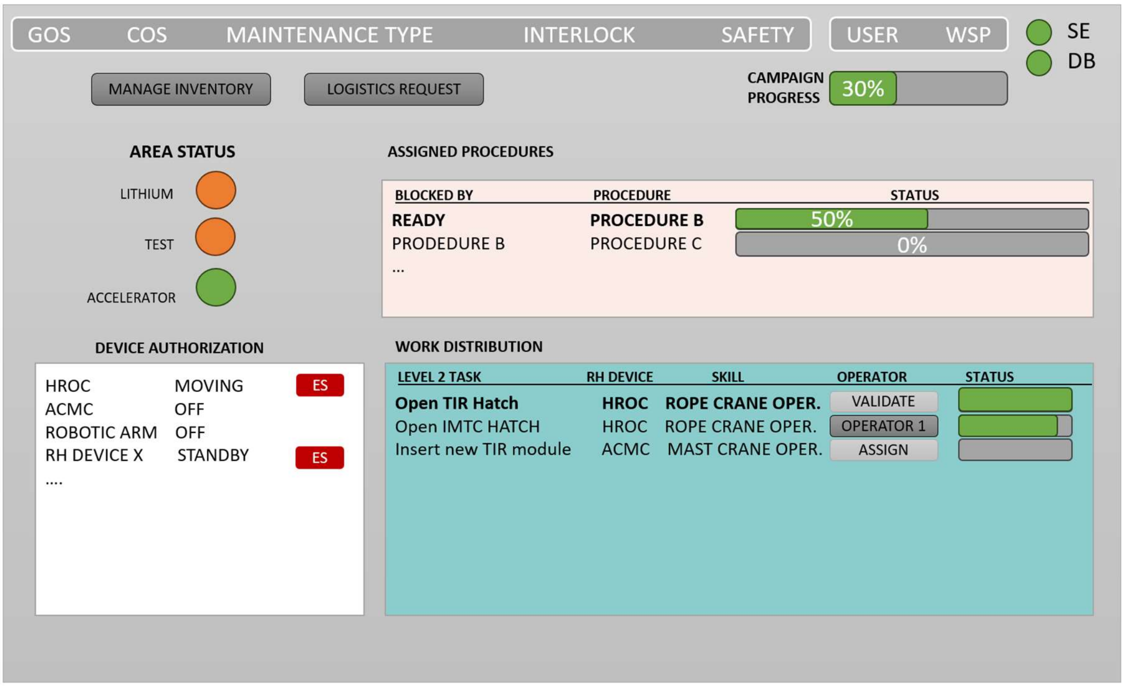


Figure 80: Workcell Supervisor Panel (WSP)

6.4.4 Operator Panel (OP)

The RH Operators receive work orders (level 2 tasks) through the OP. The panel presents details for carrying out the assigned operation showing images of the components or flowcharts, and task description via structured language. Estimated execution times will begin when the operator clicks on the corresponding task, and a timer will display the remaining time. The OP also includes a button to launch the control panel for the required RH device, handled by the Command and Control module. Operators can access additional procedure details in the form of documents or multimedia files from the RH DB, as well as log relevant information such as detected issues or acceptance test evidence. They can also send teach files to the assigned RH device for automating repetitive tasks when conditions allow.

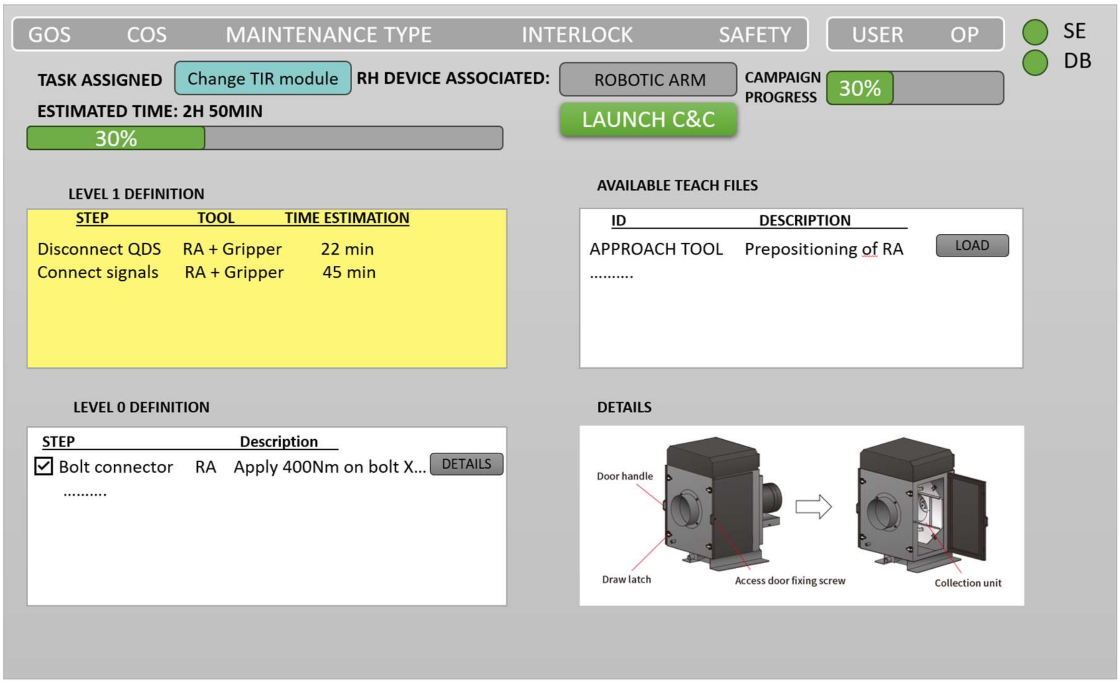


Figure 81: Operator Panel (OP)

6.4.5 Diagnostics and maintenance of RH Devices

An effective diagnostics and maintenance strategy for the RH devices is critical for the success of RH operations. It is imperative to be able to know the status of the RH devices and anticipate possible failures to avoid scenarios such as the rescue of a device that is bloqued in a highly activated zone. In addition to taking into account the possible failure modes of the RH devices from their design, adding for example redundant motors and actuators that allow moving the device in "rescue mode", it is important to be able to foreseen these scenarios by means of monitoring data provided by the device itself.

The Supervision System could integrate tools that ensure the continuous monitoring of RH devices, providing real-time insights into system health and detecting early warning signs of wear or malfunction. A key enabler of this diagnostic capability is the use of OPC UA, which offers a flexible and scalable solution for monitoring and maintaining RH systems. Studies have demonstrated that OPC UA can serve as a foundational technology for predictive maintenance, providing maintenance personnel with real-time system health indicators that facilitate proactive interventions [103]. By aggregating diagnostic data from sensors embedded in RH devices, OPC UA could allow the Supervision System user to assess remotely the condition of each device continuously, helping to avoid failures by scheduling maintenance before critical components reach their operational limits.

Different strategies can be adopted to detect the need for maintenance in a device, ranging from simple to more complex approaches:

1. Remote monitoring: Collected data is displayed, but not proccessed automatically. Human can oversee device's health, but not continuosly. To avoid possible failures, the human defines a regular maintenance schedule based on fixed intervals, regardless of the equipment's current condition (preventive maintenance). The aim is to prevent failures by conducting maintenance according to time, usage, or manufacturer guidelines.
2. Condition-based Maintenance (CBM): Automatically analyzes the current conditions of the equipment by looking for specific indicators of wear, degradation, or malfunction. Maintenance is triggered when these conditions exceed set thresholds.
3. Predictive Maintenance (PdM): Uses AI techniques and continuous monitoring of equipment through sensors and data analytics to predict when a failure is likely to occur. Maintenance is scheduled just before failure, optimizing repair schedules and minimizing downtime.

These strategies increase the complexity of the toolset that makes up the Supervisory System, but also improve efficiency and reduce the risk of unexpected equipment failure. A combination of preventive and predictive maintenance is also possible, as proposed in [104]. Figure 82 provides an overview of alternative methods to manage RH device maintenance.

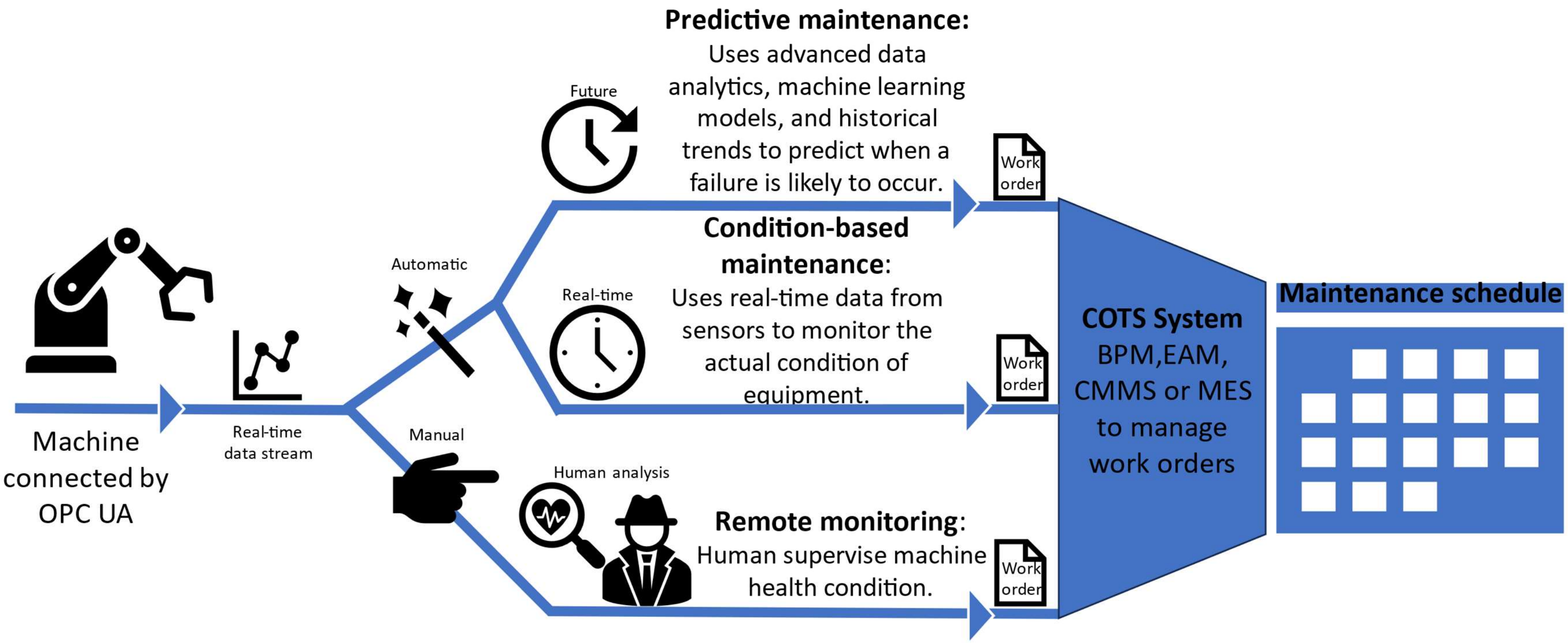


Figure 82: Maintenance strategies for RH devices. Thanks to standard data format provided through OPC UA, is possible to automate device condition monitoring to trigger work orders. This strategies could be extended to other plant systems of IFMIF-DONES, reducing the overall schedule and costs of the plant maintenance campaigns.

6.4.6 Summary table of the Supervision System

The high-level functionalities identified through the analysis of these control panels illustrate the complexity of the Supervision System and how it is involved in managing both processes and resources, as well as controlling RH systems. At this stage, it is challenging to propose a specific technological solution for implementing this module. However, two possible approaches were presented in 2.2: developing a custom system for full control over functionalities or adopting a commercial solution based on systems like CMMS, EAM, BPM, or MES. The latter would require adjusting system requirements to the capabilities of such tools. A hybrid approach combining commercial solutions with custom components could meet the needs of the Supervision System. Table 14 summarizes the high-level functionalities identified in this section.

Manual/Automated action	**Function**	**COP**	**CSP**	**WSP**	**OP**
Automated	Detect equipment failures by analysing diagnostic data collected in real time, and automatically trigger maintenance orders.	X	X	X	X
Manual	Allow a user to create a maintenance order when an anomaly or failure is detected in the device.	X	X	X	X
Automated	Display relevant information about GOS, Maintenance Status, RH COS, Interlock, and Safety.	X	X	X	X
Automated	Display maintenance campaign progress and click for details about ongoing procedures.	X	X	X	X
Automated	Display Supervision Engine and databases statuses.	X	X	X	X
Automated	Display logged user and role.	X	X	X	X
Manual	Activate procedures for execution (launch level 3 tasks)	X			
Manual	Enable maintenance areas (authorization for multiple RH devices)	X			

Manual	Individually activate RH devices	X			
Automated	Display RH Device status	X	X	X	
Manual	Edit RH Campaign definition	X	X		
Manual	Edit RH Procedures at every level	X	X		
Manual	Add details for the execution of the step using additional documents, multimedia or teach files.	X	X		
Automated	Check procedure description and sentences to be compliant with the SL	X	X		
Manual	Triger Emergency Stop (safe stop sequence) for RH devices	X	X	X	X
Manual	Design procedure sequence workflow graphically	X	X		
Automated	Update “Available procedures” according to plant maintenance status	X			
Manual	Display maintenance areas activation (authorization for multiple RH devices)	X	X	X	
Manual	Display all RH devices activation status	X	X	X	
Manual	Assign active procedure to Work Cells		X		
Manual	Schedule procedures of the active maintenance campaign		X		
Manual/Automated	Optimice maintenance schedule to reduce RH Campaign time		X		
Automated	Display “Assigned Procedure” owners		X		

Manual/Automated	Assign procedures to the specific work cell operators according to shifts and skills			X	
Automated	Display images or flowcharts of the assigned level 2 task				X
Automated	Display button to take control of the RH device associated to the assigned level 2 task				X
Manual	Launch C&C Panel for the RH device user on the assigned level 2 task				X
Automated	Display associated teach files for specific level 1 procedure				X
Manual	Load teach files to the selected device from the RH DB				X
Manual	Add logs with relevant information about the execution of level 0 tasks				X

Table 14: Functionality overview of Supervision System for each RH role

6.5 Workflow diagram of RH during maintenance campaign

To provide a comprehensive overview of how maintenance campaigns will be executed from the perspective of RH, we will analyze the entire sequence of actions that takes place from the moment CICS changes the plant status until all RH operations for the corresponding campaign are completed. To facilitate this, the following flowchart has been developed, identifying the main interactions between CICS and RH LICS, the actors involved, the panels they are using, and whether the action is performed automatically or requires user input. This approach aims to clearly identify the actions associated with each role.

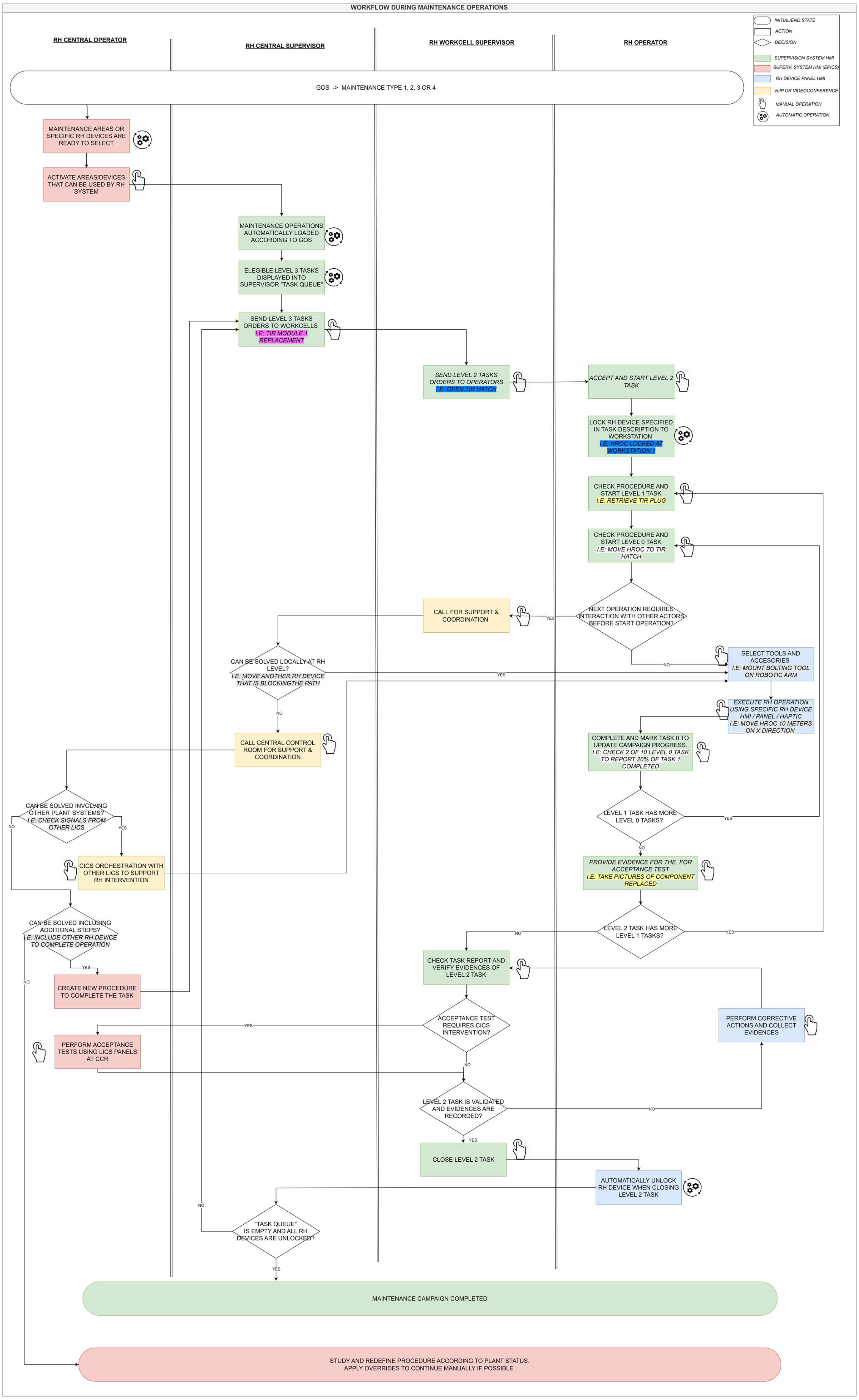


Figure 83: Flowchart showing automatic and manual actions performed by the Supervision System and RH users. Starts when plant maintenance status is changed, ends when all RH procedures foreseen for the campaign are completed. Each RH role is aligned on a different column, and the color code indicates the type of panel used for each action.

6.6 Results and discussion

In this chapter, the five main tasks of this thesis have been addressed, leading to the following outcomes:

- T1. Identification of Requirements: A thorough analysis and definition of high-level requirements for the Supervision System module were conducted, focusing on the actions carried out by each role involved in RH campaigns. Additionally, the automatic actions executed by system logic were identified and mapped accordingly.
- T3. Process and Workflow Definition: The roles of RH system users were clearly defined, establishing their responsibilities and the functionalities provided to each. Mockups of the HMIs of the Supervision System were proposed to illustrate the capabilities of each role. These efforts culminated in a high-level requirement table outlining the actions associated with each role. Additionally, the integration with CICS was analyzed, resulting in a proposed activation sequence for RH devices involving coordination between the two control rooms.
- T4. Intervention Time Improvement: The use of a structured language for RH operations was introduced, with the potential to improve the entire life cycle of maintenance campaigns. This language paves the way for automation and serves as the foundation for the Supervision System's operations.
- T5. Experimental Validation: Two experiments are presented in this section. The first evaluates the applicability of open-source BPM software to the Supervision System, while the second tests a potential mechanism for connecting RH LICS and CICS.

6.6.1 Prototype Supervision System based on BPM software

YAWL is a free, open-source BPM/Workflow system, based on a concise and powerful modelling language, that handles complex data transformations, and full integration with organizational resources, applications, and external Web Services. This language was based on the one hand on Petri nets, a well-established concurrency theory with a graphical representation, and on the other hand on the well-known Workflow Patterns.

The YAWL System (also referred to as the YAWL Environment) comprises a number of web servlets and a java-based Editor desktop application. Some of the main features of this system are listed below:

- YAWL offers comprehensive support for the control-flow patterns.
- The data perspective in YAWL is captured through the use of XML Schema, XPath and XQuery.
- YAWL offers comprehensive support for the resource patterns.
- YAWL has a proper formal foundation. This makes its specifications unambiguous and automated verification becomes possible.
- YAWL has been developed independent from any commercial interests.
- For its expressiveness, YAWL offers relatively few constructs.
- YAWL offers unique support for exceptional handling, both those that were and those that were not anticipated at design time.

- YAWL offers unique support for dynamic workflow through the Worklets approach. Workflows can thus evolve over time to meet new and changing requirements.
- YAWL aims to be straightforward to deploy. It offers a number of automatic installers and an intuitive graphical design environment.
- YAWL’s architecture is Service-oriented and hence one can replace existing components with one’s own or extend the environment with newly developed components.
- The YAWL environments support the automated generation of forms. This is particularly useful for rapid prototyping purposes.
- Tasks in YAWL can be mapped to human participants, Web Services, external applications or to Java classes.

The environment is composed by the YAWL Engine and the YAWL Editor. The first one run the required services and manages the components, and the second one allows to design the application.

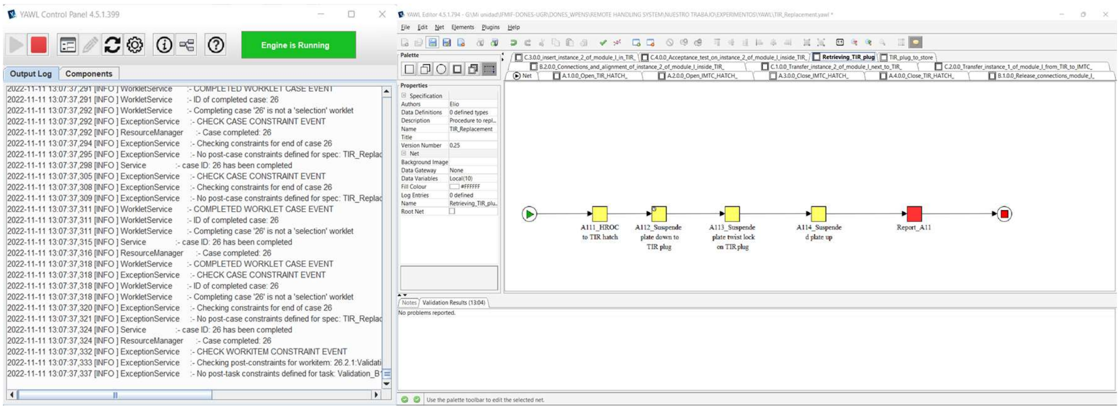


Figure 84: YAWL Engine (left) and YAWL Editor (right)

The user interface is provided via web, allowing users to log in and execute different actions depending on their privileges (capabilities assigned to each role). Figure 85 shows the actions that can be performed as admin, in particular the capability to define resources that later can be associated to a specific task:

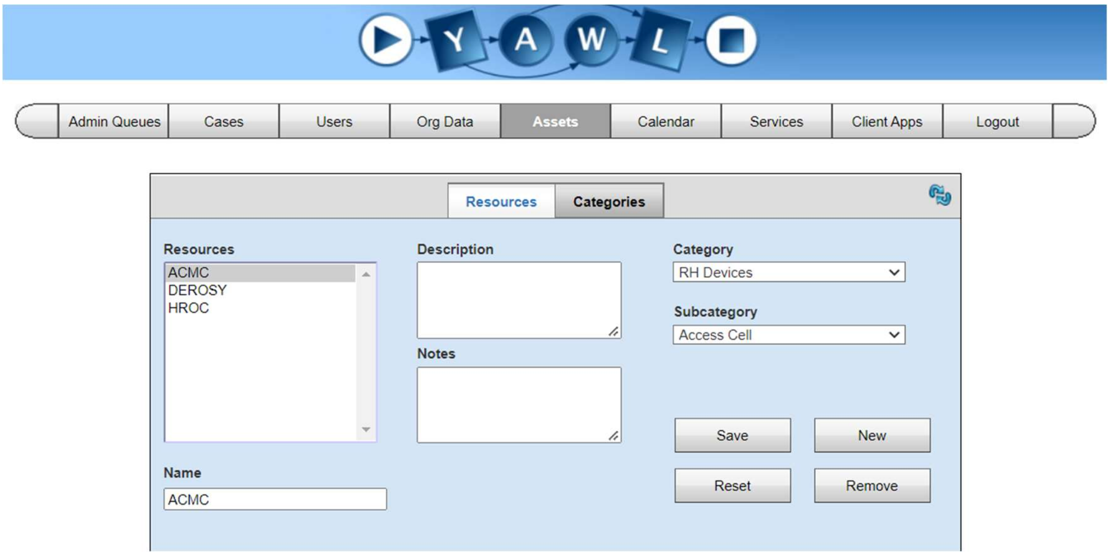


Figure 85: Resource management via web interface for admins. It allows to define users, resources, schedules, groups and other data easily.

6.6.1.1 Example for TIR Replacement

To check the capabilities of the tool, a basic example has been implemented based on the VTD V2.2 [100] describing the replacement of the module inside the TIR. The flowchart provided on the excel file shows the following sequence:

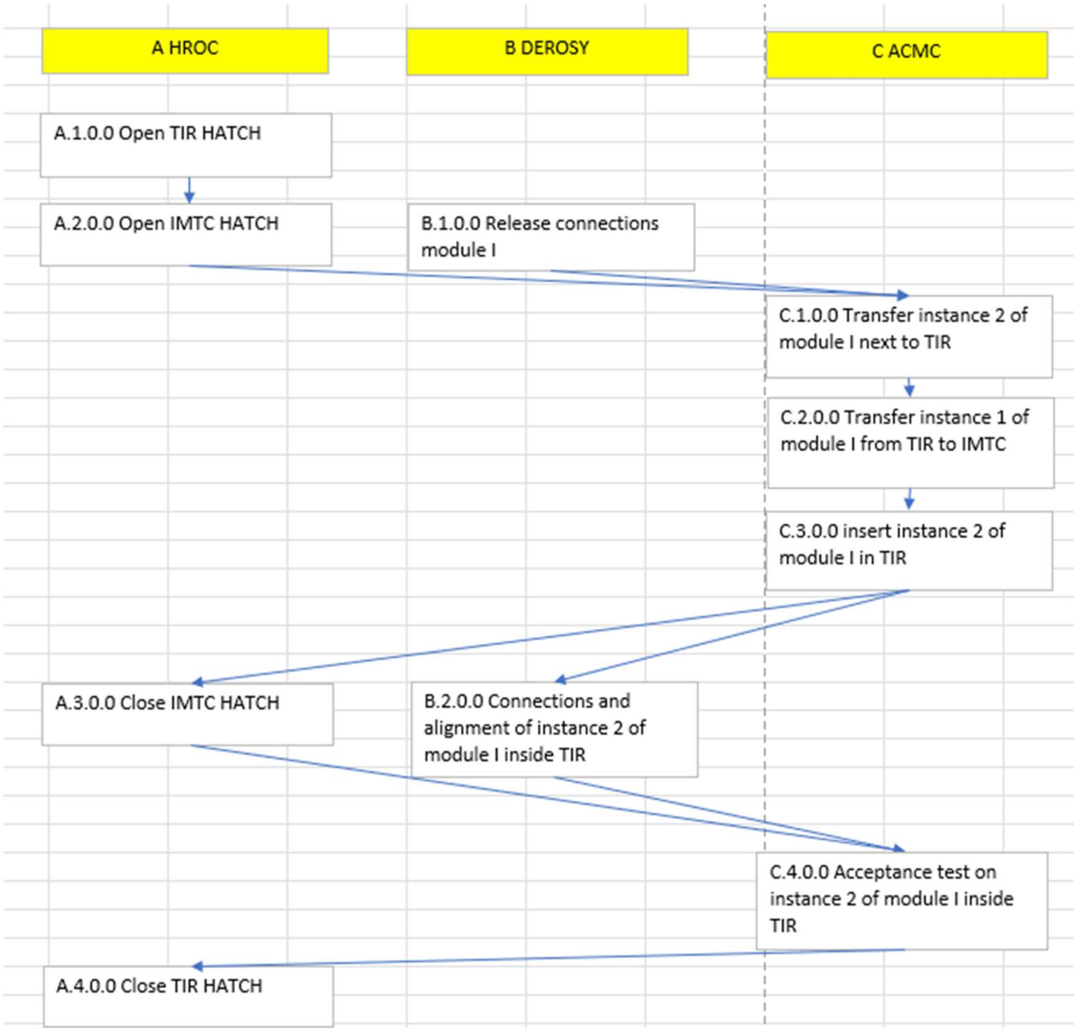


Figure 86: Flowchart describing TIR replacement procedure [100]. Each block represents a level 2 task, which are associated to a single RH device. Actions on the same column requires the same RH device, which helps to identify parallel/sequential operations.

Taking this information we have modelled this process into using YAWL. Figure 87 showsFigure 86 how this first "net" (the canvas where the workflows are designed) on YAWL is described. Each block can be decomposed into smaller tasks, up to the level of atomic task. The three levels of decomposition considered on VTD document are represented as follow on YAWL:

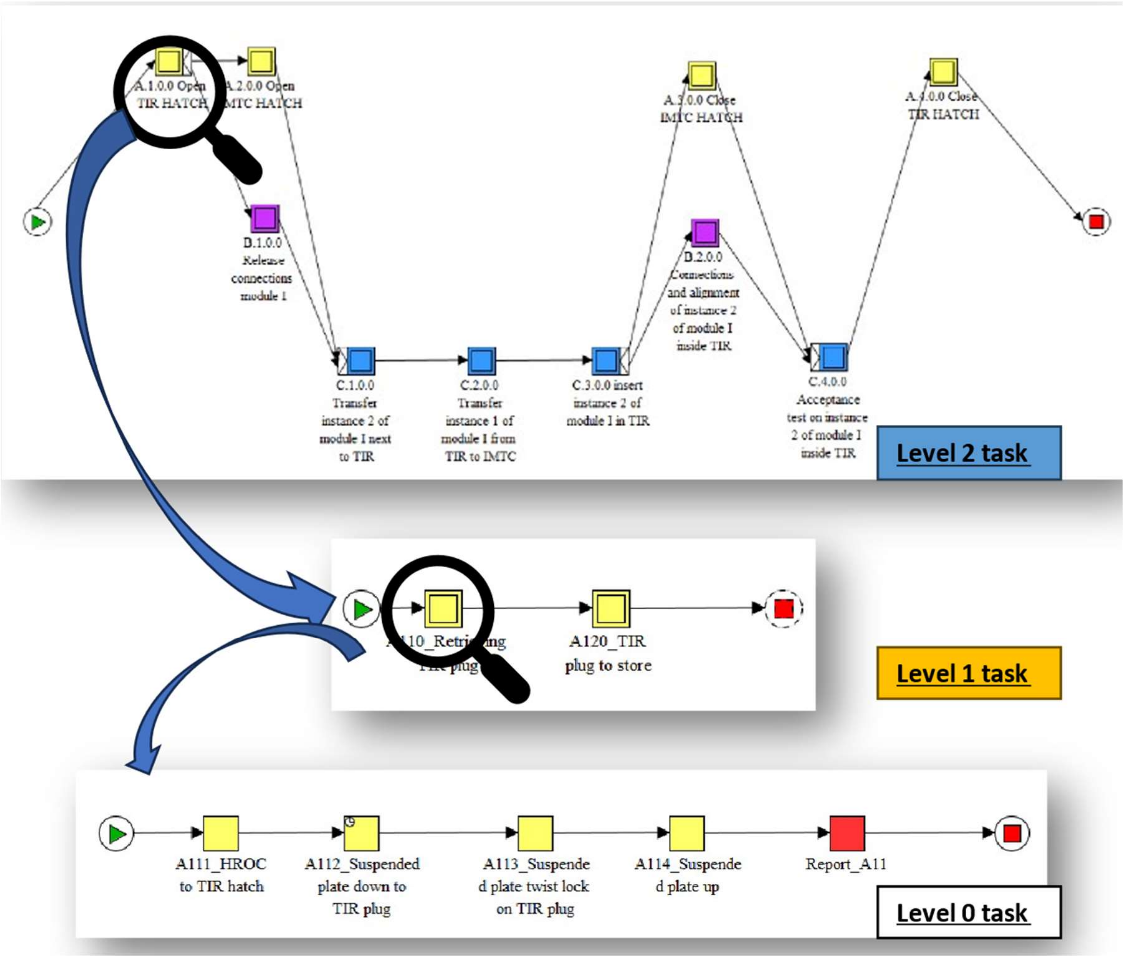


Figure 87: Definition of TIR replacement using blocks and conditions from YAWL. The double-bordered squares are composite tasks, the single-bordered squares represent atomic tasks that have a work order assigned to them.

For each atomic task is necessary to define a set of parameters, such as input/output data that will be displayed, roles enabled for the specific task execution, capabilities required, resources… This will be translated into a set of preconditions that can be used to automatically assign the task to the users and display the required information on the web application. Here is the view from a user perspective (i.e. RH Operator) assigned to atomic task A111, and the dialogue displayed to the user once the task is accepted and become active.

Figure 88: Web interface showing user panel. The system sends automatically work orders to suitable user (according to skills, resources, schedule...) and they can accept the work to start counting the execution time.

Once the user accept and start the task, the user should perform the required actions and close the task. It is possible to request related information such as entering a log, completing forms or upload evidences for task validation.

6.6.1.2 Results of YAWL evaluation

YAWL is a powerful tool for process management and workflow automation, making it suitable for handling the process and workflow definition, task assignments, and integration with other systems that could be part of the Supervision System. However, it lacks the real-time capabilities, direct device control, and integration with structured languages necessary for fully automating RH maintenance in IFMIF-DONES. To cover those gaps, YAWL would need to be complemented by specialized control systems, custom interfaces, or integration with tools that handle structured language and real-time operations.

Requirements Covered by YAWL	**Requirements Not Fully Addressed by YAWL**
Process and Workflow Definition: YAWL's strength lies in workflow modeling. Suitable for defining the sequence of tasks and procedures that need to be executed in RH campaigns. Allows	*Device Integration and Real-Time Control:* YAWL is a workflow engine and lacks real-time capabilities required for direct interaction with RH devices. For tasks that

model user roles, responsibilities, and their interactions to automate parts of the RH processes. YAWL supports advanced constructs like parallelism and conditional branching, which can help streamline and optimize RH maintenance tasks by allowing multiple procedures to run simultaneously, based on resource availability.	involve sending commands to the devices or receiving real-time feedback, YAWL would need to be integrated with other control systems, such as PLCs or dedicated control modules. Does not support OPC UA.
Role-based Task Assignment: YAWL supports task allocation based on user roles and permissions, which means it can effectively manage who is assigned to each task. This would help in assigning tasks to RH Operators, Supervisors, and others.	*Structured Language:* While YAWL can model workflows, it is not designed for complex SL that are required for RH-specific automation or fine-grained control tasks. YAWL would need to be complemented by other tools focused on robotic control and automation.
Integration with Other Systems: YAWL can integrate with external systems using web services and custom code extensions. This capability allows YAWL to potentially connect with other components of the RH system or higher-level systems like CICS for synchronization and coordination of maintenance procedures.	*Visualization and HMI Customization:* YAWL's interface is more functional than visual. The user interface can be minimally modified, and the diagrams showing the procedure sequence are shown only in the editor window.

Table 15: Requirements of RH Supervision System covered by YAWL.

Table 15 offers a concise overview of the primary requirements for the Supervision System, indicating the extent to which they are addressed by the YAWL tool. In summary, YAWL emerges as an open alternative that facilitates process management in a straightforward manner, accompanied by a relatively modest entry barrier. The simplicity of the system, coupled with the abundance of online resources such as tutorials and documentation, facilitates the modeling of a reference procedure for the RH of DONES in a relatively short timeframe without the necessity of extensive development or programming, as would be required by other specific tools, as the ones presented in Section 2.2.2.

However, it should be noted that this tool lacks native interfaces that would enable its integration within the proposed control framework. Despite being an open solution that does not require licensing, it appears unfeasible to propose modifications that would enable integration with OPC UA or ROS, or the utilization of a distinct semantics that would facilitate interaction with a RH structured language.

The conclusion of this proof of concept is that it is challenging to determine whether to employ an expert system for RH process management based on commercial tools (Section 2.2.1) or to develop a customized solution (Section 2.2.2). On the one hand, the particularity of the RH use case makes very difficult to find a commercial solution that completely covers the required functionalities, or that is flexible enough to add them. On the other hand, the investment required to develop and maintain a proprietary tool from the ground up appears to exceed the financial and resource capacities of the project. This issue remains unresolved and is an open question that must be addressed in the near future by the project.

6.6.2 GOS and COS interaction

A key consideration in the proposal outlined in this thesis is the need to establish a control system dedicated to RH and independent of the CICS, but integrated within it to coordinate operations and procedures at both levels. This has raised a number of issues that have been discussed throughout this chapter. However, from the technological point of view it raises a more immediate question regarding the adoption of a control framework utilizing technologies and standards distinct from those used for the Central Control System (CICS) and the remaining LICS in the facility.

The current candidate for plant-wide control is EPICS (Experimental Physics and Industrial Control System), as it is already implemented in IFMIF-EVEDA (Engineering Design and Validation Activities) for the prototype accelerator control (see Figure 2). EPICS is widely used in facilities with particle accelerators, making it a de facto standard within the field.

The proposed control framework for the RH system architecture deviates from this approach (refer to 4.1), yet compatibility with EPICS remains essential. To validate this compatibility, an EPICS IOC (Input/Output Controller) node was deployed in the laboratory network. This node manages its communications through Process Variables (PVs) and represents the CODAC system, responsible for transmitting the GOS to other plant subsystems LICS.

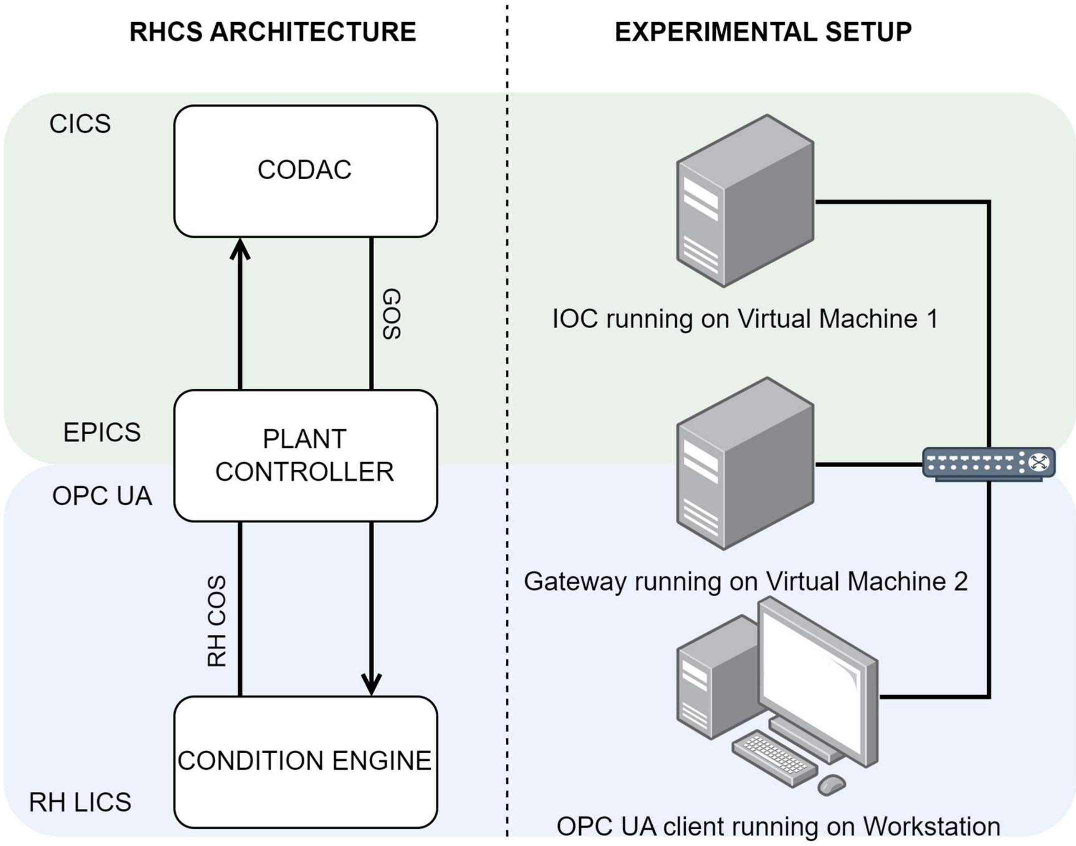


Figure 89: Experimental setup to validate EPICS/OPC UA integration through a custom gateway

The experiment aims to validate the integration of EPICS and OPC UA using a gateway based on pvAccess and open62541, which was specifically developed for this project and presented in [105]. pvAccess is a high-performance protocol for signal monitoring and scientific data services, designed to support the structured data types of EPICS 7 and above [106]. It succeeds the EPICS Channel Access protocol. On the other hand, open62541 is an open-source implementation of OPC UA written in a platform-independent subset of C99 and C++98, providing the tools needed to implement dedicated OPC UA clients and servers[107].

The CODAC user interface, tasked with defining the GOS, was implemented using the web version of Phoebus, the tool used for developing EPICS user panels. This interface was integrated into the SCADA developed for the test bench. It allows users to define a numerical value for the COS, which corresponds to a specific state. To modify the GOS, the OPC UA client UAExpert was employed to change the numerical value, with the corresponding state displayed on the panel. Figure 90 demonstrates both interfaces, showing updated COS and GOS values with minimal delay (below 100 milliseconds for 10000 variables) for both frameworks. This experiment confirms the potential for seamless integration between EPICS and OPC UA within the RH control system.

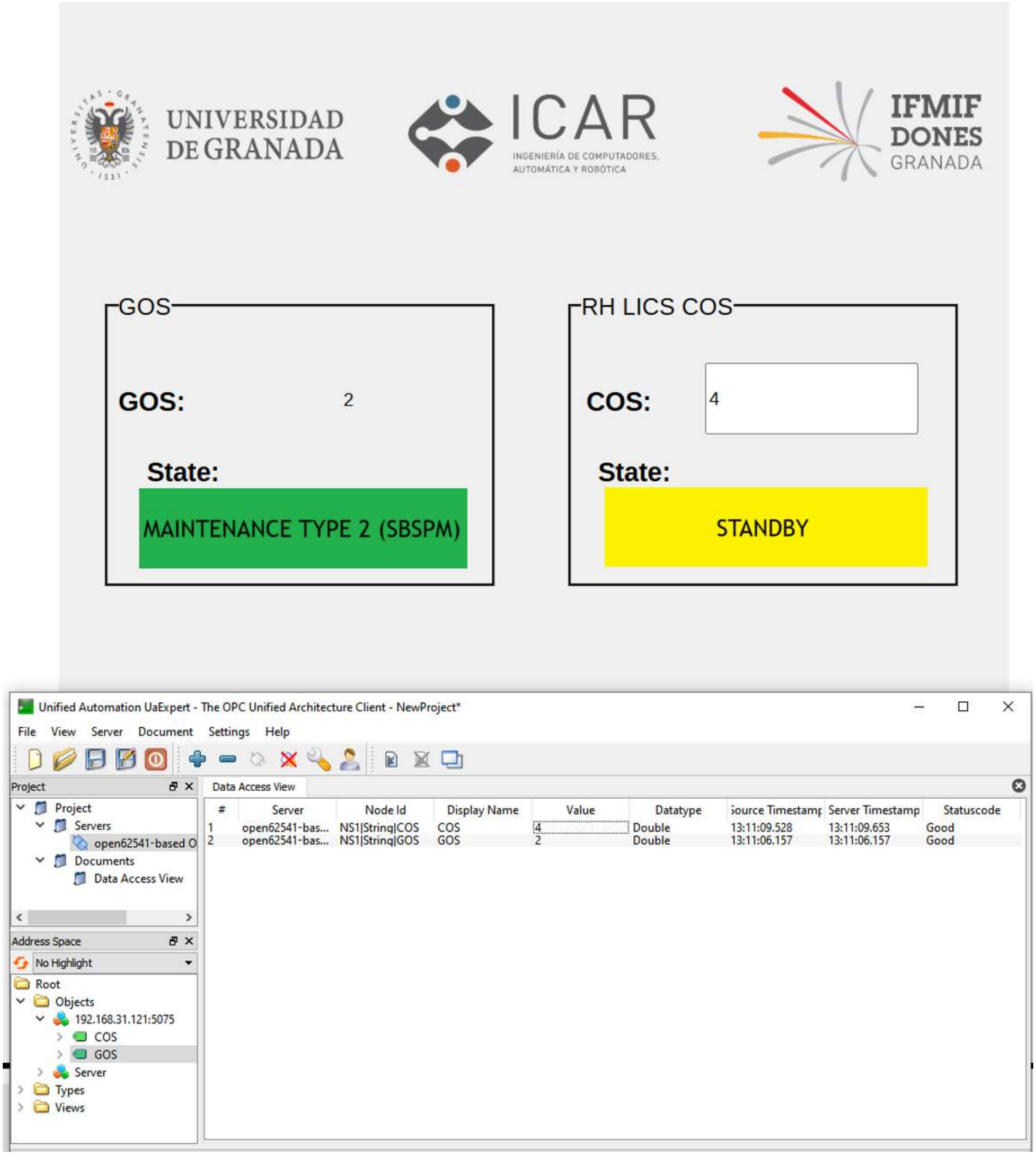


Figure 90: Phoebus web panel (EPICS) on top showing the numeric values of GOS and COS, and interpreting its associated status. UAExpert client on the bottom showing the same numerical values from OPC UA side.

6.6.3 Conclusions of Chapter 6

In this chapter, the RH Control System was explored from a process-oriented perspective, with a focus on creating a proposal for the roles, responsibilities, and coordinated actions required to conduct successful RH operations and maintenance campaigns. RH operations involve a wide array of systems and personnel, making it essential to identify and define each role's contributions and establish a structured workflow to meet the operational objectives. This foundational work lays the groundwork for a human-in-the-loop control approach that emphasizes operator involvement while aiming to incrementally increase automation.

A key aspect of this chapter's approach has been to reduce RH intervention times, increase automation, and streamline development by incorporating commercial solutions where possible, while retaining the flexibility to adapt the system for future advancements or modifications. Achieving this will require a dedicated team of professionals who can focus on the development, preparation, and execution of RH maintenance campaigns.

The Supervision System is positioned as the core element responsible for coordinating RH processes. As part of this, BPM software has been evaluated for its potential to manage roles, resources, scheduling, and work order management within the Supervision System set of tools. While BPM tools are useful in handling these aspects, they alone are insufficient to cover the full spectrum of functionalities required of the Supervision System. Consequently, additional tools and custom modules will need to be integrated to create a comprehensive and flexible supervisory system tailored to the specific needs of IFMIF-DONES. This combined approach should enable the RH Control System to meet high standards of efficiency, adaptability, and automation.

The integration of EPICS and OPC UA, demonstrated through the experimental setup, has confirmed the feasibility of establishing seamless communication between these two frameworks. The experiment opens the doors for leveraging the strengths of EPICS, a widely adopted standard in particle accelerator facilities, alongside the flexibility and interoperability of OPC UA, a cornerstone of modern industrial communication. This dual-framework approach offers a promising path for enhancing modularity, compatibility, and operational efficiency in IFMIF-DONES.

Chapter 7
Networks and data

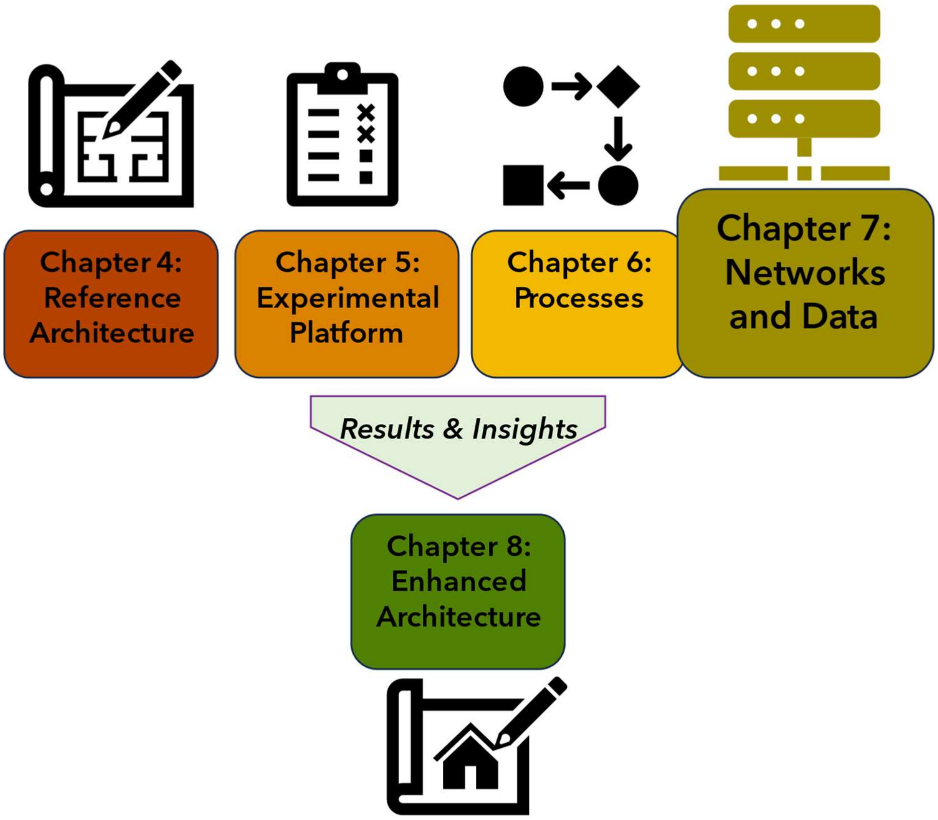
This chapter presents an in-depth analysis of networking solutions tailored for the RH systems in the IFMIF-DONES facility, representing a significant contribution to this thesis. The chapter establishes a comprehensive framework for **integrating and optimizing network performance** in such a critical environment, introducing advancements aligned with the specific requirements of RH systems.

Building on prior work from Chapter 4, where the reference RH Control System architecture was introduced, this chapter expands on network requirements and **data flow analyses**. It identifies **four primary traffic categories** (Operational, Process, User, and Critical Data) and defines their respective performance, reliability, and safety requirements. The proposed networks are further developed using **TSN to enable deterministic performance, IT/OT convergence, and efficient bandwidth utilization**, addressing the complexities inherent in RH systems.

A highlight of this chapter is the **experimental validation of TSN** capabilities in the laboratory test bench. These experiments measure latency performance for critical traffic, providing a data-driven rationale for implementing TSN in RH applications. Results showcase how TSN's deterministic scheduling **minimizes delays**, even under congested conditions, ensuring robust network behavior for safety and control operations. Insights from this chapter form the foundation for the proposed physical architecture, aligning TSN deployments with IFMIF-DONES's operational needs.

Overall, the chapter not only advances the technical design of RH networks but also lays the groundwork for unified control strategies, explored in greater detail in Chapter 8. By demonstrating **TSN's applicability**, this work supports the overarching goal of delivering a highly reliable and efficient control system for RH operations, marking a crucial contribution to the thesis's objectives.

7 Networks and data



In Chapter 4, the reference architecture for the RH control system was introduced, along with a list of the main networks that comprise it. This chapter aims to provide a detailed analysis of these networks, outlining their primary requirements based on the information currently available. This analysis will focus on a qualitative approach, rather than quantitative, to identifying expected traffic types and the systems that each network needs to connect. At present, insufficient data is available to estimate metrics such as the number of devices, bandwidth requirements, or quality of service levels.

In the following chapter, an exploration of the expected data flows and traffic types is conducted for the RH system in DONES. These data flows and traffic types are based on the requirements and control architecture defined in preceding chapters. The utilization of telemanipulators equipped with haptic feedback necessitates a real-time, low-latency traffic profile. Conversely, video traffic associated with cameras will necessitate high bandwidth. A distinct consideration pertains to safety and interlock signals, which are of paramount importance and must be transmitted within the network in a timely manner. These considerations must be incorporated into the design of the RH networks, which serve as the foundational infrastructure upon which the RHCS is implemented.

Lastly, the chapter proposes the adoption of TSN as a network technology that enables precise configuration and management of various traffic flows within a deterministic network framework. An experimental scenario will be designed with real equipment and traffic to analyze TSN's performance and capabilities, specifically for its application in the RH systems of IFMIF-DONES.

7.1 Overview of Network Requirements for RH Control Systems

The RH Control System in IFMIF-DONES represents a critical subsystem with unique network requirements, as discussed in 3.2. The control architecture is divided into two horizontal layers, CICS and LICS, and three vertical segments: CODAC, MPS , and SCS. Figure 91 represents the case of RH LICS over the general Instrumentation and Control System approach for DONES represented in Figure 34.

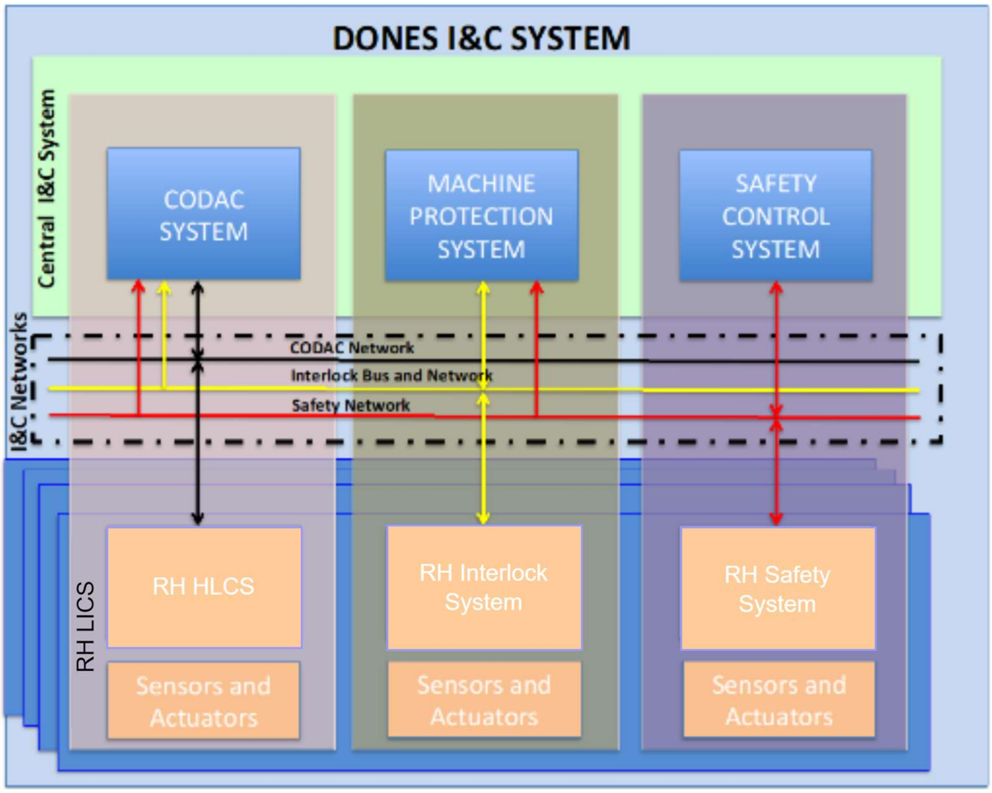


Figure 91: RH LICS layout under CICS standard networks. The upper horizontal layer contains the Central I/C System, which orchestrates the plant's subsystems or LICS. The three vertical layers extend to all LICS.

These vertical layers, each covering essential functions for the plant, has different network requiments as described in [108]. They are mirrored within the RH LICS, focusing on the distinct operational, protective, and safety requirements for RH operations. Table 16 summarises the basic information about these three networks to provide an overview of the expected network capacity and applicable protocol and technologies as they are described today. This can be changed in the future, since this is an ongoing work open to discussion.

Network	Description	Requirements	Protocols/Technologies
CODAC	Coordinates plant control, supervision, and data access. Manages time synchronization, data transfers, and access to other LICS information.	**Functions**: Real-time monitoring, time synchronization, and data transfers. **Latency**: 100 ms for control operations (10 Hz). **Safety Integrity:** N/A	IEEE 802.3 Ethernet (Gigabit) PTP (IEEE 1588-2008) FTP EPICS Channel Access (CA)
MPS	Provides communication infrastructure for machine protection functions, including slow, fast, and hardwired links.	**Functions**: Protection against failures in equipment, systems, or controllers. **Latency**: - Slow: >300 ms - Fast: 1-300 ms - Hardwired: <30 µs. **Safety Integrity**: SIL3.	ProfiNet EtherCAT FailSafe over EtherCAT (FSoE)
SCS	Ensures the safety of personnel and equipment through four dedicated subsystems: PSS, OSS, PASS, and RAMSES.	**Functions**: Safe signal acquisition and processing, redundant management, and connection with sensors and actuators. **Latency**: Depends on the subsystem: - PSS (hardwired): < 1ms. -OSS (bus-based): 1-10ms -PASS: 0.1-1 s. - RAMSES: 0.1-1 s. **Safety Integrity**: Based on assigned SIC of each subsystem.	Fieldbus RS-485 Direct Hardwired Connections

Table 16: Requirements and technologies of CICS layers extended to RH Control System

Signals and data can be classified as critical and non-critical based on their relation to safety-relevant events. CODAC will not manage any critical or safety related signal, MPS will manage machine related critical signals, and SCS will manage equipment and personnel critical signals.

Critical signals are transmitted over isolated media to ensure deterministic delivery, requiring field-buses capable to ensure a deterministic behaviour or even hardwired connections to implement hardware logic to reduce delays and failures. Non-critical signals, which include commands, configurations, and status updates, are managed over shared Ethernet connections that prioritize compatibility and data transfer without stringent safety requirements.

7.1.1 Dedicated Networks for RH High Level Control System

Within the RH LICS, the MPS and SCS networks will be extensions of the plant's central systems, utilizing the same network technologies and operational principles. These networks are designed to meet the stringent demands of systems with fast reaction times, such as the Accelerator System, which requires a beam shutdown in less than 1 ms upon detecting a failure. In contrast, the motion of RH devices operates on a larger temporal scale, where differences of several hundred milliseconds do not significantly impact the stop sequence. Therefore, the RH system will integrate into the existing MPS and SCS frameworks without requiring significant modifications.

However, the RH HLCS introduces specific network requirements distinct from the rest of the plant. These specialized networks support unique RH operational needs and are based on standard Ethernet technologies, providing isolation to safeguard against unauthorized access and maintain system reliability.

- RH User Network: Located in the RHCR, this network connects workstations with the RH HLCS servers. It supports internet connectivity with a focus on cybersecurity, as well as VoIP and video conferencing for communication with the CCR. This network uses standard communication protocols like TCP/IP, HTTP, and FTP, prioritizing data transfer and interoperability over real-time performance.
- RH Operational Network: This isolated network links RH device controllers in the Main Access Building to the HLCS servers in the Main Building through a redundant backbone. It predominantly supports industrial protocols such as OPC UA, Industrial Ethernet, and PROFINET.
- RH Real-Time Network: This network is optimized for low-latency performance and connects haptic devices and master controllers in the RHCR to RH controllers in the Main Building. It uses real-time protocols such as UDP and relies on a dedicated redundant trunk to ensure efficient and prioritized traffic for control commands.
- RH Video Network: Dedicated to RH video feeds, this network connects cameras in the Main Building to the Viewing System server in the Main Access Building. It interfaces with the User Network and the Central Video Network, supporting RTP and RTSP for video streaming, as well as PELCO-D for PTZ camera control, enabling real-time monitoring across different control rooms.

An important consideration for the RH networks in IFMIF-DONES is the potential need for external connectivity. Establishing a duplicate control room at an alternate location could prove highly beneficial, ensuring continuity of RH operations in the event of an accident or failure in the primary control room. One viable option for this backup functionality is the integration of the RH training facility, potentially located in the nearby UGR-DONES building.

This training facility is envisioned as a critical installation, featuring mockups and operational RH devices alongside a dedicated control room for operator training. It would enable comprehensive testing and validation of RH procedures in realistic environments prior to deployment. Moreover, the facility would allow operators to train on both virtual and real devices using a setup identical to the primary RHCR at the IFMIF-DONES site.

The replica control room, designed to mirror the equipment and interfaces of the primary RHCR, could seamlessly take over RH operations during emergencies or while updates and maintenance are performed. This setup would significantly enhance the resilience and continuity of RH control capabilities.

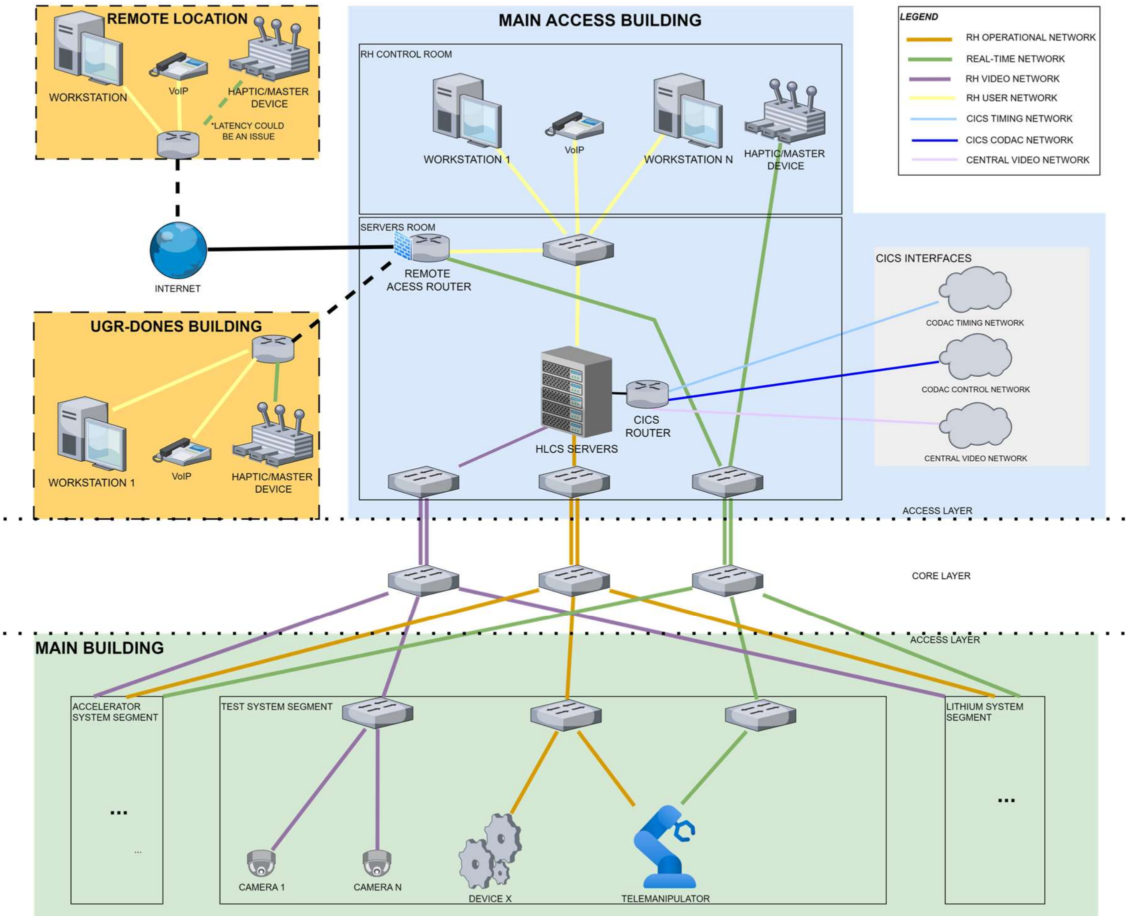


Figure 92: Simplified deployment of RH networks. In yellow boxes the possible replica control rooms. Green box represent the Main Building. Blue box is the Main Access Building.

From a network architecture perspective, RH internal networks generally span three hops, except for the User Network. This network requires only a single hop to connect the RHCR workstations to the HLCS servers located within the same building. The Operational, Real-time, and Video networks include an access layer designed to aggregate traffic from various maintenance areas in the Main Building, identified as segments in the network diagram.

In scenarios where the number of devices is limited or distances to the cubicle rooms are short, this initial hop could be bypassed, enabling direct connections to the Core Layer. The Core Layer aggregates traffic from all segments and distributes it to the Main Access Building via redundant trunk links. These links then feed traffic to the upper access layer, connecting workstations in the RHCR and server devices in the server rooms.

RH networks feature two primary external access points. The first router (part of the RH Plant Controller) interfaces with the Central Control and Instrumentation System (CICS) networks, facilitating central services. The second router manages internet connectivity and potential connections to external control rooms outside the IFMIF-DONES facilities.

For connectivity with the UGR-DONES building, a dedicated link could be established given the short distance of less than 500 meters. If the connection relies on the internet, challenges may arise, particularly for Real-time network traffic (specially the traffic of devices providing haptic force feedback), due to latency and reliability concerns. In this scenario, where there is the possibility of deploying a dedicated link thanks to the proximity of both locations, the use of TSN technology becomes particularly important as it would enable the ability to integrate all these networks in the same physical link while maintaining a deterministic behaviour capable of providing limited latencies.

Although this aspect has not yet been fully addressed by the project, careful consideration is essential, as it will directly influence the network design and may impact the functionalities of the potential replica control room.

7.2 Data Flows in the RH Control System

To understand the network requirements and configurations for the RH Control System, it is essential to model and analyze the various data flows specific to each network segment. By defining the data flows in terms of application, origin, destination, message frequency, and communication protocols, a baseline network design can be established. The data flows within the RH Control System are grouped into four primary categories: Operational Data, Process Data, User Data and Critical Data. Each category has distinct performance and reliability requirements, shaping the technical and structural aspects of the network:

- Operational Data includes control, diagnostics, and monitoring information directly associated with RH device operations. This data encompasses critical metrics such as device position, speed, force readings, and alerts or alarms. These exchanges occur predominantly between the RH LICS and the RH HLCS core, typically not extending to the Central Control System (CICS). However, in cases requiring centralized alarm management or historical data storage, the Plant Controller acts as a mediator, aggregating, filtering, and transmitting the necessary information to the CICS. The flow of Operational Data demands high reliability, low latency, and often deterministic communication to ensure real-time responses. Protocols such as OPC UA are essential as they ensure secure, synchronized exchanges while meeting real-time performance and resilience requirements in RH operations.

- Process Data refers to data flows essential for coordinating and organizing RH operations. This category connects the RH Control Rooms with the Supervision System and Condition Monitoring Engine, which manage RH procedures and authorize device usage. The Plant Controller functions as a gateway between the CICS and RH LICS, performing necessary protocol conversions. Unlike Operational Data, these flows are less sensitive to strict real-time requirements but emphasize periodic updates for process synchronization.
- User Data supports communication between the RH HLCS and the RH Control Room. This flow involves GUI visualizations, operator alerts, historical trend data, logs, and multimedia resources, which assist in visualization, analysis, and user interaction. In contrast to Operational Data, stringent timing requirements are not typically necessary for User Data since its primary function is to inform rather than directly control. Standard protocols such as TCP/IP and HTTP are typically sufficient, complemented by real-time updates for video streaming or VR scene visualization when required.
- Critical Data represents safety-related and interlock signals required to ensure the protection of personnel, equipment, and the environment. This data flow includes signals for safety interlocks, emergency stop activations, and machine protection systems. These signals must adhere to strict timing constraints, typically requiring low latency and deterministic delivery. They often originate from Safety PLCs or interlock devices and are directed towards actuators or higher-level control systems, including MPS and SCS. Communication protocols used for these signals typically involve redundant and fail-safe mechanisms, such as PROFINET or hardwired connections, to guarantee timely and reliable execution.

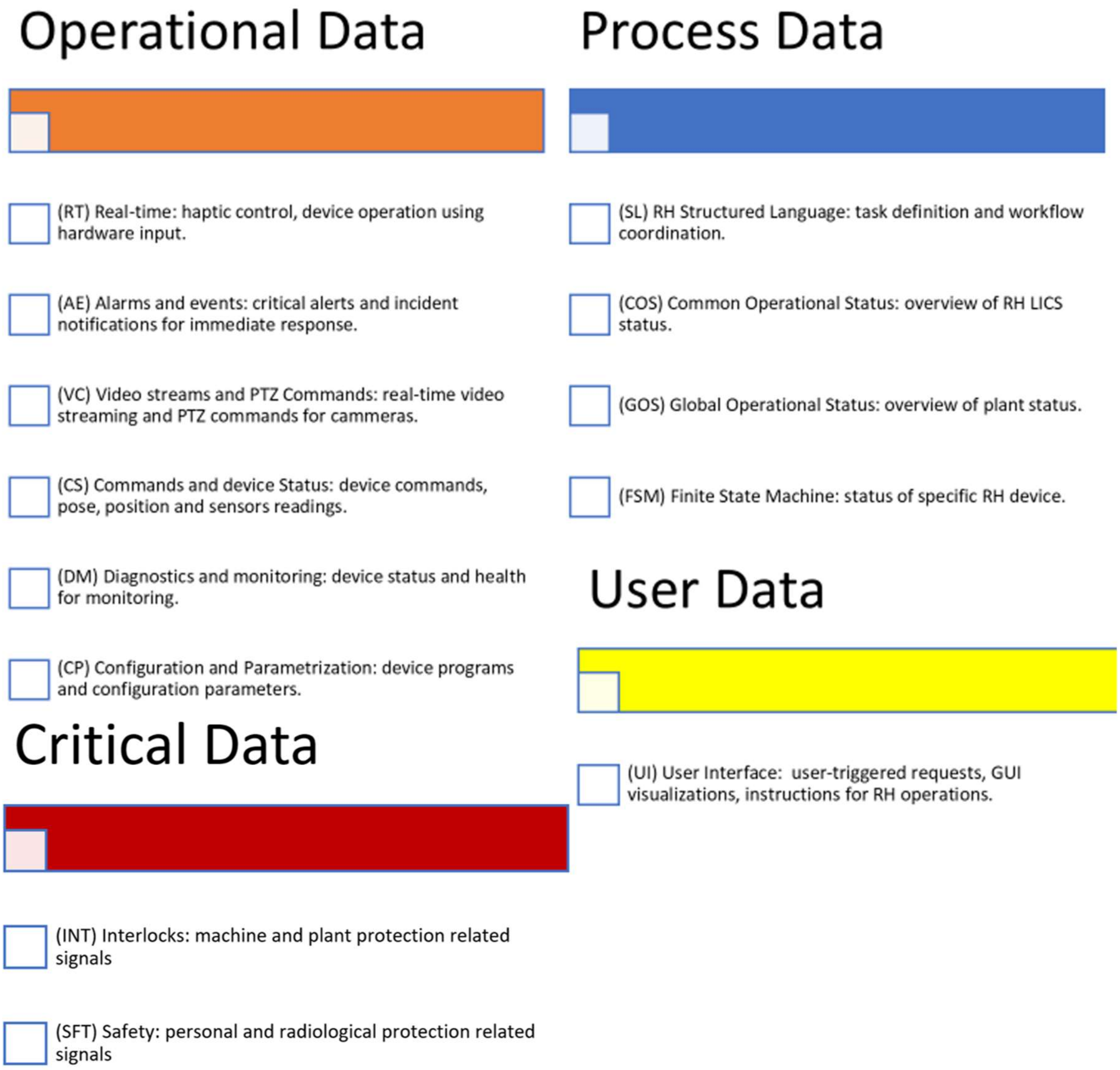


Figure 93: Different types of traffic for each data category.

In Figure 93 we have identified the specific traffic flows expected within each category based on their functionality. This classification serves as a foundational model to estimate network behavior, offering a comprehensive view of expected performance and the requirements to be implemented. Figure 92 highlights the various networks involved, detailing components of the High- and Low-Level Control Systems alongside the traffic types generated according to the above classification. Figure 94 highlights the various networks involved, detailing components of the High- and Low-Level Control Systems alongside the traffic types generated according to the above classification

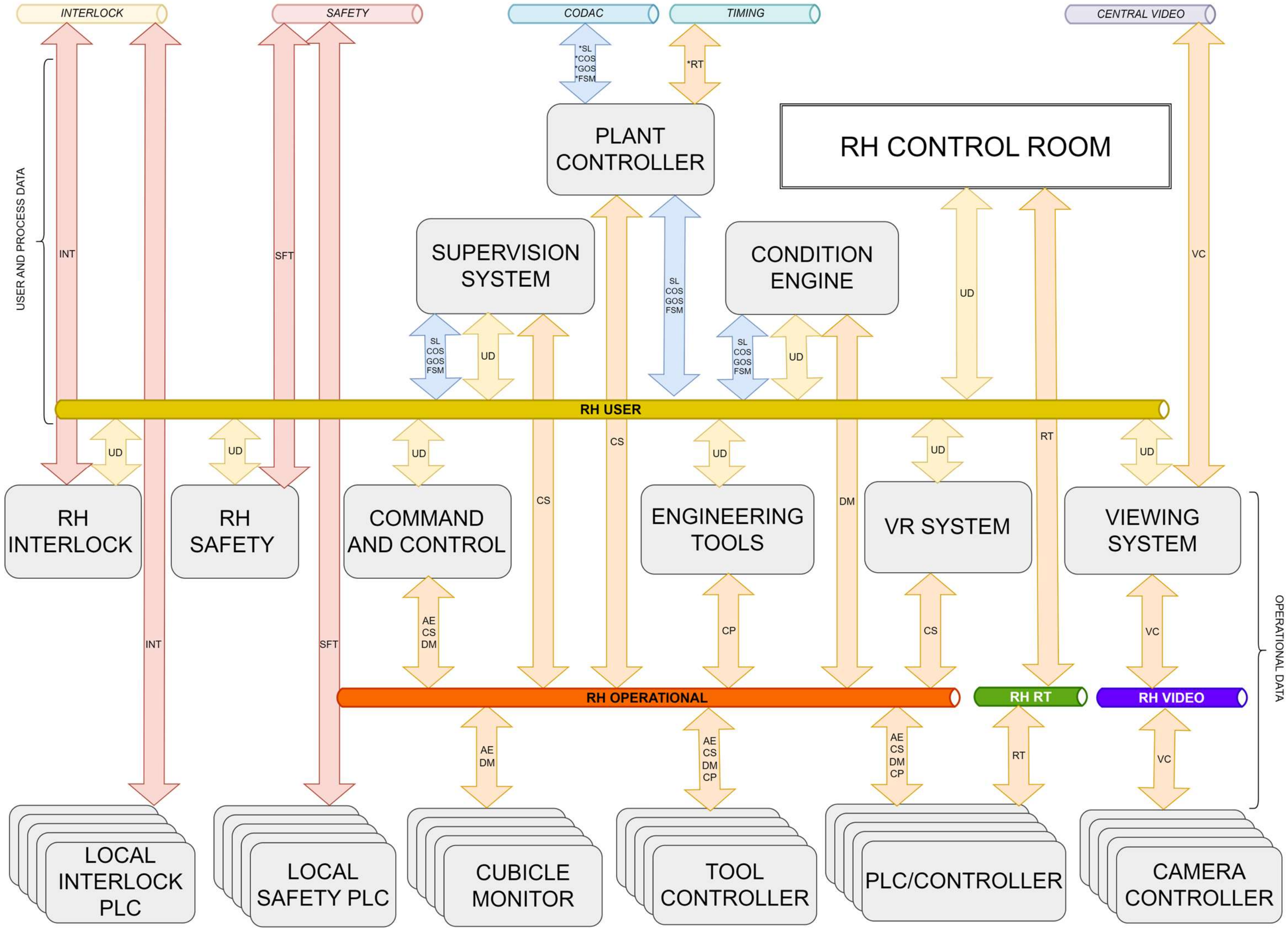


Figure 94: Logical networks and data traffics involved in RH. Each arrow indicates the type of traffic, and the connection of the modules to the networks. The top part of the diagrams group all modules related to Process Data, and the bottom part deals only with Operational Data.

The top part of the diagram illustrates the five CICS networks interfacing with the RH Control System. These networks connect to the RHCS through four RH HLCS modules, forming a barrier for Operational Data, which typically only extends to the upper level for video traffic (integrated into the Central Video Network for Central Control Room access) and time synchronization provided via NTP (denoted as *Real-time traffic in the diagram). User Data remains isolated from RH devices through the RH User Network, mitigating the risk of unauthorized interactions or breaches. For Critical Data, the CICS-defined network infrastructure is extended into the RH system, maintaining the same stringent requirements.

7.3 Time-Sensitive Networking applicability to IFMIF-DONES RHCS

TSN is one of the most promising technologies gaining traction in recent years within the field of industrial networks. It is a set of standards defined by IEEE 802.An, designed to enhance the real-time capabilities of Ethernet networks, as discussed in **Error! Reference source not found.**. Its applications span automotive, Industry 4.0, and mobile technologies like 5G/6G, driving rapid development and adoption among major manufacturers such as Cisco, Siemens, or Texas Instruments.

Applying TSN to the IFMIF-DONES RHCS offers several advantages, covering some of the top-level requirements stablished in Section 4.3:

- Network Consolidation: Reduces the number of networks required, thereby minimizing cabling, hardware, power consumption, management, and maintenance needs.
- IT/OT Convergence: Facilitates the integration of Operational (OT) and Information Technology (IT) networks, enabling shared physical mediums for operational, process, user, and critical data flows.
- Real-Time Transmission: Ensures the reliable delivery of time-critical applications, such as closed-loop controls, sensor data acquisition, and motion control.
- Bandwidth Efficiency: Supports data-intensive applications like video streaming and IT systems without compromising network performance.
- Deterministic Behavior: Guarantees bounded latencies for packet delivery, independent of overall network traffic, ensuring predictability.

The outlined network diagram shown in Figure 95 simplifies connectivity, consolidating all traffic types into a single backbone for RH. Only systems interfacing with the Central Control System (CICS) require multiple network connections.

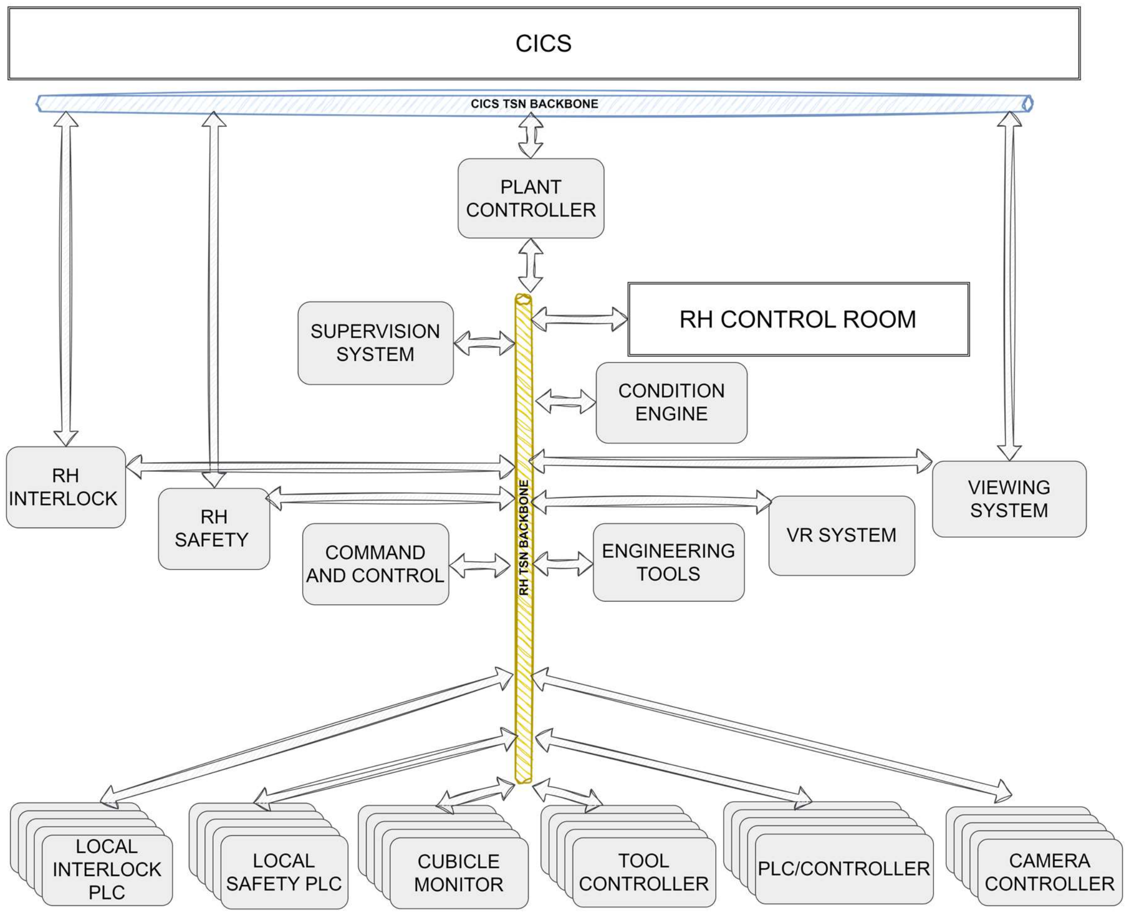


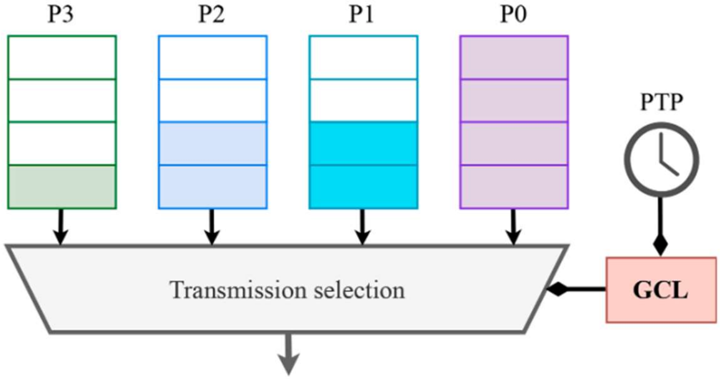
Figure 95: Possible deployment of TSN in IFMIF-DONES. RH networks would be integrated into a single backbone, as in CICS.

In order to integrate all traffic within the same physical network using TSN technology, it is necessary to: configure a priority for each traffic flow, synchronize all the nodes in the network to a common time reference and establish a coordinated scheduling through all the network. In TSN this is achieved by means of a component called Time Aware Shaper (TAS) that performs the scheduling of the packets. It oversees the scheduling of the different types of traffic awaiting to be sent. The traffic differentiation is provided by priorities, defined by the application layers.

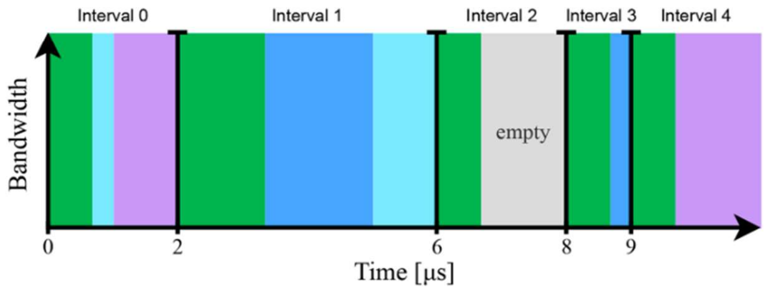
The TAS uses a two-dimensional array called Gate Control List (GCL), which specifies the priorities that can be transmitted at each time interval. The execution of the GCL is repeated cyclically with a constant period (sum of all time intervals). A “1” bit indicates that the transmission gate is open, and a “0” means that it is closed. Figure 96 extracted from [109] provides an example of a GCL together with a simplified diagram of TAS operation.

Gate Control List (GCL)						
Interval	Duration	P3	P2	P1	P0	Settings
0	2 μs	1	0	1	1	*0xb*
1	4 μs	1	1	1	0	*0xe*
2	2 μs	1	0	0	0	*0x8*
3	1 μs	1	1	0	0	*0xc*
4	2 μs	1	1	1	1	*0xf*

(a) GCL configuration example for the intervals (duration) and gates (priorities - P*k*) control.



(b) Internal structure of the TAS component.



(c) A representation of the resulting data transmission over time (intervals).

Figure 96: GCL example and Time Aware Shaper (TAS) simplified diagram extracted from [109]

When there are several switches in the network, the GCL cycles should be aligned to reduce the queueing time in each network node. This coordinated scheduling is achieved by means of the PTP synchronization protocol, which keeps all the nodes synchronized in the order of nanoseconds. This mechanism ensures a minimum bandwidth for each traffic flow, as well as timely and low-latency transmission of time-sensitive flows. Traditional Ethernet networks often experience unpredictable communication delays mainly due to frame queueing at the network switches, necessitating large buffers at the receiving end to manage data flow. However, this lack of real-time capability is problematic for flows like audio and video, or safety signals that have limited time constraints on their transmission. TSN is able to ensure a bounded transmission interval compared to traditional ethernet, regardless of the network load, as shown in Figure 97.

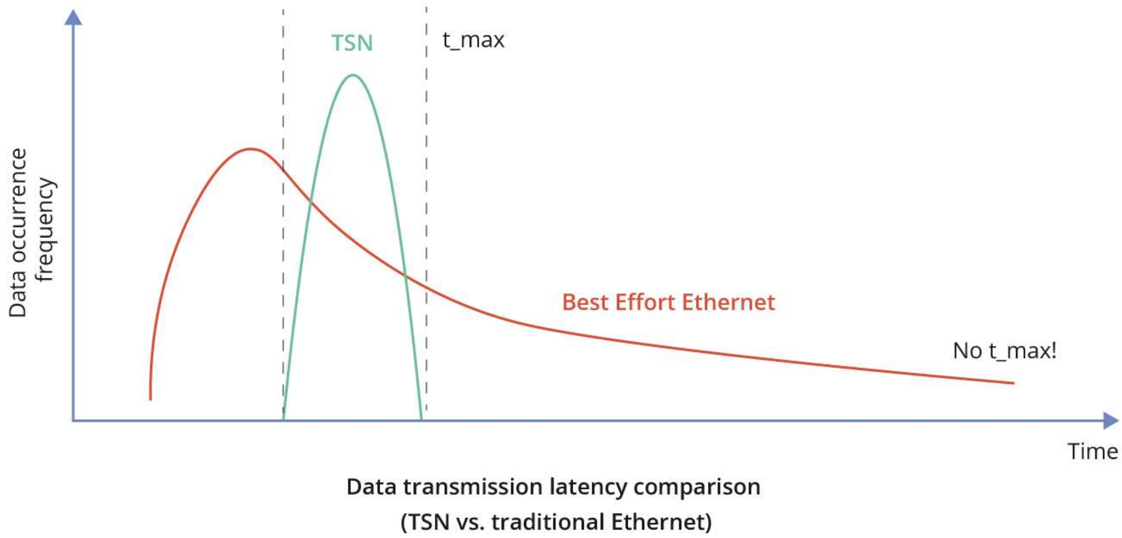


Figure 97: Data transmission latency comparison of TSN vs traditional Ethernet. Source [70].

7.4 Experimental setup

TSN is a technology that has been developed in commercial products for only a few years, so it was decided to perform an experimental test in the laboratory test bench to evaluate its technological maturity, performance and features, as well as the extra complexity introduced in the networks for the configuration and operation of this standard beyond the theorical perspective.

The starting point for the evaluation is the existing laboratory network, which is based on standard Ethernet and lacks segmentation or Quality of Service (QoS) capabilities for different traffic types. Within this setup, four primary types of traffic have been identified for focused testing, while residual traffic such as network status and time synchronization messages (e.g., ARP, IGMP, NTP) will also be considered. These traffic flows are detailed and analyzed in the following table:

Traffic type	Description	Requirements	Priority level
Time-critical video	Computer vision applications that require the correlation of images obtained at the same instant of time by different cameras (connected in different network hops) on a common node (application running on the Workstation).	Medium bandwidth. Periodic and sequential packets (frames segmented into multiple packets). Delay between receiving frames from different cameras taken at the same time must be less than the inter-frame interval (33 ms for 30 fps).	3
Synthetic interlocks	Simulates Safety or Interlocks related event traffic. UDP packets generated from a Python application that have the same packet size as a standard PROFINET packet, copy its header fields, and contain in its payload a cyclic counter (64 bytes packet size). They are generated periodically with a random timeout between packets between 100 and 200ms.	Low bandwidth. Non-periodic, individual packets. Strict maximum latency to ensure rapid response to events that could compromise safety or equipment integrity.	6
Commands	Commands and device monitoring. Most of them in OPC UA format, except those related to the robot's TCP position, which require UDP to reach a higher frequency. OPC UA variables have a minimum update rate of 150ms, while robot trajectories are sent every 10ms.	Medium bandwidth. Combination of periodic (OPC UA monitoring + UDP trajectories) and non-periodic (OPC UA commands, alarms, and events). High frequency for robot trajectory control.	3
Traffic injection	Additional traffic generated by additional cameras and a traffic generation tool. We use iperf3 to create synthetic UDP traffic that allows us to emulate congestion situations in the network without the need to increase the number of	High bandwidth. Periodic and sequential packets (camera images) and non-periodic traffic injection. Best-effort traffic should occupy	0

	devices. The packet size we generate is 1500 bytes, which is the maximum allowed in an ethernet frame, and the bandwidth generated is 1Gbps.	leftover bandwidth and maintain the lowest priority.

Table 17: Network traffic types in the RH test bench.

The network topology represented in Figure 98 has four switches. Two of them implement TSN and allow the creation of a TSN backbone through which all the traffic between the devices and the Workstation will circulate. These switches are 4-port 1G Time-Sensitive Networking Switch manufactured by the Spanish company Relyum [110], and support a wide range of TSN standards (including the Time Aware Shaper). The other two switches are standard MikroTik switches, and allow VLAN header tagging/untagging by applying ACL rules for those devices sharing ingress ports on the TSN switches. This is necessary for the TSN setup, which makes use of VLAN headers to distinguish between different types of traffic. In addition, the setup has a small PROFINET network, which functions as a fieldbus that communicates the tools and devices controlled by a Siemens PLC with the robotic arm controller. This traffic passes through one of the MikroTik switches, sharing the medium with the rest of the standard ethernet packets without any problem. Figure 98 shows the network in more detail, distinguishing by color the 4 types of traffic and listing the ports occupied on each network equipment.

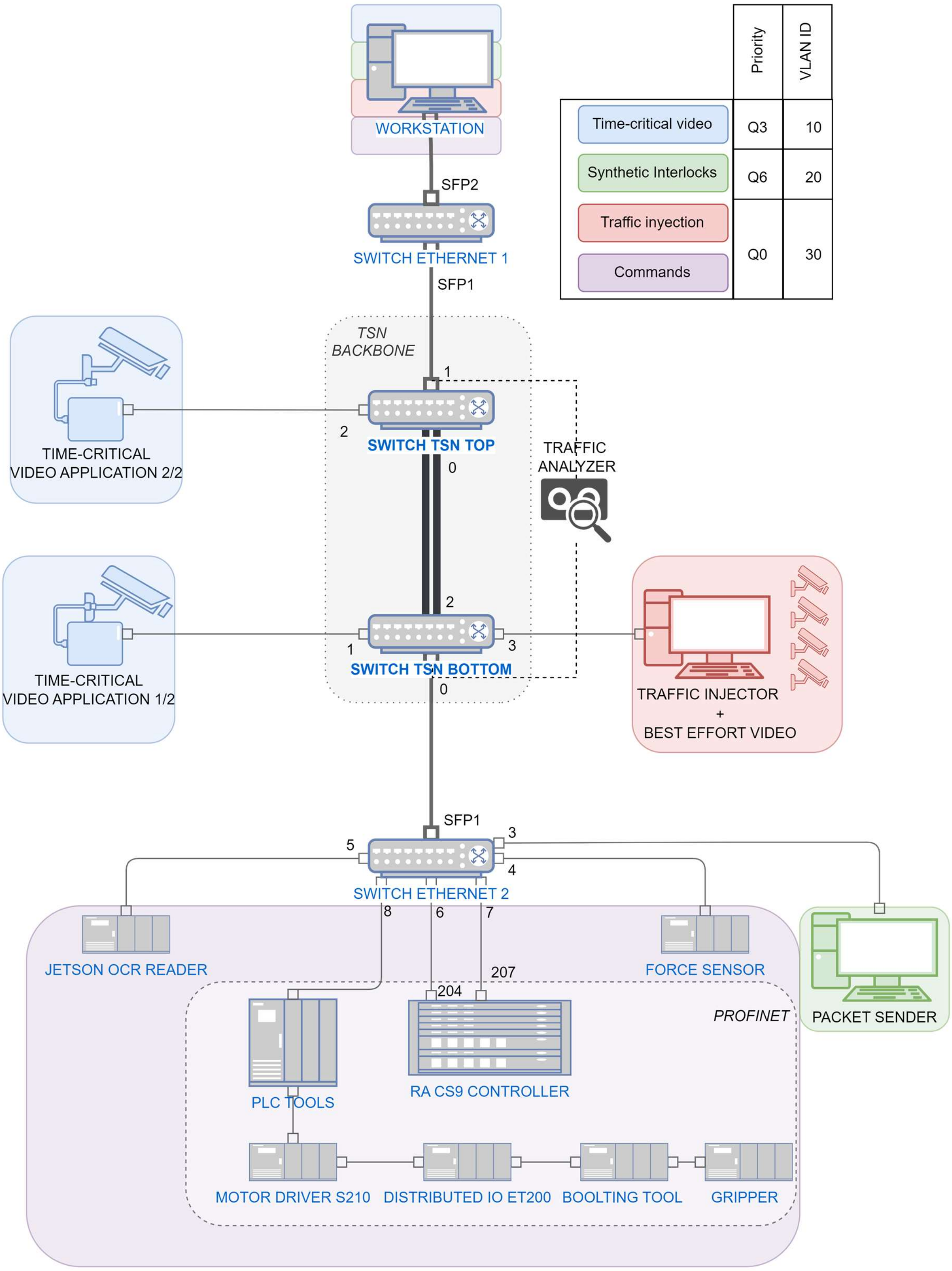


Figure 98:Network topology of the RH test bench integrating TSN.

Relyum equipment is capable of performing this VLAN tagging/untagging individually for each of its ports, as is the case, for example, with ports 1 and 3 of the TSN Bottom Switch. In this case, only one type of traffic arrives at the equipment port, Time-critical video and Traffic injection respectively. However, on port 0 of the same switch, there are two types of traffic, Command traffic and Synthetic Interlocks. For this reason, VLAN tagging/untagging is performed on Ethernet Switch 2, so that all packets arrive at the TSN Bottom switch already labeled. In addition, this switch allows the connection of a number of different devices at the bottom of the diagram that would not fit in the 4 ports offered by the TSN switches. In an ideal situation, this equipment would be replaced by a TSN device, or even eliminated if the end devices would support TSN in a way that would allow us to extend the TSN domain throughout the network.

Ethernet Switch 1 may seem unnecessary at first glance, but as in the case of Ethernet Switch 2, the ACL rules provided by the MikroTik operating system allow us to tag/untag the VLAN headers for the different flows. This simplifies everything, since the Workstation at the top of the diagram runs Windows and makes VLAN management more complex. This way the Workstation only runs the applications and does not have to deal with network traffic management. Again, this would be unecessary if the final equipment were compatible with TSN and it is just a temporary solution.

Finally, it is worth mentioning that a more adequate solution would be to have TSN switches with a greater number of ports, so that a more simplified setup could be achieved where each device could be identified with a port. However, at the time of acquiring the TSN devices, there were no versions of this equipment with more than 4 ports. This together with a high price made us opt for a hybrid solution that combines the TSN devices with conventional ethernet switches.

Once the equipment is connected according to the diagram shown in Figure 96, it is necessary to identify the different traffic flows. For this purpose, the IEEE 802.1Q standard, which defines the operation of VLANs, is utilized. Specifically, the priority field in the VLAN headers is employed, which will later serve for TSN flow configuration. This field consists of 3 bits and indicates the priority of the frame, with 0 being the lowest and 7 the highest.

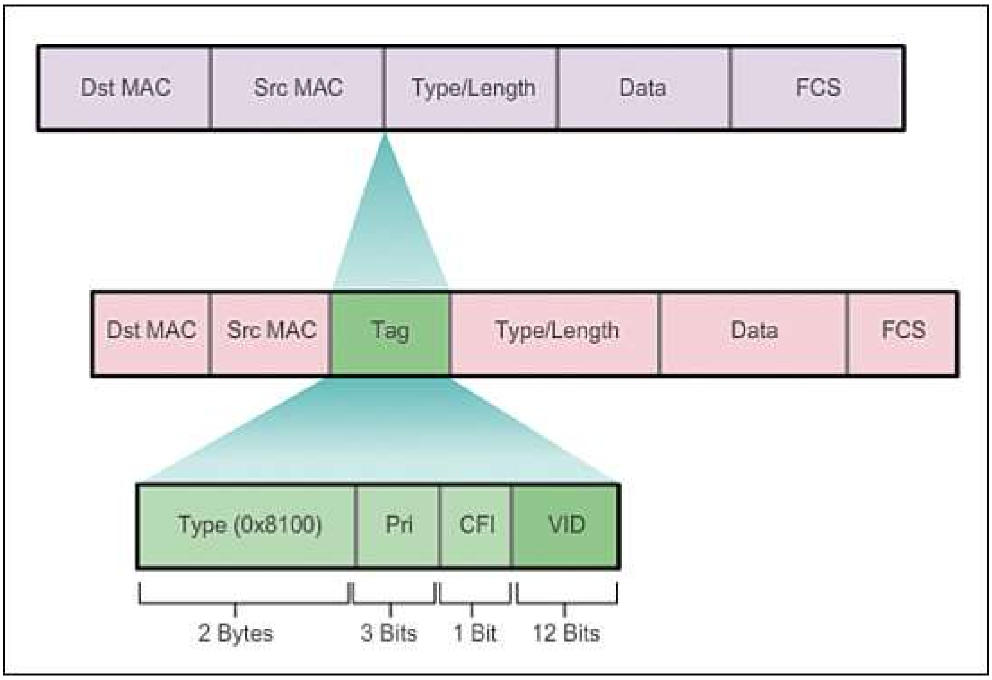


Figure 99: 802.1Q VLAN header

Tagging will be applied to both TSN and standard Ethernet switches as previously mentioned. In TSN switches, tagging is performed only on ports receiving a single type of traffic using the Port VLAN ID (PVID), which indicates the VLAN to which the traffic on that port belongs. This information is combined with a VLAN table specifying the ports associated with each VLAN, enabling proper packet routing. The priority of traffic received at each port is marked using the Priority Code Point (PCP) field, which will later assist in configuring the TAS of TSN. Ports configured with these fields are referred to as "Access Ports" following the manufacturer's terminology. Ports receiving pre-tagged traffic are configured as "Hybrid Ports."

Table 18 outline the port configurations and tagging for the Switch TSN Bottom. To simplify the configuration, traffic has been segregated into three VLANs, each associated with a priority level. VLAN 10 represents real-time traffic (RT) requiring strict periodicity, VLAN 20 exemplifies critical events that must ensure bounded transmission times, and VLAN 30 encompasses high-bandwidth traffic. To achieve this segregation across three VLANs while accommodating the four identified traffic types, Command Traffic and Traffic Injection have been combined. The Switch TSN Top is configured analogously, as detailed in Table 20**.** These configurations ensure that traffic flows are properly prioritized and routed, meeting the requirements of the experimental setup for TSN evaluation.

Table 19 and Table 21specify the ports associated with each VLAN under the "Port Members" column. It also indicates whether outgoing traffic should be untagged via the "Untagged Ports" column.

SW Bottom Port	Port type	Traffic type	PVID	PCP
Port 1	Access Port	Time-critical video	10	3
Port 3	Access Port	Traffic injection	30	0
Port 0	Hybrid	-	10, 20, 30	-
Port 2	Hybrid	-	10, 20, 30	-

Table 18: Port configuration of Switch TSN Bottom.

VLAN name	VID	Port members	Untagged ports
RT Video	10	1, 2	1
Interlocks	20	0, 2	-
Best Effort	30	2, 3	3

Table 19: VLAN table of Switch TSN Bottom.

SW Top Port	Port type	Traffic type	PVID	PCP
Port 2	Access Port	Time-critical video	10	3
Port 1	Hybrid	-	10, 20, 30	-
Port 0	Hybrid	-	10, 20, 30	-

Table 20: Port configuration of Switch TSN Top.

VLAN name	VID	Port members	Untagged ports
RT Video	10	1, 2	2
Interlocks	20	1, 0	-
Best Effort	30	1, 0	-

Table 21: VLAN table of Switch TSN Top.

To configure Ethernet switches, Access Control List (ACL) rules are applied, enabling tagging or untagging of packets from a specific port or group of ports based on defined conditions. Figure 100 illustrates the fields that can be set in an ACL rule.

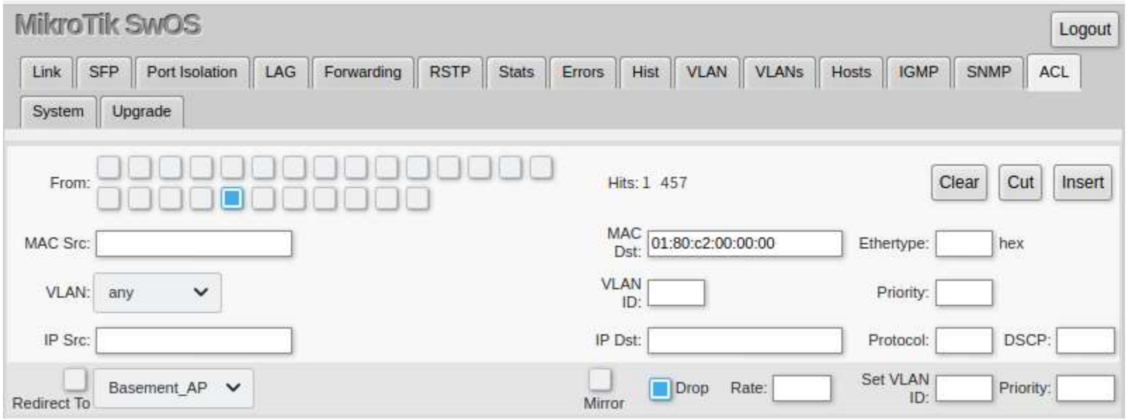


Figure 100: ACL rule configuration example on standard ethernet switch using MikroTik SwOS.

This approach is combined with VLAN tables on both switches, similar to those used in TSN switches. For Ethernet Switch 2, the following rules are applied:

- Incoming traffic to ports 4, 5, 6, 7, and 8 is tagged with VLAN ID 30 and priority 0 (upstream traffic).
- Traffic entering port SFP1 with VLAN ID 30 is untagged and forwarded to ports 4, 5, 6, 7, and 8 based on the destination IP (downstream traffic).
- Incoming traffic to port 3 is tagged with VLAN ID 20 and priority 6 (upstream traffic).
- Traffic entering port SFP1 with VLAN ID 20 is untagged and forwarded to port 3.

For Ethernet Switch 1, the ACL rules are slightly different:

- All traffic entering port SFP1 with VLAN IDs 10, 20, or 30 is untagged and forwarded to port SFP2 (upstream traffic).
- Traffic entering port SFP2 is tagged with VLAN IDs 10, 20, or 30 based on the destination IP and forwarded to port SFP1 (downstream traffic).
- With these configurations across the four switches, the network achieves segmentation with traffic isolation and prioritization.

To validate the configurations:

1. The Workstation's ability to communicate with each device was tested, ensuring that only devices within the same VLAN can communicate with each other.
2. To verify prioritization, the frames-per-second (fps) displayed by the video application for real-time (RT) images were monitored. Even under network congestion, the fps remained consistent, demonstrating the effective prioritization of RT traffic.

This setup confirms that the applied configurations ensure correct segmentation and prioritization, essential for a high-performance and secure network.

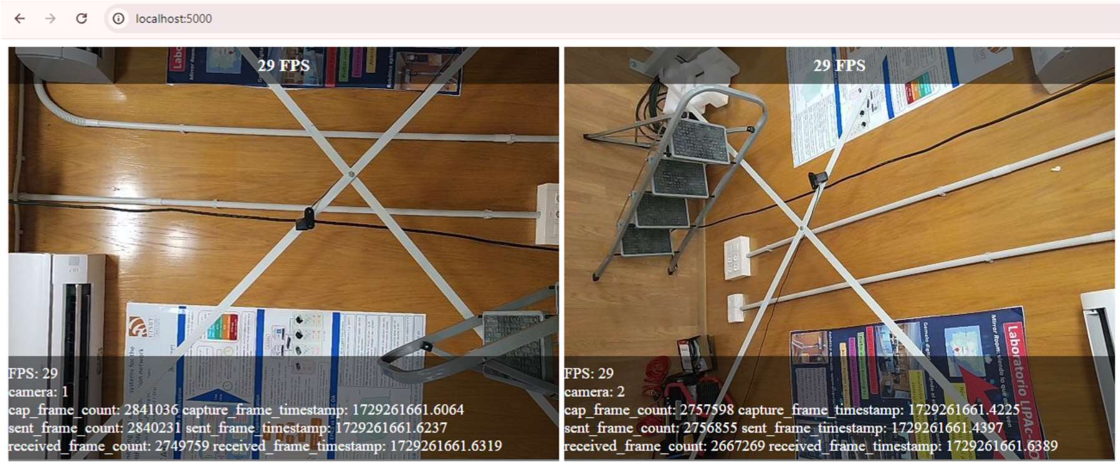


Figure 101: Web interface of the real-time video application. The fps received are shown in the upper part. Without priorities it can be seen that the fps drops to 0 when the network is congested, while with priorities the 29 fps are maintained with any level of congestion in the network.

To inject traffic into the network and simulate congestion conditions, we have used the iperf3 tool. It is an open tool available for both Linux and Windows. To run it we will launch a server on the Workstation (Windows) and a client on the Traffic Injector (Linux). In this way what we are looking for is to saturate the TSN Backbone. With the following commands we generate UDP traffic at 1Gbps with 1500 bytes packets (the standard maximum size for an Ethernet frame without jumbo frames) for 60000 seconds.

#Server command :   iperf3 -s

#Client command: iperf3 -c <IP_Worksation> -u -b 1G -l 1500 -t 60000

The tests presented below will focus on saturating the upstream backbone link using this tool and real traffic from the cameras, as this direction typically experiences the highest traffic load in a network deployment within an industrial facility. This is due to the need to transmit all field device data to the higher-level control systems.

7.5 Results and discussion

In this chapter, three of the main tasks of this thesis have been addressed, leading to the following outcomes:

- T1. Identification of Requirements: The main requirements for RH networks have been identified, encompassing both internal demands within the LICS and plant-wide requirements for seamless integration with the CICS.
- T2. Development of a Control Framework: A network design based on TSN has been proposed to integrate the various data flows identified. This design unifies

multiple networks into a common TSN-based infrastructure and outlines a potential deployment for the reference architecture.

- T5. Experimental Validation: Through the deployment of TSN networking equipment on the test bench, the functionality of this technology has been validated in an operational environment. In addition to verifying the proper handling of diverse traffic flows, experimental results have been gathered to demonstrate the deterministic behavior of the network.

7.5.1 Base scenario

To highlight the specific advantages of TSN, the key metric selected for evaluation is packet latency, as this characteristic is uniquely addressed by TSN compared to other technologies that also offer traffic segmentation or prioritization. The term latency will be used as the sum of all delays in the system, total packet delay, or network delay as referred in Figure 103.

For the latency analysis, the Synthetic Interlocks traffic has been chosen as the reference, as it demands bounded maximum latency. The time required for packets to traverse the TSN Backbone under various scenarios is measured, generating a graph such as the one shown in Figure X. To capture these measurements with high precision, a Relyum traffic analyzer is utilized, capable of accurately recording packet ingress and egress times across two TSN ports. All tests will be conducted over a duration of 10 minutes.

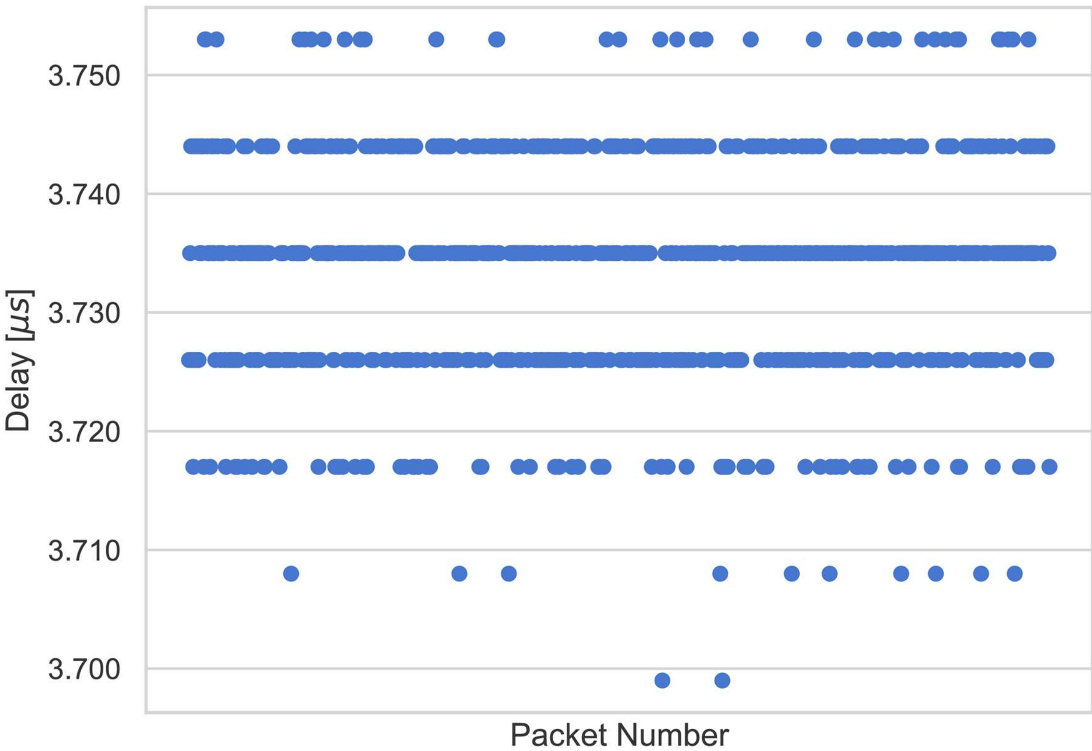
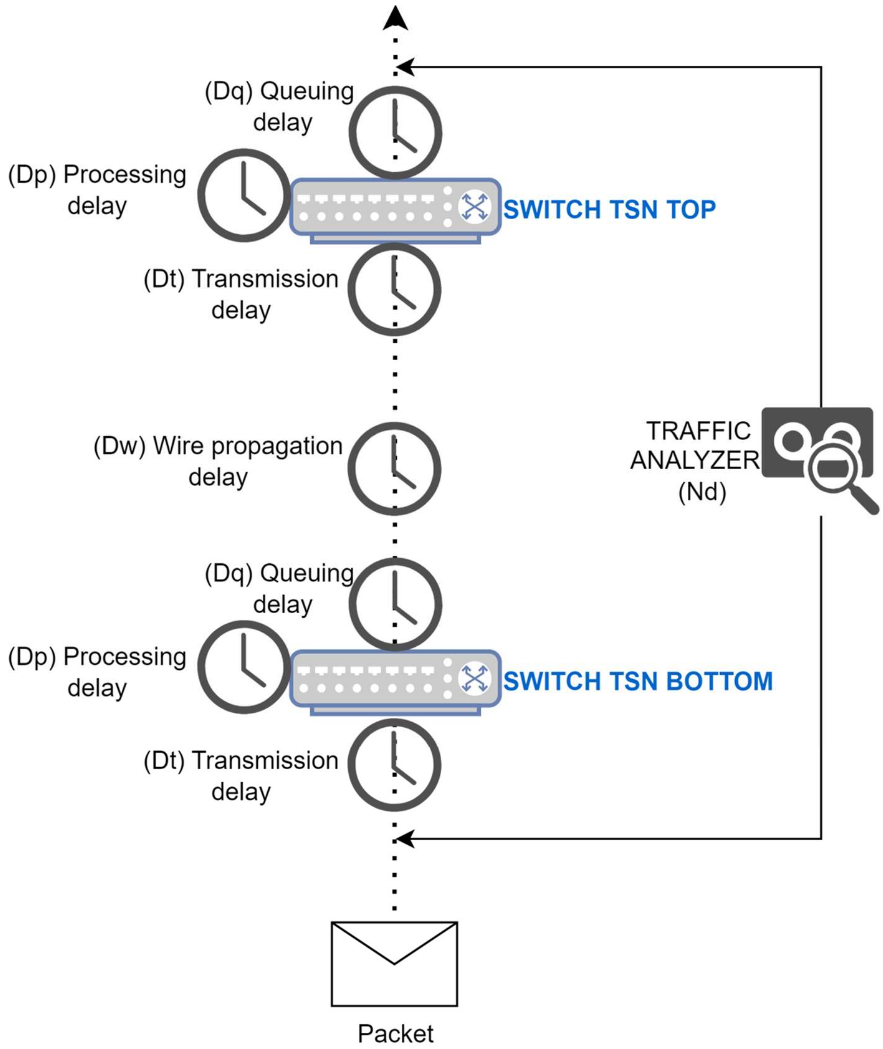


Figure 102: Latencies for synthetic interlocks in the baseline scenario, which excludes additional traffic or applied priorities. The latency observed is minimal, corresponding primarily to packet serialization, transmission, and processing times. The step-like distribution of data points in the graph suggests that the temporal granularity of the traffic analyzer is slightly less than 10 ns.

Packet transit delay through a network (or latency) consists of four components: propagation (wire) delay, processing delay, transmission delay, and queuing delay [111]. Figure 103 breaks down the contribution of each of these components to the recorded latency. Given that the fiber cable connecting the two TSN switches is 1 meter long and that the propagation speed in the medium is approximately 70% of the speed of light in a vacuum, the propagation delay is negligible (below 0.001 µs). Considering that the packet size is 64 bytes and the link speed is 1 Gbps, the packet transmission time is calculated to be 0.512 µs.

$$Transmission\ delay\ (Dt) = \frac{Packet\ size\ (bits)}{Transmission\ speed\ (bps)} = \frac{512\ (bits)}{10^9\ (bps)} = 0.512us$$

The queuing and processing times depend on the hardware and its implementation, so they will be unknown to us. However, we can assume that the processing time will be a fixed value for packets of the same size, and that the queuing time will be variable depending on network conditions.



$$Nd = 2Dq + 2Dp + 2Dt + Dw$$

Figure 103: Measured Network delay (Nd) or latency on the TSN backbone, indicating the delays introduced on each step of the packet path.

The behavior of packet delays was analyzed under conditions of network congestion, with priority mechanisms deactivated for this test.

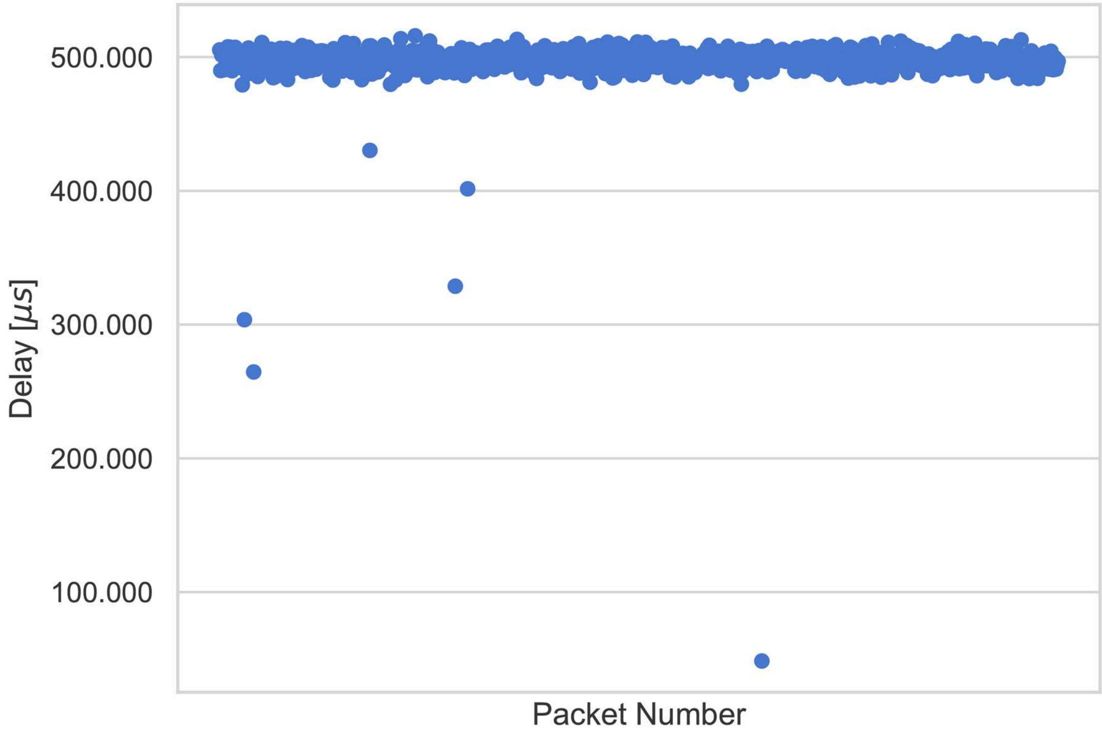


Figure 104: Latencies of the synthetic interlocks in the base scenario with congestion and without priorities. It can be seen that the latency is maximal because the packets must be stored in the equipment until they can be transmitted.

Figure 104 illustrates a significant increase in latency, reaching up to 500 µs. This value is notably high, considering it is observed across a single network hop. The increase in delay is attributed to network saturation, causing interlock packets to queue within the switches until transmission is possible. Unlike the prior scenario without congestion, the lack of prioritization mechanisms exacerbates this queuing effect.

The queuing behavior is governed by the internal logic of the TSN switches, which allocate bandwidth among ports. However, the exact algorithms and logic are proprietary and dependent on the switch manufacturer. Despite the elevated latency, all transmitted packets were successfully received, confirming no packet loss occurred during the test, even though UDP was used. This result can be attributed to the small size of the packets and their low transmission frequency (5–10 Hz), which allows for effective queuing without exceeding the buffers' capacity.

7.5.2 Priority scenario

In this scenario, network traffic prioritization is applied using the mechanisms provided by the IEEE 802.1Q standard. This standard enables the assignment of priorities to Ethernet frames through the Priority Code Point (PCP) field, a 3-bit value in the VLAN tag. The PCP field allows traffic to be categorized into one of eight classes, with priorities ranging from 0 (lowest) to 7 (highest). This mechanism is widely used to implement Quality of Service (QoS), ensuring that critical or time-sensitive data, such as real-time control signals or video streams, receive transmission priority over less urgent traffic.

For this analysis, the PCP values have been configured as follows:

- Time-critical video: PCP 3
- Synthetic interlocks: PCP 6
- Commands: PCP 3
- Traffic injection: PCP 0

This configuration assigns the highest priority to interlock traffic. Packets tagged with PCP 6 will always be placed at the front of the transmission queue, bypassing packets with lower priorities (PCP 3 and 0) that may already be waiting. This ensures minimal latency for critical interlock signals, even in scenarios with competing traffic.

The first test examines latency when Time-critical video traffic is present but without overall network congestion. This controlled scenario isolates the impact of prioritization on latency under normal network conditions, providing a baseline for comparison with congested environments.

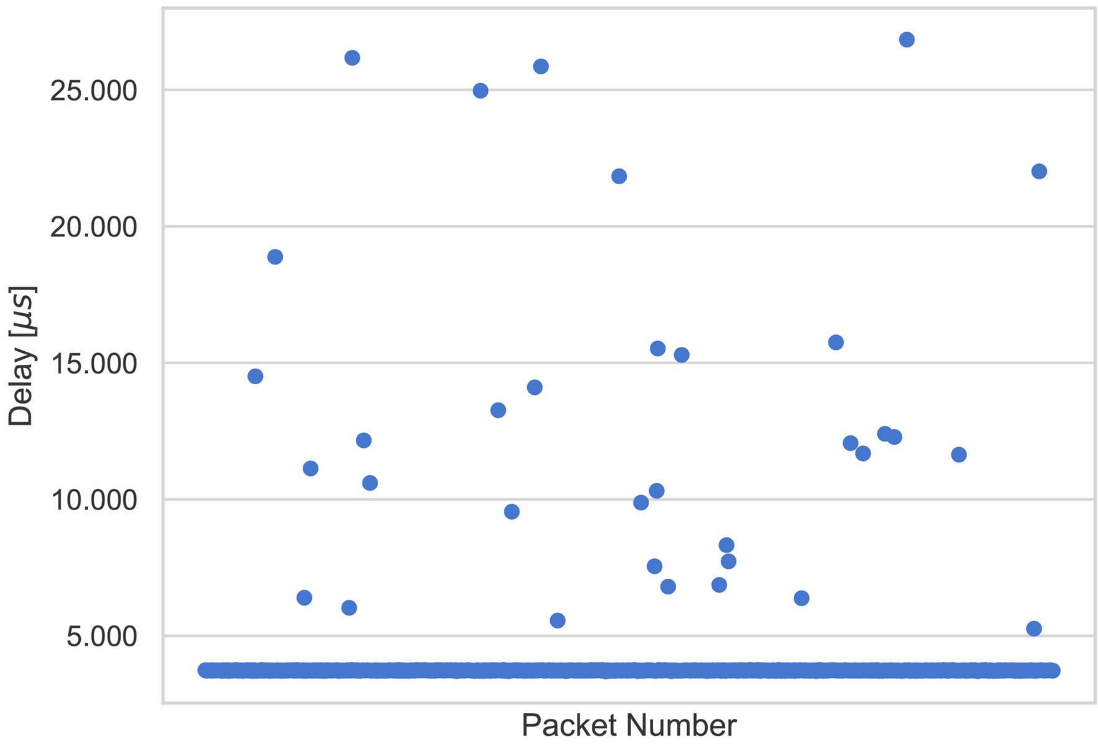


Figure 105: Latencies of the synthetic interlocks in the priority scenario with time-critical video traffic and without congestion. Most of the packets are around 3.7us (base scenario), but some of them are delayed up to 27us when they reach the switch just at the beginning of the transmission of a video packet.

Figure 105 illustrates how the majority of samples exhibit latencies around 3.7 µs, consistent with the baseline results observed in Figure 102. However, some packets experience higher delays, with an upper bound of approximately 27 µs. This discrepancy arises due to the presence of video traffic, where the frame size is set to the maximum allowed for standard Ethernet (1500 bytes). The transmission time for each video packet is 12 µs.

$$Transmission\ delay\ (Dt) = \frac{Packet\ size\ (bits)}{Transmission\ speed\ (bps)} = \frac{12000\ (bits)}{10^9\ (bps)} = 12us$$

According to the formula presented in Figure 103, the only additional delay compared to the baseline scenario is introduced by queuing delays (Dq). In the worst-case scenario, the maximum delay occurs when an interlock packet arrives at the switch just after the transmission of a video packet has started. Under these circumstances, the interlock packet must wait for the video packet to finish transmission. Adding this 12 µs queuing delay to the base delay of 3.7 µs results in the observed upper bound of 27 µs.

The next test introduces congestion via iperf, producing the latency distribution depicted in Figure 106.

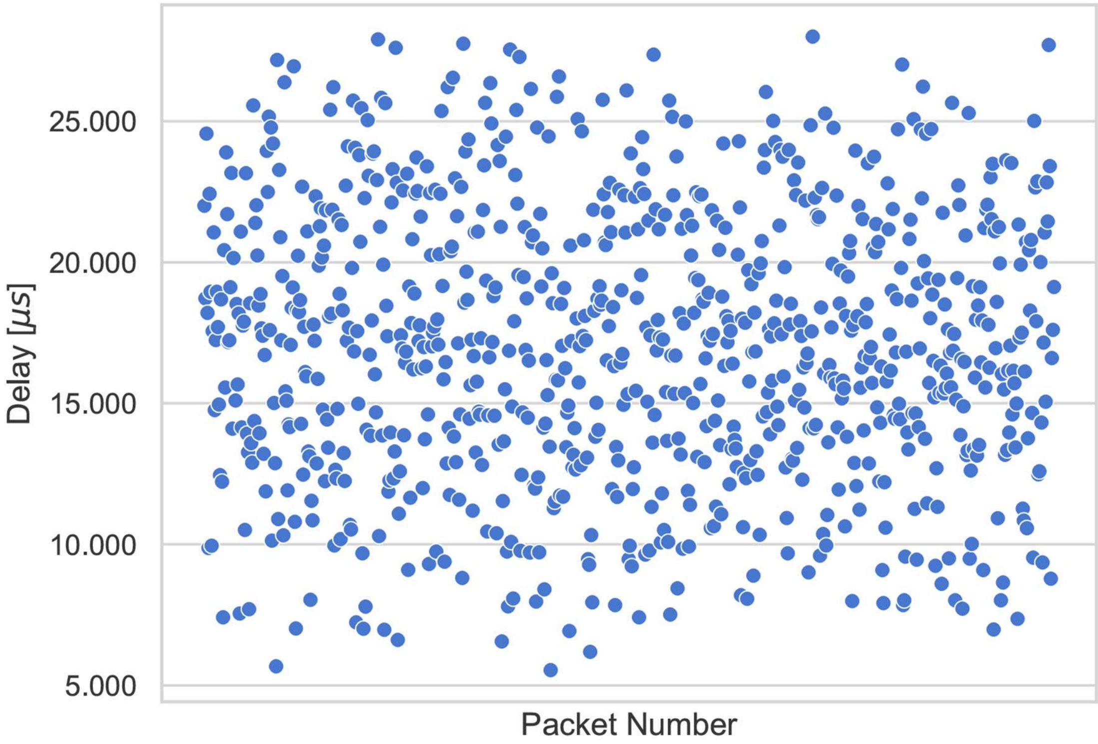


Figure 106: Latencies of the synthetic interlocks in the priority scenario with time-critical video traffic and congestion. The packets are more dispersed because they will always find some packet in transmission, so they will always have to be queued until the end of their transmission.

In the congestion scenario, no samples fall below 5 µs, indicating a significant shift compared to the previous case. This increase is attributed to the constant queuing delays caused by network congestion. Interlock packets must always wait until the current packet transmission is completed. The spread in latency values is significantly larger than in the prior scenario, reflecting the random generation times of interlock packets. This randomness results in packets encountering the transmission of video packets at varying stages, ranging between 0-99% of completion.

The upper bound of latency remains close to the 27 µs observed in the previous test, with slight increases. Similarly, the lower bound is slightly higher than in the baseline case, confirming the impact of congestion on interlock packet queuing delays.

7.5.3 TAS scenario

The upper latency bound observed in Figure 106 can be reduced by leveraging the TAS mechanism provided by TSN. This is achieved by configuring an appropriate GCL tailored to the existing traffic profiles, specifying the duration each gate remains open for the different traffic classes. While the GCL configuration is identical for both switches in the test setup, they are phase-shifted by a value defined through the "base_time" parameter. This parameter allows precise alignment of the initial time t0 across the switches, allowing to accommodate the delays between the packet entrance from one switch to the next.

The optimal base_time was determined experimentally, starting at an initial value of 10 µs and incrementally reducing it until the minimum value ensuring stable network behavior was identified. The primary reference for stability was the 30 fps requirement of the Time-critical video traffic.

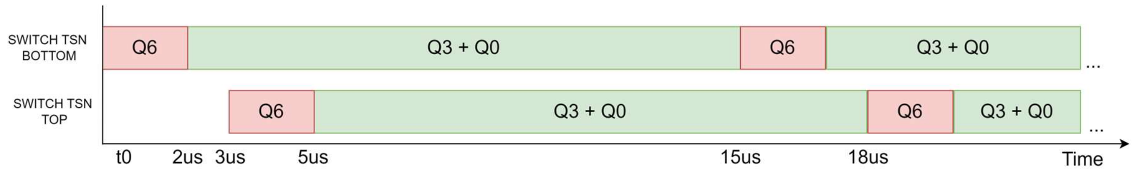


Figure 107: GCL configuration for the TAS.

After configuring the TAS, the interlock packet delay test was repeated under the same conditions of network congestion as in the previous scenarios, using both video and iperf traffic.

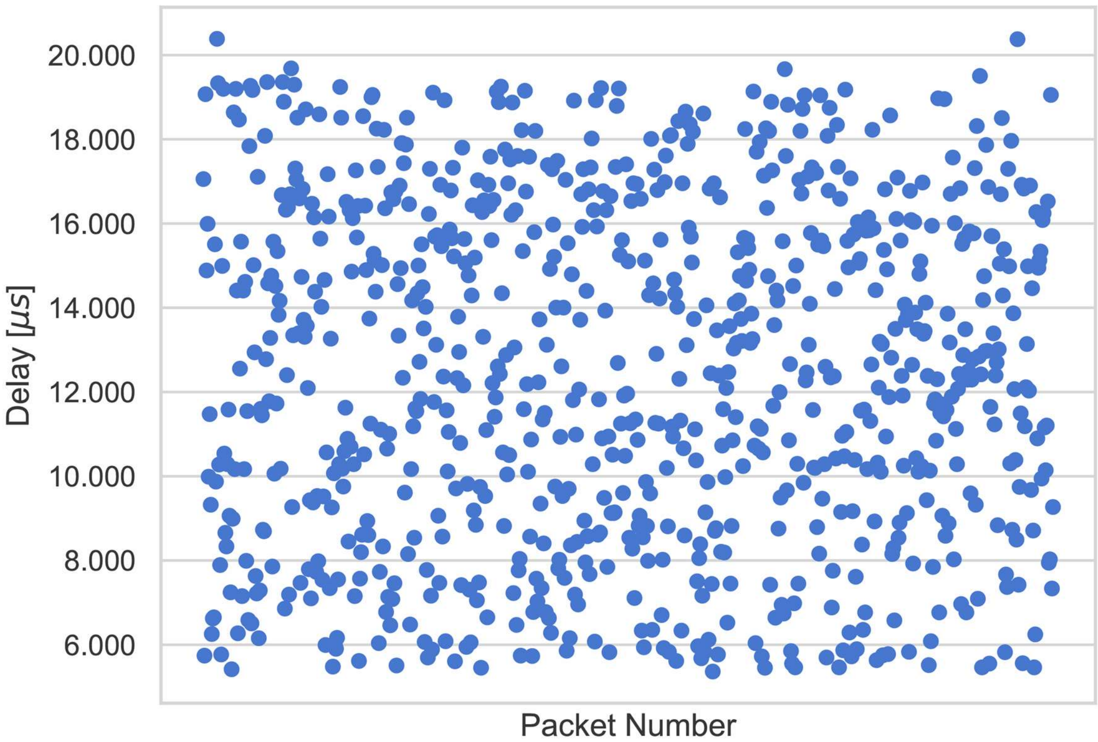


Figure 108: Latencies of the synthetic interlocks in the TAS scenario with time-critical video traffic and congestion. The upper bound has decreased up to 20.5us.

The results reveal a reduced dispersion of delay values, with the upper bound constrained to approximately 20.5 µs and the lower bound around 5.5 µs. This demonstrates an improvement over the 27 µs observed in the priority-based scenario, as the interlock packets are only queued at the first TSN switch if they arrive while the Q6 gate is closed. Once the packet passes through the first TSN hop, it encounters an open Q6 gate at subsequent hops, accumulating only the base_time offset of each switch.

The use of TAS also affects the available bandwidth. As illustrated in Figure 96, the bandwidth is allocated periodically for each priority level, regardless of whether traffic is present or not. Measurements show that the combined traffic for Q3 and Q0 is limited to approximately 820 Mbps, compared to the 950 Mbps achievable at the base scenario (the effective capacity of a 1G link). However, assigning the same time slot to Time-critical video traffic—which has a higher priority than best-effort traffic—ensures that the video application has the necessary bandwidth, albeit at the expense of best-effort traffic availability.

This behavior highlights the trade-off introduced by TAS: while it guarantees deterministic behavior and prioritization, it also enforces a structured allocation of network resources, which may reduce the maximum throughput for best-effort traffic.

7.5.4 Estimation diagrams

The experimental results give us an idea of the improvements in latency that can be achieved by using the TAS (Time-Aware Shaper) of TSN for a single network hop, as represented in the ECDF (Empirical Cumulative Distribution Function) of the data presented in the previous sections.

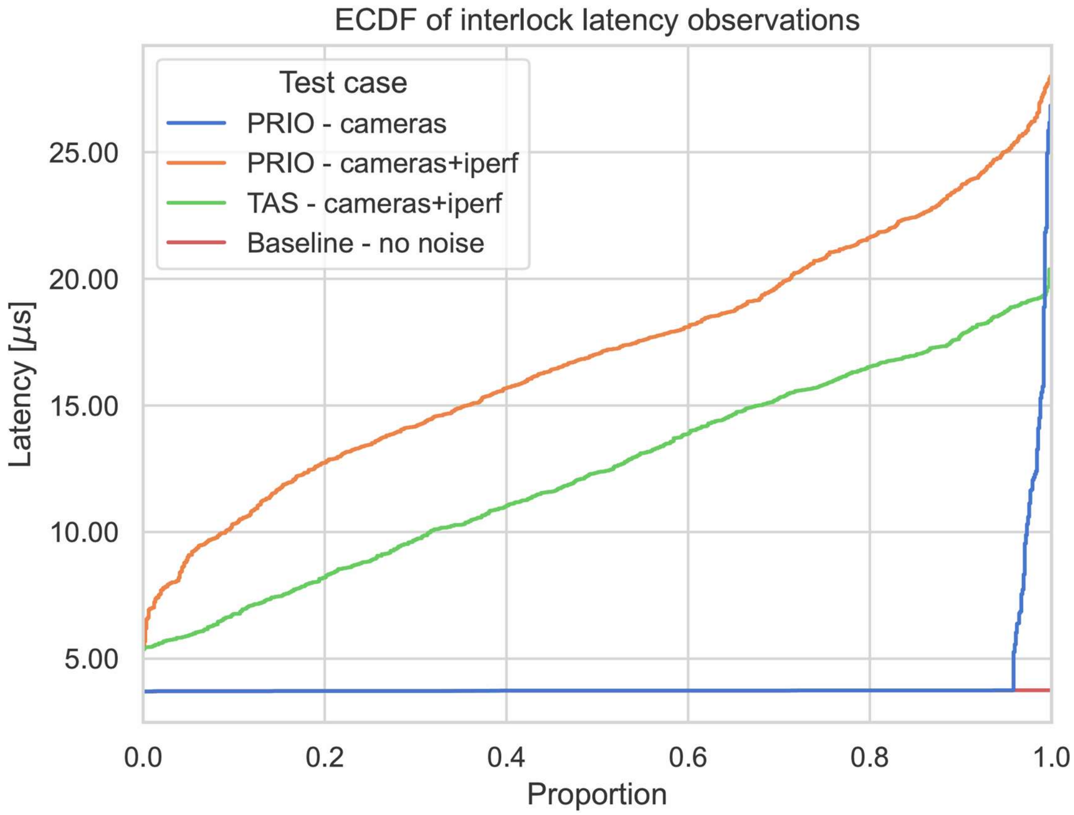


Figure 109: ECDF of interlock latency of the previous scenarios.

The Figure 109 shows that the variability of the samples in the case of using the TAS of TSN is reduced, and the latency values obtained consistently outperform those achieved through the use of priorities offered by the IEEE 802.1Q standard. This difference becomes even more noticeable as the number of network hops increases.

When there is more than one network hop, the use of the TAS of TSN ensures that queuing delays from the first switch onward are fully bounded, regardless of the congestion conditions in the network. This situation can be exemplified with a traffic analogy, where the network is an "smart avenue" signalled by precisely synchronised traffic lights. Each intersection of the avenue has a traffic light, which corresponds to the different hops of our network. To enter the avenue, a packet arriving at a random time may encounter a red light and have to wait for a random period. However, once inside, thanks to TAS, the packet can travel at maximum speed, encountering all subsequent traffic lights green, and reach its destination within a bounded time, regardless of the existing traffic.

The use of TAS allows us to eliminate queuing delays (Dq) after the first network hop, which cannot be achieved solely with priorities. In a priority-based scenario, the system only ensures that, of all the packets waiting to be transmitted, the highest-priority packet moves to the front of the queue. However, there is an increasing probability, as network congestion grows, that a packet is already in transmission, forcing the high-priority packet to be queued until the current packet completes its transmission.

The following diagrams analyze this difference based on worst and best times extracted from the experimental results, and provides an estimate of the behavior we could expect when adding successive hops to the network for both scenarios

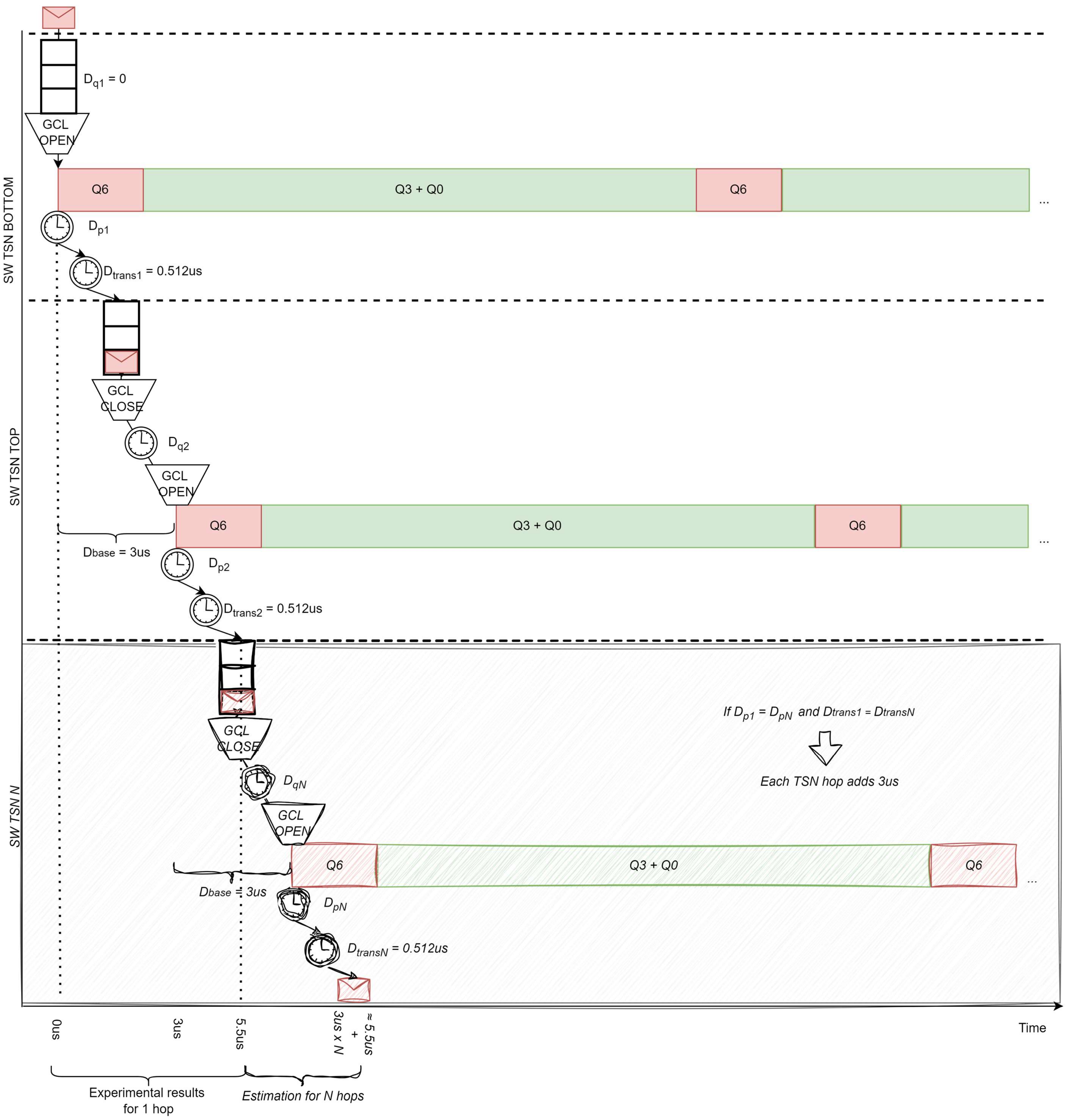


Figure 110: Timing diagram of best case scenario using TAS.

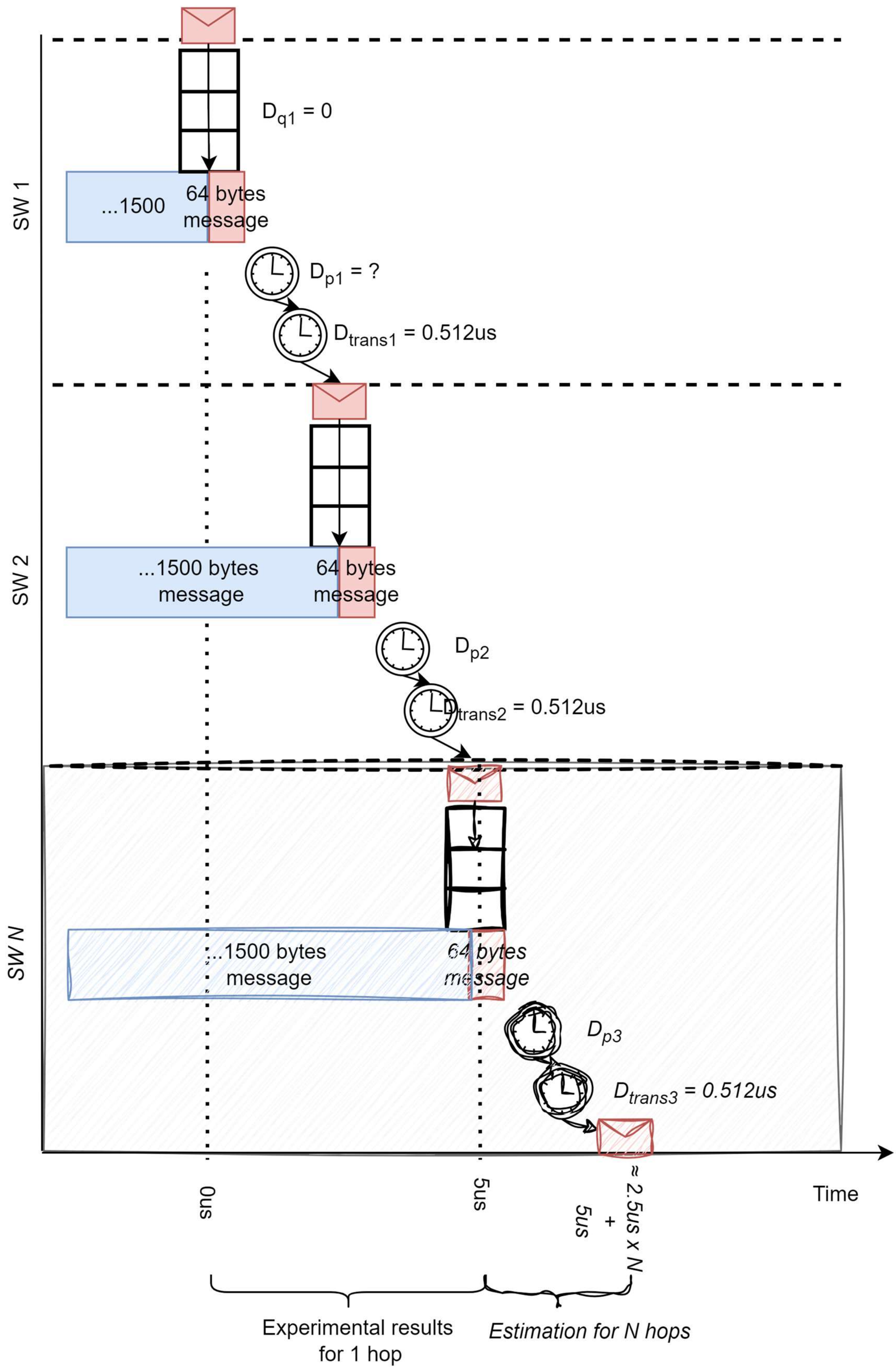


Figure 111: Timing diagram of best-case scenario using priorities.

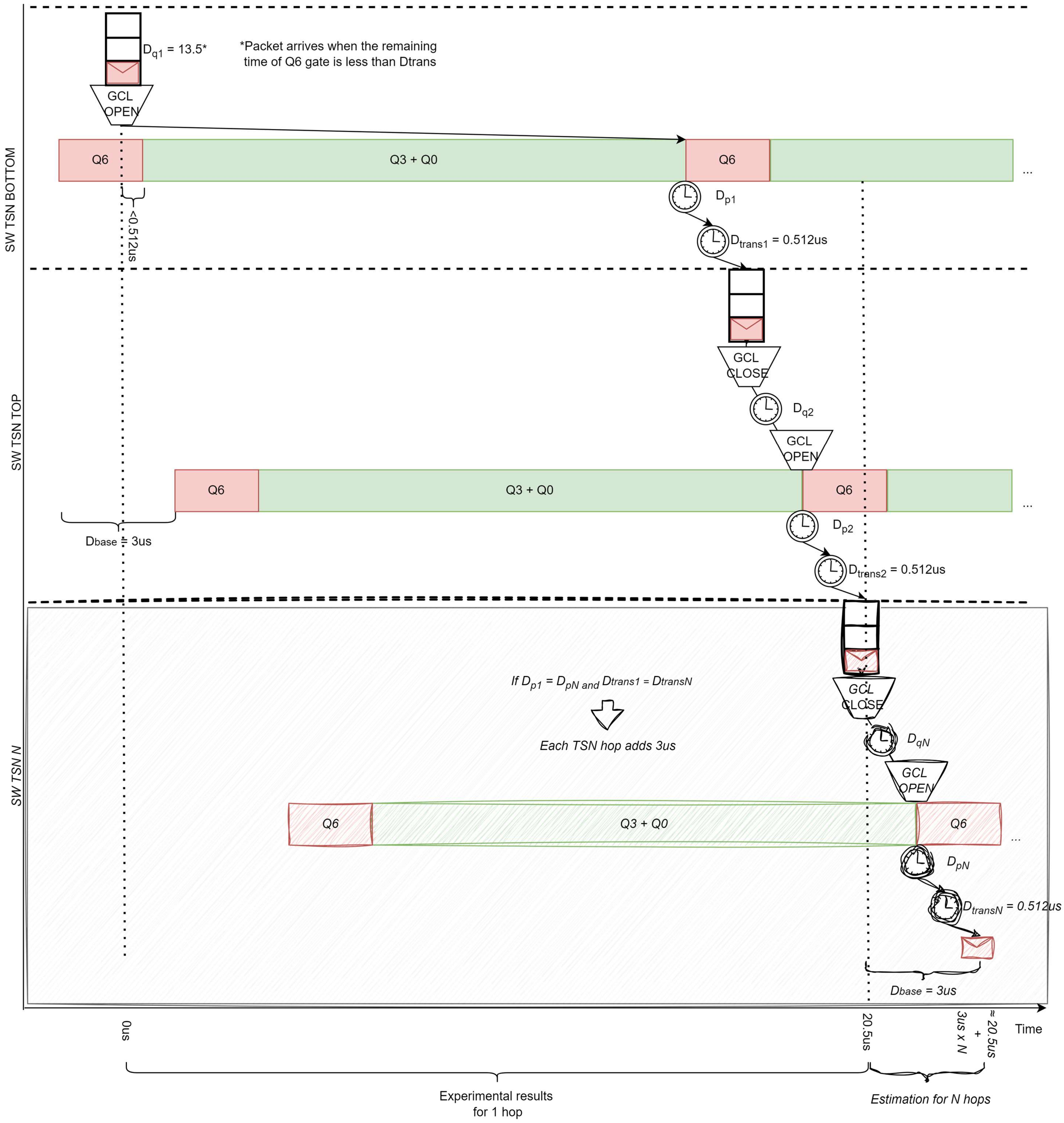


Figure 112: Timing diagram of worst-case scenario using TAS.

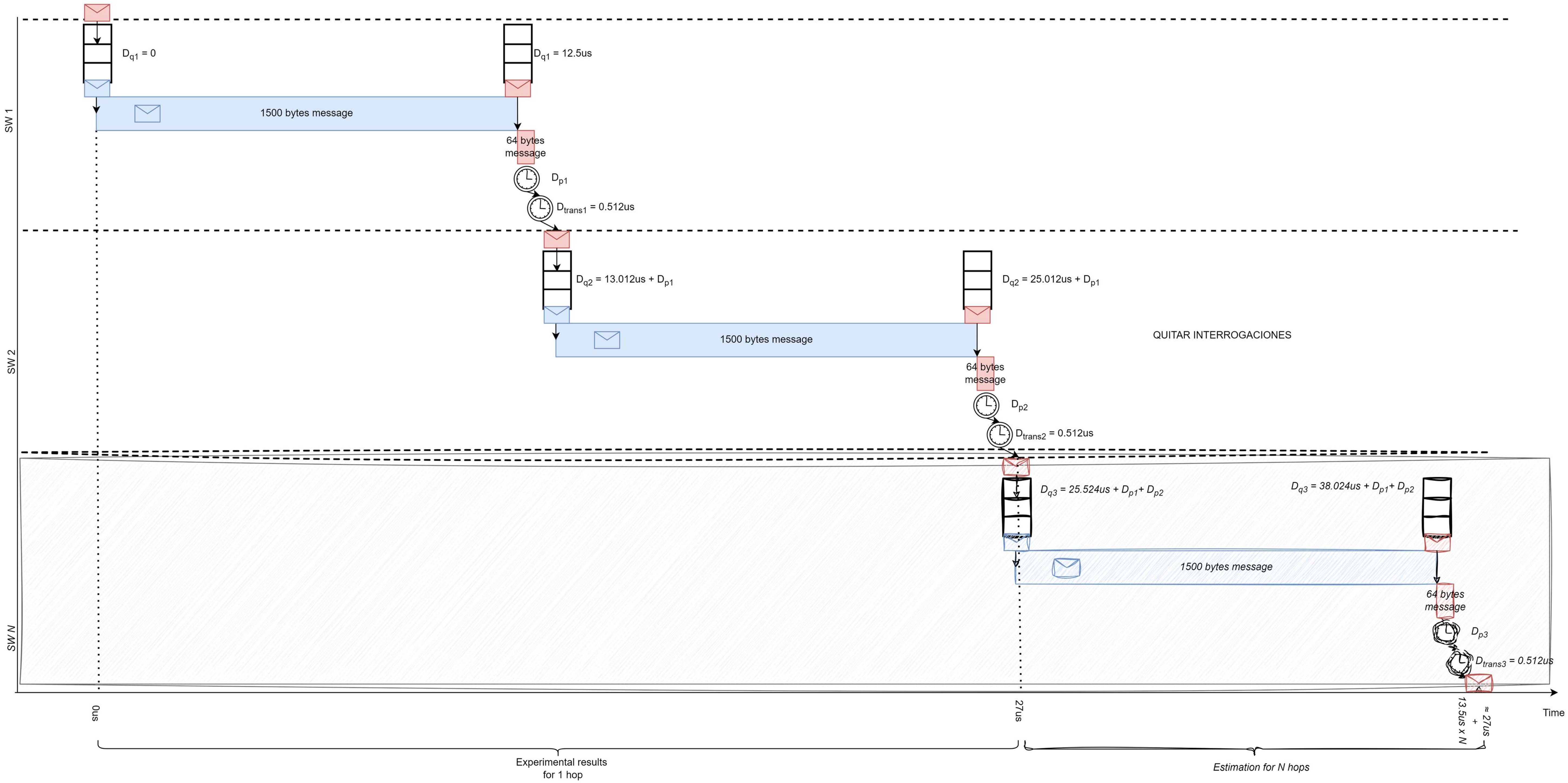


Figure 113: Timing diagram of worst-case scenario using priorities.

Based on the analysis performed using the four previous diagrams, we can make an approximate estimation of the latencies introduced for N network hops.

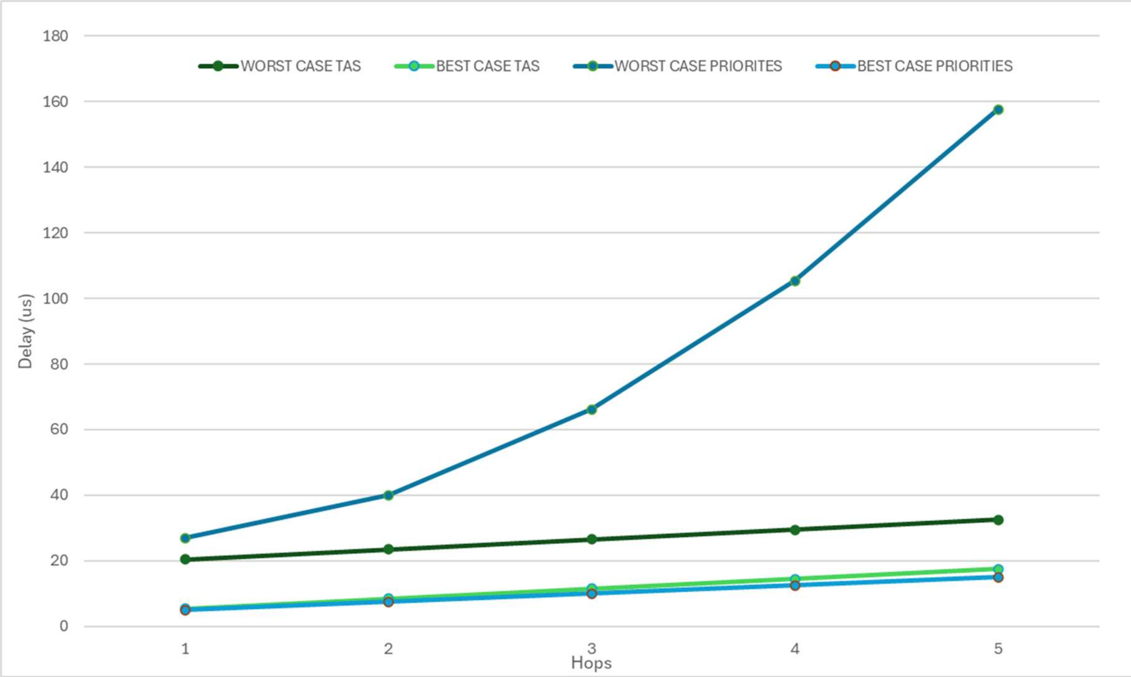


Figure 114: Latency estimation for 5 network hops on RH test bench.

The graph shows a linear behavior in both TAS cases, where the latency increases only by the base_time (3 µs) for each network hop. In scenarios with priorities, we observe that in the Best-Case scenario, the behavior is also linear, showing a similar progression. However, this ideal behavior only occurs when there is no other traffic on the network, so this result is only theoretical and does not occur in any real network deployment. As network congestion increases, the progression of this line gradually approaches that of the Worst-Case scenario.

7.5.5 Conclusions of Chapter 7

This chapter has focused on the analysis of networking solutions for the RH systems in IFMIF-DONES. Starting with an overview of the networks established at the plant level by the Central Instrumentation and Control System in Section 7.1, it delved into the detailed description of the proposed networks within the RH High-Level Control System. This theoretical framework was complemented by a proposal for the physical implementation of these networks, which included the suggestion of deploying a replica control room.

In addition to addressing network infrastructure, an analysis was conducted on the types of data and traffic profiles expected from RH systems in Section 7.2. Traffic flows generated by each block in the RH reference control architecture were categorized into four primary groups. Performance and reliability requirements were subsequently discussed and mapped to the proposed architecture, tying these considerations back to the broader RH operational context previously described in Chapter 6.

The chapter's primary contribution lies in evaluating TSN as a transformative technology capable of replacing the previously analyzed networks. Incorporating TSN into the proposed architecture would unify network infrastructure into a single solution, simplifying management and maintenance, reducing costs, ensuring efficient bandwidth utilization, and offering deterministic behavior.

To assess the applicability and benefits of TSN, the test bench devices were integrated into a TSN backbone. Experimental efforts, detailed in Section 7.4, focused on measuring latencies for transmitting critical packets under various scenarios. Results demonstrated that TSN provides bounded latencies even under maximum network load, emphasizing its potential to meet the stringent requirements of RH systems, as originally defined in Section 4.3.

In conclusion, this chapter has thoroughly analyzed and justified the use of different network types within the control architecture for RH systems. While TSN emerges as a suitable candidate for this scenario, offering numerous benefits, it remains a technology in active development. Its deployment would require additional effort, yet the advantages in terms of unifying network infrastructure and achieving deterministic performance make it a promising choice for the RH systems in IFMIF-DONES. These findings align closely with the design principles outlined in Chapter 8, demonstrating how TSN can serve as a foundation for an Enhanced Remote Handling Control System.

Chapter 8
Enhanced Remote Handling Control System

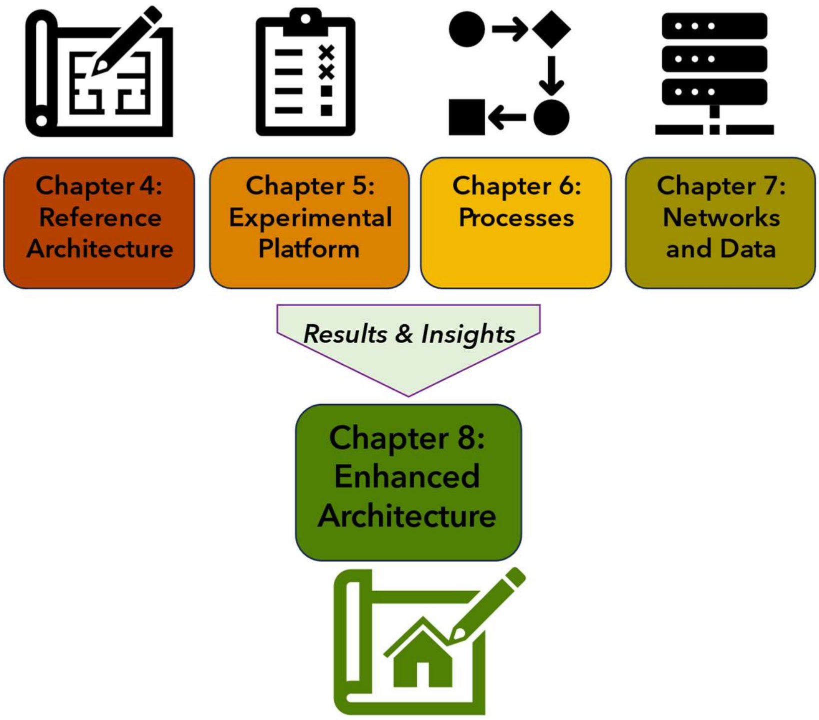
This chapter presents a novel and pivotal contribution of this thesis, building directly on top of the reference architecture from Chapter 4, and **including the results and insights discussed in Chapters 4 to 7**. It introduces a comprehensive and scalable RHCS architecture tailored to meet the complex demands of IFMIF-DONES while anticipating future needs. This design builds upon the framework of Chapter 4, incorporating significant **improvements in performance, autonomy, and intelligent capabilities.**

The proposed architecture is presented through two complementary perspectives: the **logical architecture**, which defines functional components, their interactions, and modularity; and the **physical architecture**, which focuses on hardware design, network topology, and physical connectivity. Drawing from the findings of Chapter 7, advanced industrial technologies like TSN and OPC UA are integrated to ensure robust and reliable communication. Additionally, **cutting-edge tools** such as Artificial Intelligence (AI) for predictive maintenance and real-time operator assistance, explored in earlier chapters, enhance adaptability and operational efficiency.

One of the defining features of this design is its focus on integration and interoperability, creating a foundation that not only bridges current technological challenges but also accommodates **emerging technologies** from both industrial and research domains. The architecture emphasizes **scalability and forward compatibility**, making it well-suited for adoption of advancements in robotics, industrial automation, and remote control, with great potential for application in RH systems.

By incorporating a formal RH ontology, as introduced in Chapter 6, this framework facilitates knowledge **standardization and reuse**, providing a transferable model for other facilities. This chapter's proposal goes beyond incremental improvement; it represents a paradigm shift, blending theoretical insights with practical, future-ready solutions.

8 Enhanced Remote Handling Control System



The development of an Enhanced RHCS Architecture represents the culmination of the analyses and insights presented throughout this thesis. In Chapter 4, the reference architecture was introduced to meet the baseline requirements of the RH system for IFMIF-DONES. This initial design emphasized modularity and outlined the core functionalities necessary to manage the diverse and demanding operational tasks within Remote Handling.

The purpose of this chapter is to propose an enhanced and scalable architecture for the RHCS as a whole. This chapter outlines the architecture in two complementary parts: the logical architecture, which defines the functional components, their interactions, and their logical organization; and the physical architecture, which focuses on hardware design, network topology, and physical connectivity.

8.1 Design Principles of the Enhanced Architecture

The development of an enhanced RH control system architecture for IFMIF-DONES is guided by the conclusions drawn from the analysis in previous chapters. These findings have provided a robust foundation for identifying key areas of improvement and proposing a system that optimizes the capabilities of RH system. The design principles of the enhanced architecture are structured to address both current operational needs and future challenges, ensuring adaptability and scalability over time.

At the time of writing this thesis, certain critical aspects of the functional requirements and processes assigned to the RH control system in IFMIF-DONES remain undefined. To advance the development of the proposed enhanced architecture, a series of assumptions have been made. While these assumptions may not fully align with the final project direction, they provide a foundation for this design:

1. **Reference RHCS architecture is the project baseline**: The design outlined in Chapter 4 reflects the basic needs of the project. The independence and autonomy of the RHCS described above is suited to the type of operations and processes envisaged in DONES. The main focus of the RHCS is to integrate a number of heterogeneous mechatronic devices under a single framework. On this basis, the enhanced architecture proposes advanced functionalities through the application of state-of-the-art technologies.

2. **System Objectives**: The enhanced architecture aims to enhance safety, optimize intervention times, improve reliability, and provide flexibility to carry out new operations. These objectives will be achieved by increasing automation and supervision capabilities and supporting operators through expert systems. This approach balances technological innovation with practical usability, ensuring the system addresses current operational demands while preparing for future challenges.

3. **In-house Development and Management**: It is assumed that the development, maintenance, and operation of the RH control system will be primarily carried out by an internal project team. Although certain components and services may be outsourced, it is crucial for the project to retain the necessary knowledge and tools to manage these systems internally. This ensures long-term sustainability, reduces dependency on external entities, and provides greater control over critical RH operations.

4. **Knowledge as a Core Asset**: The most valuable outcome of the RH control system is expected to be the knowledge and expertise gained during RH operations. This know-how will play a pivotal role in continuously improving RH processes. To support this goal, the system must adopt a standardized structured language that facilitates the transfer of operational insights to other facilities and projects. By creating a transferable framework, IFMIF-DONES can establish itself as a reference point for future RH applications in fusion research.

5. **Budget Justification and Long-Term Value**: Achieving the aforementioned objectives may require an increase in the allocated budget. However, this investment should not be seen as a cost but as an opportunity to generate long-term value. The proposed system is designed not only to meet the immediate needs of IFMIF-DONES but also to serve as a testbed for similar systems in other fusion facilities, such as DEMO. By adopting a forward-looking perspective, the enhanced architecture positions IFMIF-DONES as a leader in RH control innovation, yielding returns through efficiency gains, operational improvements, and the dissemination of knowledge to future projects.

Two key principles underpin the proposed architecture: integration and flexibility. Integration involves unifying RH devices and RHCS modules to create a cohesive platform, facilitating seamless communication and control between them. Flexibility ensures the architecture can adapt to evolving RH capabilities, whether through new hardware, software updates, or process changes.

The modular and flexible nature of the system is another cornerstone of this design. Essential modules will be identified to enable basic manual operation of RH devices without any additional support. These modules will serve as the foundation, while additional modules will provide enhanced functionalities such as assisted or supervised control. These extensions will focus on improving efficiency, reliability, and safety in RH operation.

The enhanced architecture is conceived with a forward-looking perspective, leveraging insights from technological trends. By prioritizing solutions with long-term development potential, the system ensures that its design remains relevant and effective throughout its implementation lifecycle and beyond. Moreover, the design has been made with scalability in mind, providing a suitable framework that could integrate advancements in industrial communications, robotics or AI. This proposal aims to address long-term challenges that are critical in the roadmap of projects like DEMO, while offering immediate value to IFMIF-DONES. The following sections will delve deeper into the components and strategies that bring this vision to fruition.

8.2 RH ontology

This section proposes to further develop the RH ontology presented in Section 6.2 to provide a framework that supports integration, automation, and knowledge reuse within the RHCS of IFMIF-DONES and potentially other facilities.

In the context of this thesis, an RH task refers to a specific, individual action performed as part of a procedure, while an RH operation encompasses the broader set of tasks and activities required to complete a defined objective within a maintenance or intervention campaign. A RH task can be represented through five primary components:

- Operator: Defines human operators, their roles, and skills, capturing task assignments, training records, and competency levels.
- Device & Tooling: Specifies robotic devices, tools, sensors, and actuators, including their specifications, operational status, and capabilities.
- Material: Covers consumables and spare parts, mapping their use, storage locations, and task-specific requirements.
- Procedure: Encodes the workflows and control commands necessary for RH operations.
- Measurement: Focuses on feedback data, including force readings, execution times, positional metrics, and sensor outputs, enabling diagnostics and monitoring.

The interaction among these five components creates a detailed representation of RH tasks as shown in Figure 115. It can be interpreted by both human operators and automated systems, allowing the ontology to represent relationships between entities, such as assigning specific tools to tasks or mapping operators to roles.

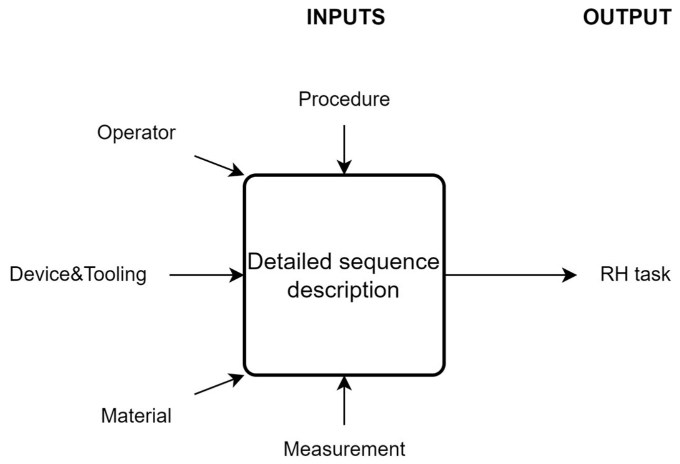


Figure 115: Structure of RH ontology to describe a RH task using 5 input components

To construct this ontology, a hybrid methodology as outlined in [112] is proposed, emphasizing modular development and agile principles. Each component can be developed iteratively and independently before being integrated into a unified framework. Figure 116 illustrates this methodology, highlighting the iterative process of conceptualizing modules and their subsequent integration. This modular approach mitigates scalability challenges, supports efficient reuse, and simplifies updates.

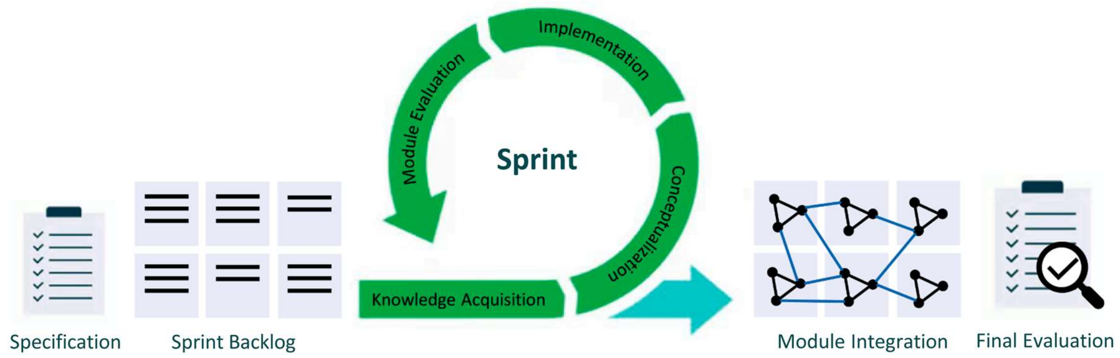


Figure 116: Ontology hybrid development approach using Agile [112]

OPC UA standard was proposed in a previous chapter as a foundation to provide the required infrastructure for a standard data format and communications. Its guidelines and rules for creating a standardized semantic information model are essential for structuring the components of an ontology that supports integration, automation, and knowledge sharing. By applying the semantic framework provided by OPC UA, components can be modeled in a structured and interoperable manner, resulting in the creation of Companion Specifications tailored to the specific requirements of RH operations.

The "Device & Tooling" component is a good candidate to apply the OPC UA Robotics Companion Specification [113], developed by the OPC Foundation and VDMA. This specification describes motion device systems and aims to enable the vertical integration of condition data into higher-level systems (e.g., MES or cloud platforms) for diagnostics and information purposes. Figure 117 presents the structure of this specification, which could be extended to cover additional use cases such as safety or motion control.

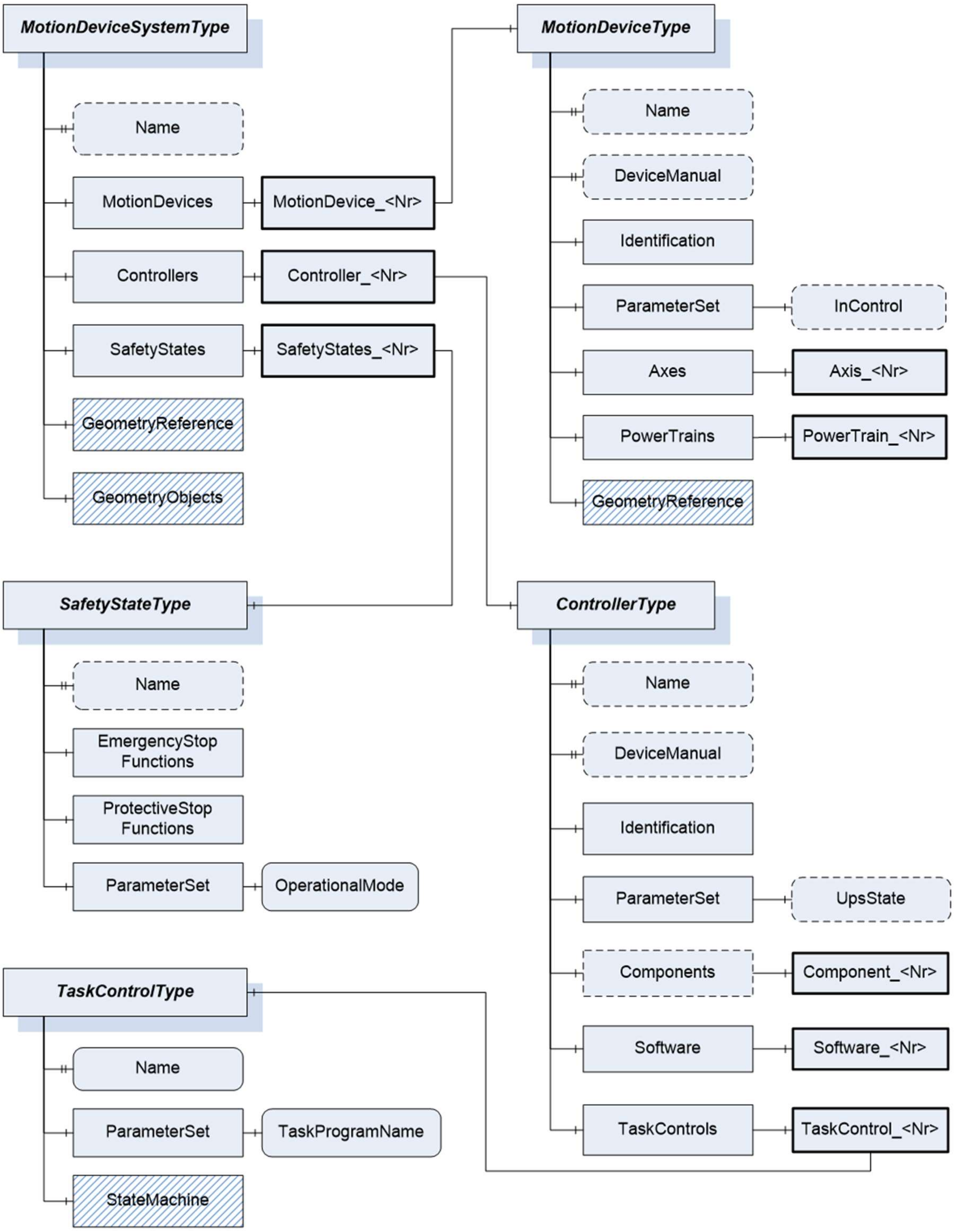


Figure 117: Overview of OPC UA Companion Specification for Robotics (OPC Robotic) [113]

Various other Companion Specifications exist, tailored for specific industries, and are readily accessible. In the case of IFMIF-DONES it requires unique functionalities not foreseen in any other specification already existing, new specifications can be developed following the guidelines of the OPC Foundation.

8.3 Operator Assistance

The incorporation of fully automated tasks within RH maintenance campaigns and interventions frequently appears to be impractical, given the relatively infrequent nature of operations (e.g., Target Assembly is replaced once a year). In other instances, the implementation of such tasks is inherently constrained by their critical nature and complexity. Most operations cannot be entrusted to autonomous systems; instead, the priority is to develop tools and systems that assist human operators, reducing fatigue and cognitive load during operations.

One emerging technology with significant potential in this field is the Digital Twin (DT). A digital twin is a virtual representation of a physical object, system, or process that bridges the physical and digital realms [114]. These virtual training platforms enable operators to interact with simulated equipment, practice procedures, and respond to potential emergencies in a risk-free setting [115]. For RH systems, the concept of DTs are commonly used as a VR system capable to align virtual robot configurations with their physical counterparts in real time [116].

Virtual Controllers form a critical component of DTs, offered by many industrial vendors to simulate hardware behavior, resource usage, and even physics simulation of the robotic component and the environment. These tools bring significant benefits to RH control systems:

- Early virtual commissioning before on-site deployment.
- Testing and evaluation of control strategies in secure, virtual environments.
- Integration testing without requiring physical equipment (virtual commissioning).
- Safe, controlled environments for operator training.

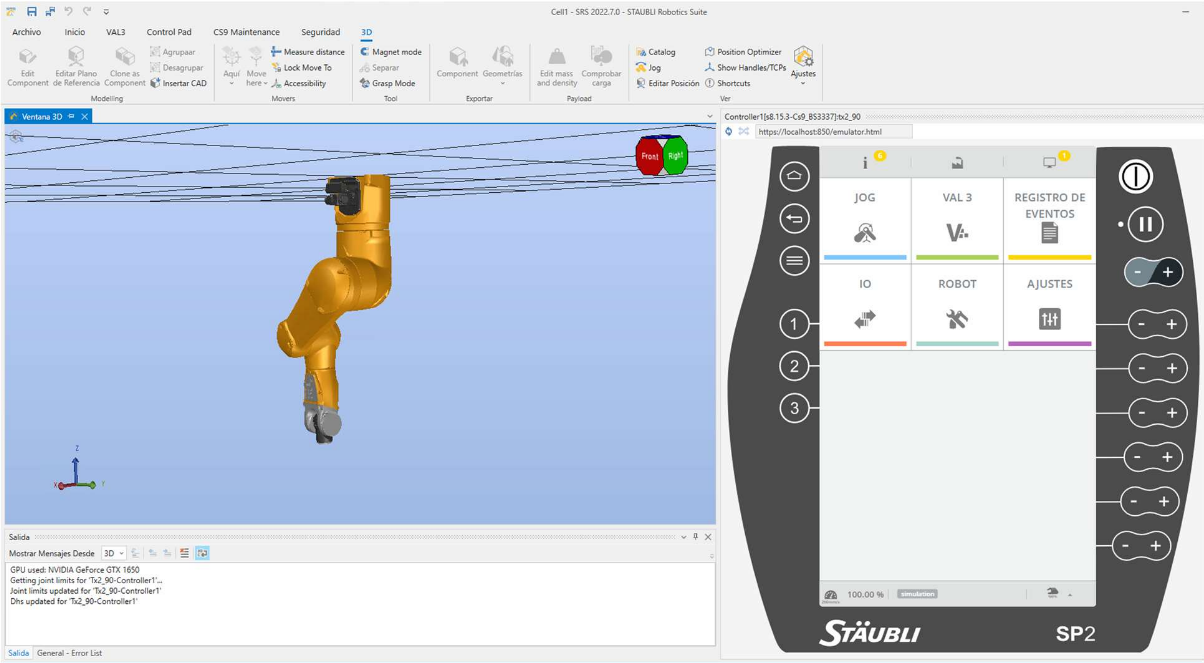


Figure 118:Virtual CS9 controller and 3D model of Staübli TX2-90. This is an example of simulation environment provided as part of the engineering tool by the manufacturer (Staübli Robotics Suite).

A notable framework for implementing DTs is the ROS-based architecture, integrating physical controllers, process simulators, and decision-making algorithms through scalable, topic-based communication [117]. As depicted in Figure 120, physical and virtual controllers interconnect seamlessly using ROS nodes, ensuring modularity and compatibility across devices, sensors, and actuators.

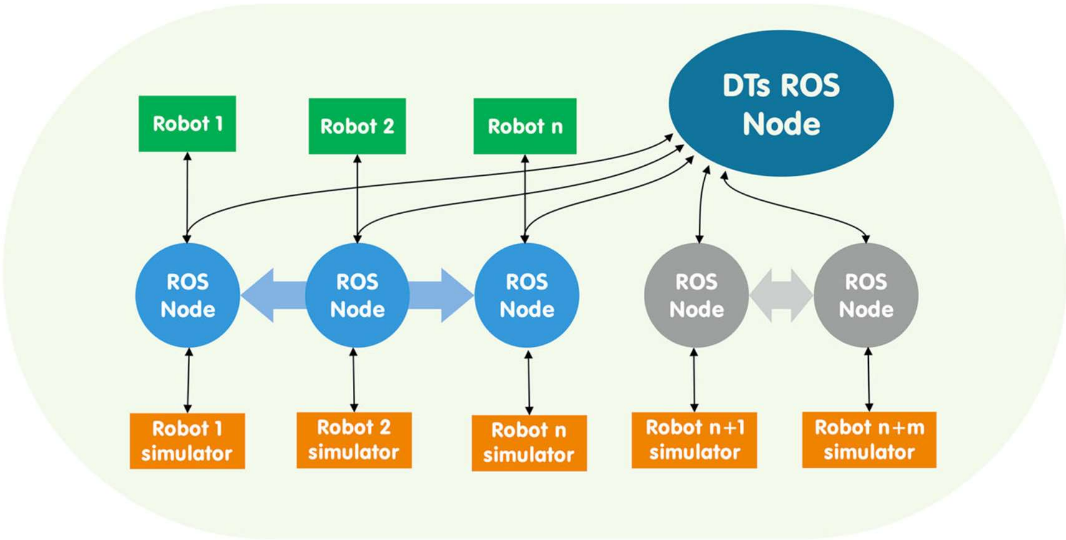


Figure 119: Integration of physical and virtual controllers in ROS nodes, and their connection with ROS nodes in charge of providing digital twin (DT) functionalities [117].

When mapped to the RH control architecture of IFMIF-DONES, this ROS-based framework requires minimal adjustments due to proven interoperability with OPC UA. The integration of these two technologies has been successfully proven in different ways [118] [119]. We have succesfully tested in the UGR-DONES control laboratory to bridge ROS nodes with the OPC UA server included in the Staübli robotic arm [120]. The bridge used for these experiments has been developed by Fraunhofer IPA, and is available publicly in [121]

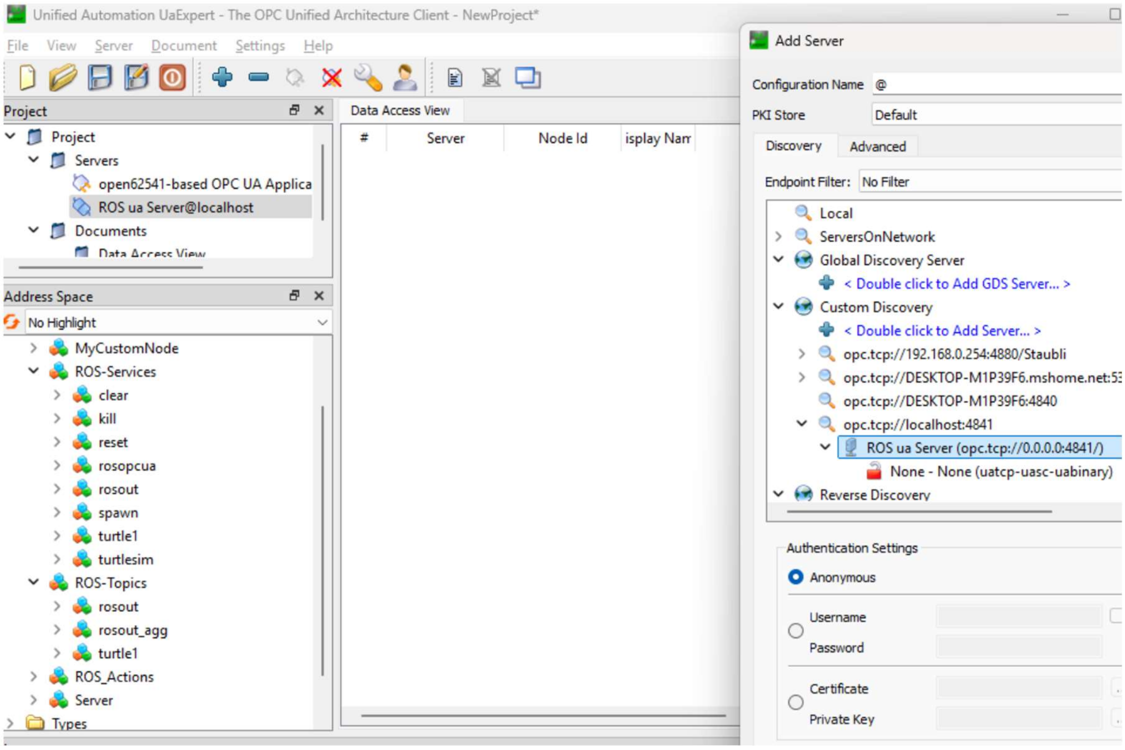


Figure 120: View of the ROS environment from an OPC UA client extracted from [120]. By using a communication bridge, we can connect the ROS ecosystem and the OPC UA address space, ensuring compatibility and semantic mapping.

With the proposal described, we have a suitable scenario for the use of Artificial Intelligence (AI) techniques. The boom in this field of knowledge and its exponential growth in recent years suggests that its application in real operation environments such as DONES will become more and more common. Potential applications for AI within our proposed RH control systems include:

1. **Predictive and Preventive Maintenance Planning**: AI algorithms can optimize maintenance schedules, improving preventive and predictive maintenance to reduce unplanned downtime [104].

2. **Environment Modeling and Object Pose Estimation**: Advanced neural networks enable real-time identification and pose estimation of objects using low-resolution cameras [122].

3. **Shared Control Algorithms**: AI-powered shared control improves the efficiency of tele-operated tasks, enhancing operator precision and reducing workload [123]

4. **Compensation for Deformations in Equipment**: AI-driven models can predict and mitigate mechanical deformation, increasing the reliability of RH devices in high-stress environments [124].

5. **Intelligent User Interfaces**: By adapting user interfaces to operator behavior, AI can enhance user performance and minimize operational errors [125].

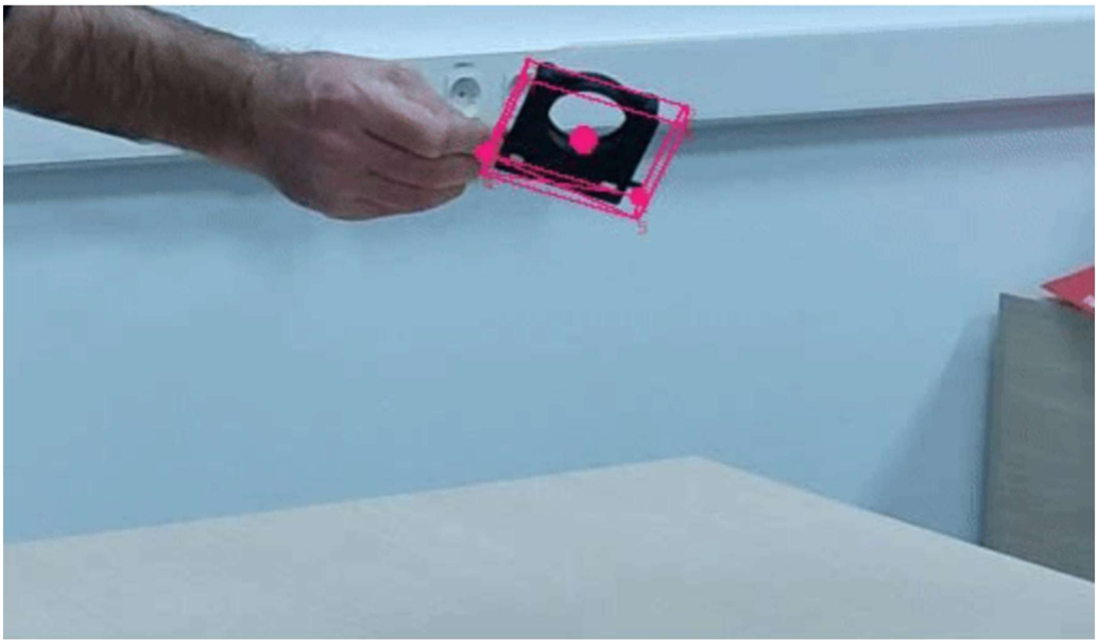


Figure 121: Application for real-time pose estimation of objects using Convolutional Neural Networks and images taken by a low-resolution camera. [126]

8.4 Detailed RHCS Architecture

This section presents the updated version from the reference architecture from Chapter 4, incorporating refinements in design principles, additional functionalities, and considerations to address the challenges specific to the RHCS context. The contents developed about the control framework selection (Section 4.4.1), the control hierarchy definition (Section 4.4.2), the use of OPC UA as standard interface (Section 4.4.5), the definition of the Low Level Control System components (Section 4.4.6), the approaches to mitigate radiation problems (Section 4.4.7) and the proposal for the RH Control Room (Section 4.4.8) will remain applicable throughout this chapter.

The proposed modifications will therefore concentrate on refining, redefining and, in some cases, adding modules of the HLCS (initially described in Section 4.4.3), in addition to proposing a physical design centred on the RH networks previously defined in Section 4.4.4.

8.4.1 Logical architecture

Represents the functional relationships and logical structure of the system, independent of the physical location or implementation details.

The logical architecture of the enhanced system is represented in Figure 122. It illustrates the functional relationships and logical organization of the RHCS while abstracting from the specific physical locations or implementation details. By focusing on the logical level, we aim to provide a clear depiction of how various modules and subsystems interact to ensure efficient operation, seamless communication, and scalable integration. In the diagram different symbols are used to define modules, databases, interfaces and networks external to RH according to the legend in the upper right corner.

This enhanced logical architecture serves as the foundation for defining the physical layout and network topology described in subsequent sections, bridging conceptual design with practical implementation.

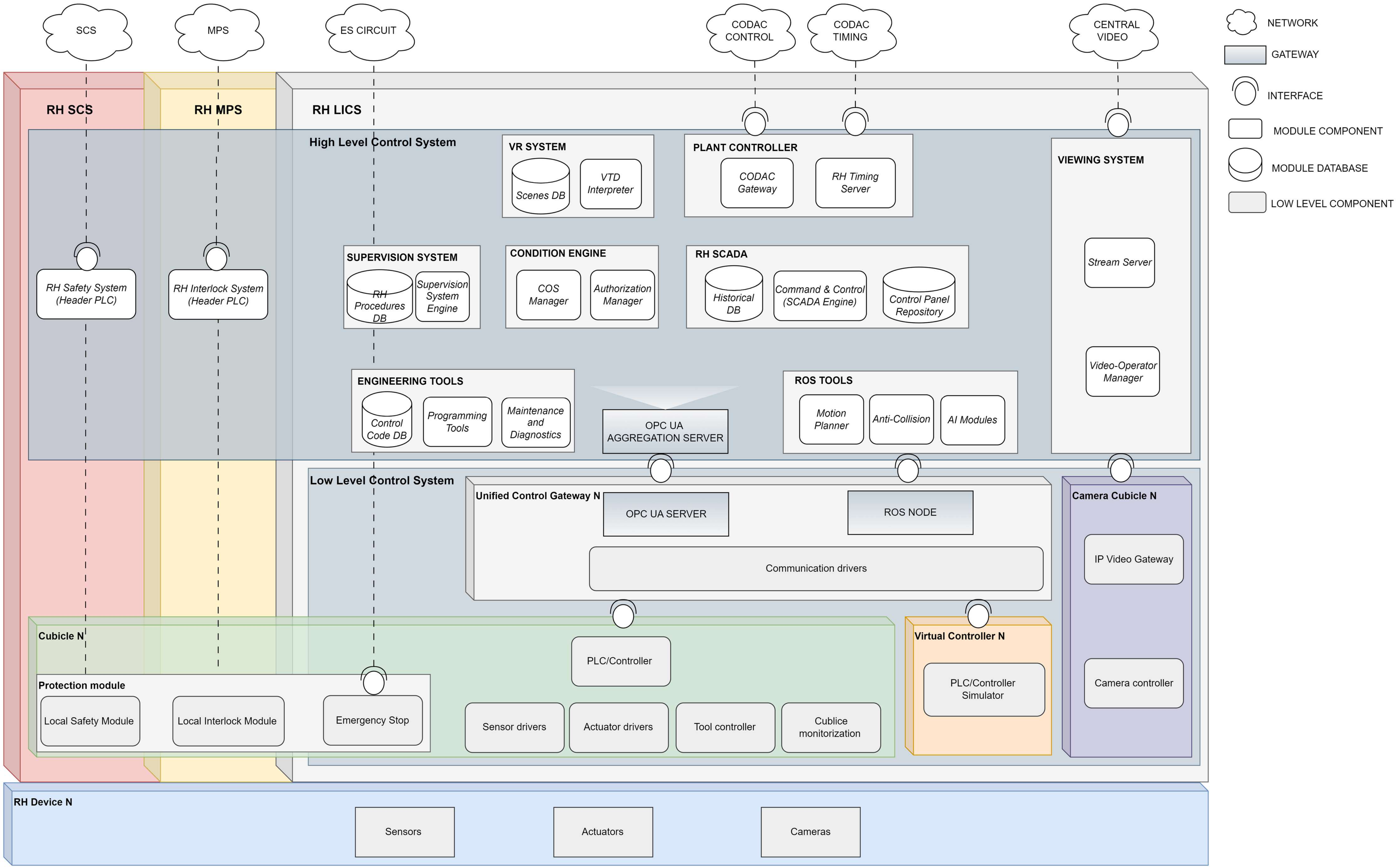


Figure 122: Logical architecture of the enhanced RH Control System

8.4.1.1 RH Device

RH devices refer to the mechatronic systems dedicated to performing RH tasks. The estimated number of these devices ranges today between 30 to 40, with each incorporating a series of sensors and actuators. Cameras, which fall under this category, can either be fixed or mobile. Mobile cameras may be mounted on RH devices to provide dynamic visual support, while fixed cameras will be installed at strategic locations within the Main Building for general monitoring.

Given their deployment in high-radiation zones where RH interventions are required, these devices must use components capable of withstanding the radiation doses specified in the system's operational requirements. Their design should ensure durability and reliability under such conditions to guarantee operational integrity throughout the equipment lifecycle.

8.4.1.2 Cubicle

The cubicle serves as the enclosure for housing the control electronics associated with each RH device. They may be subdivided into distinct sections to protect sensitive electronics from radiation and comply with cabling length limitations as described in Section 4.4.7. Located in designated areas of the Main Building, the cubicles are grouped into rooms located as close as possible to the primary RH intervention zones: the Lithium System, Accelerator System, and Test System.

Within each cubicle, the **sensor drivers** and **actuator drivers** are responsible for managing the bidirectional communication between the RH device's components and the PLC/Controller. The **PLC/Controller** serves as the primary decision-making unit at the low-level control tier, utilizing engineering tools such as programming languages, functional blocks, and flow diagrams to execute tailored strategies. Whenever feasible, it incorporates an integrated OPC UA server to harmonize its functionalities with the RH ontology or established guidelines. In addition to control execution, the PLC/Controller manages communication, monitors environmental conditions such as temperature and door status, and oversees the operation of auxiliary **cubicle monitorization** systems like fans.

A **tool controller** may also be integrated to manage specialized tools or equipment associated with the device's operations. Additionally, the **protection module** includes interfaces with the Local Safety Module, Local Interlock Module, and Emergency Stop systems. This component is vital for ensuring that the device transitions into a safe state whenever one of these three systems activates a corresponding signal, as detailed in Section 4.4.6.

8.4.1.3 Virtual Controller

Its function is to replicate the behaviour of PLC/Controllers by means of a virtual simulator, so in most cases it will be a software tool running on a server or virtual machine. The DONES organisation should make it a requirement for the Site Integration Test (SIT) of a RH device to deliver its correctly configured Virtual Controller.

8.4.1.4 Unified Control Gateway

The Unified Control Gateway provides a communication interface for both OPC UA and ROS in each RH device, bridging the operational protocols and enabling seamless interaction with the RHCS architecture. If the PLC/Controller already offers a native OPC UA server, this module will only need to deploy a ROS node, using a bridge solution such as the one discussed in the previous sections. When the PLC/Controller lacks an integrated OPC UA server, the gateway must include the necessary communication drivers to interface with the device (such as serial communication, fieldbus, or UDP) and map its data and functions within a dedicated OPC UA server.

This module will be implemented on an embedded PC or other specialized hardware platforms. It will reside within the **Cubicles** for physical RH devices to ensure proximity to the control electronics. For virtual controllers, the Unified Control Gateway will be a software component capable of running on the same machine hosting the virtualized environment, maintaining flexibility across different configurations.

8.4.1.5 Camera Cubicle

Each of the three main RH intervention zones will be equipped with a **Camera Cubicle** to handle camera operations for their respective areas, starting with a total of three cubicles. These units are crucial for managing the signals (often analog) transmitted by the deployed cameras to the controllers, ensuring optimal signal quality and system responsiveness. Given that most cameras have signal transmission limits of approximately 100 to 150 meters depending on the model and manufacturer, careful consideration must be given to the placement of these cubicles in dedicated rooms close to the RH zones.

To enable video transmission to the Main Access Building, these analog video feeds will need to be converted to digital streams for IP-based transport. This process will be facilitated by an **IP Video Gateway** integrated into each cubicle, ensuring high-quality and low-latency video delivery for monitoring and supervision purposes. These gateways serve as an essential link between analog camera signals and the RH network infrastructure, supporting real-time visualization and operational reliability.

8.4.1.6 Viewing System

The Viewing System builds upon the description in Section 4.4.3 by introducing two submodules: the **Video-Operator Manager** and the **Stream Server**. The system not only provides real-time video feeds from cameras positioned in critical areas of the Main Building but also incorporates advanced user management. The **Video-Operator Manager** ensures that cameras are reserved for single-user operations, avoiding conflicts and enabling seamless interaction. Additionally, the **Stream Server** centralizes the management and distribution of video streams, allowing for image adjustments (i.e. contrast or illumination) and control over camera movements (pan, tilt, and zoom).

8.4.1.7 RH Safety System

Expanding on the Safety Control System described earlier, this module provides localized personnel and radiological protection actions specific to the RH subsystem. Unlike the centralized SCS, the RH Safety System focuses exclusively on local events that do not require intervention from the broader safety system.

8.4.1.8 RH Interlock System

Building on the centralized MPS framework, the RH Interlock System specializes in protecting RH equipment and assets. This subsystem handles local interlock events originating within the RH framework, ensuring that the control and protection measures respond swiftly to scenarios involving RH components. This localized focus reduces latency and ensures seamless coordination with the Central MPS for plant-wide interlock actions.

8.4.1.9 ROS Tools

This new module leverages the advanced features of the Robot Operating System (ROS) to enhance and support RH operations. It consolidates computational tools essential for task efficiency, safety, and reliability, focusing on three specialized subcomponents that align with the evolving needs of modern RH systems:

The **Motion Planner** is responsible for creating optimized robotic trajectories that adhere to operational constraints like joint limits, velocity parameters, and predefined workspaces. By factoring in the unique geometries of RH equipment and tools, it ensures task precision and efficiency. Sensors integrated into the system enable real-time trajectory corrections, allowing the module to respond dynamically to environmental changes or unforeseen obstacles. This capability supports both pre-intervention planning and mid-operation adaptability. The integration of MoveIt into the UGR-DONES control laboratory was successfully proved in [127], providing the capability to describe paths for the robotic arm from a ROS environment as shown in Figure 123.

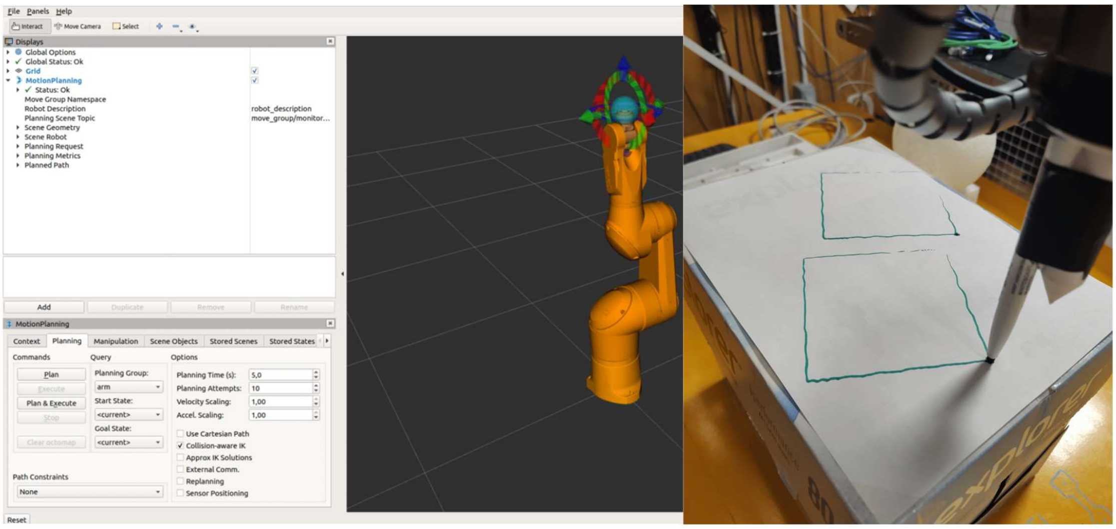


Figure 123: MoveIt configuration assitant for Staübli robot (left) and example of basic trajectory execution using four points on the real robot using ROS (right).

The **Anti-Collision System** significantly enhances safety by preventing collisions within the operational workspace. Using sensor data, environmental models, and video streams from the Viewing System processed via computer vision and AI techniques, this subcomponent calculates secure and obstacle-free paths in real time. Its integration with dynamic avoidance solutions not only ensures equipment protection but also minimizes potential operational delays caused by manual corrections during high-risk tasks.

The **AI Modules** integrate advanced artificial intelligence solutions to drive improvements in predictive maintenance, object recognition, operator assistance, or adaptive task execution among others. These tools empower the system to identify emerging patterns within real-time data, schedule tasks dynamically, estimate object poses with accuracy, and assist operators through advanced guidance systems. The AI components reduce cognitive workload, enabling operators to focus on high-level decision-making and further elevating the operational reliability of RH systems.

Together, these components establish the ROS Tools module as a critical innovation hub within the RH system. This module not only addresses current challenges but also positions the RH system for seamless integration with future advancements in robotics and automation. In combination with the broader architecture, these tools enable a more adaptive, responsive, and resilient environment for managing RH operations.

8.4.1.10 OPC UA Aggregation Server

Centralized module for standardizing and managing data integration across various OPC UA servers. Acting as a pivotal intermediary between the HLCS and the LLCS, this module consolidates data streams, harmonizing process variables from devices such as PLCs, robotic controllers, and other RH subsystems into a unified address space. Its functionality ensures consistent and organized data access, streamlining operations and improving the interoperability of the entire control system.

It must implement a pub-sub communication model, allowing real-time updates to flow seamlessly between interconnected subsystems without overloading the network. The emphasis on high availability and redundancy in its design is critical, as this server functions as the main interface linking HLCS and LLCS.

8.4.1.11 Engineering Tools

Centralize and facilitate the development, maintenance, and troubleshooting tasks within the RH control system. This module provides an integrated suite of functionalities tailored to optimize system performance and streamline the lifecycle of control software and hardware management.

The **Control Code Database (Control Code DB)** serves as a repository for storing and managing programs and configurations for PLCs, robotic controllers, and other RH devices. This ensures traceability and version control, enabling efficient deployment, updates, and rollback capabilities during maintenance and upgrades.

The **Programming Tools** gathers all software used for creating, modifying, and testing control programs and configurations of the Low Level Control System. It bridges various programming standards and formats to simplify the interaction between developers and the system's hardware.

The **Maintenance and Diagnostics** component delivers real-time insights into the health of RH devices and control systems. Unlike the alarms and diagnostics offered by SCADA, this component makes use of proprietary tools offered by the PLC/Controller manufacturers that allow detailed diagnostics or complex calibration, parameterization or fine-tuning operations.

8.4.1.12 Supervision System

This module must be designed to integrate high-level operational planning with robust real-time management, enabling streamlined execution of RH operations. It comprises two main components: the **RH Procedures Database (RH Procedures DB)** and the **Supervision System Engine**, both critical for coordinating, managing, and optimizing RH activities.

The **RH Procedures DB** serves as the central repository for storing procedural knowledge. Structured around a standardized semantic framework as suggested in the ontology model (see Section 8.2), it consolidates hierarchical descriptions of RH operations, linked tool and material requirements, spare parts catalogs, and embedded authorizations for specific operations. By aligning the Procedures DB with the proposed RH Ontology, the system benefits from a common vocabulary that bridges human and machine-readable workflows, ensuring consistency and semantic clarity across RH operations.

The **Supervision System Engine**, building upon the RH ontology's structured representation of knowledge, acts as a dynamic interface between procedural descriptions and real-time operation. This engine integrates feedback data (e.g., from sensors or AI-enhanced diagnostic tools) with operator interactions and machine states, ensuring adaptive task management.

Drawing upon the standardized framework of the RH ontology, this system establishes a cohesive link between human operators, automated modules, and control systems. It does not only reduces complexity in task management but also supports broader applications in fusion energy facilities like DEMO, ensuring that knowledge captured during IFMIF-DONES operations sets the foundation for next-generation RH systems.

8.4.1.13 Condition Engine

The Condition Engine serves as an intermediary for managing the interplay between the operational conditions of RH systems and the high-level control demands of the Central Control System (CICS). Through its **COS Manager**, this module consolidates the states of various RH devices and subsystems within the RHCR to generate an aggregated COS. The COS reflects the real-time operational readiness of the RH system, providing critical insights to the CICS for monitoring and decision-making processes.

Additionally, the Condition Engine processes the received GOS from the CICS and integrates authorization commands issued via the Supervision System in the Central Control Room. These inputs are routed through the **Authorization Manager**, which activates and configures the appropriate RH devices and configures the Emergency Stop circuit to connect the ES Button of the authorized workcell to the corresponding RH Cubicle ensuring secure and coordinated operation.

8.4.1.14 RH SCADA

Provides monitoring, control, and historical analysis of RH systems within the HLCS. By integrating subsystems for data storage, command execution, and visualization, this module ensures real-time control, actionable insights, and seamless operator interaction during RH operations.

The **Historical Database** plays a vital role in storing time-stamped data from RH systems, including operational metrics, commands, and alarm logs. This centralized repository enables trend analysis, fault diagnosis, and optimization of RH processes over time. It also supports the retrospective assessment of maintenance campaigns, providing valuable feedback to enhance both operator performance and system reliability.

The **Command & Control (SCADA Engine)** is the processing hub of this module, enabling the real-time control of RH devices and subsystems. Acting as the primary interface between the operator and the RH field devices, it manages the distribution and execution of operational commands and processes incoming data streams for visualization and decision-making. Its real-time processing capabilities ensure low-latency control essential for complex and synchronized RH operations.

Finally, the **Control Panel Repository** stores the different versions of the graphical interfaces to provide version and change control.

8.4.1.15 Plant Controller

The Plant Controller module serves as a intermediary between the RHCS and the Central Instrumentation and Control System (CODAC). This module ensures seamless communication, synchronization, and interaction between these critical layers, aligning RH processes across the facility.

The **CODAC Gateway** is responsible for managing the interface with the centralized control and monitoring systems of IFMIF-DONES. This component facilitates the exchange of essential data, including the GOS, ensuring that the RHCS operates within the overarching facility framework. By translating and routing commands between the RHCS and CODAC, the gateway ensures compliance with plant-wide coordination and maintains system interoperability.

The **RH Timing Server** provides precise time synchronization across RH systems by receiving the time reference provided from CODAC Timing network and distributing it via NTP to all RHCS devices.

8.4.1.16 VR System

This module integrates advanced virtual reality capabilities into the RH operations of IFMIF-DONES, enhancing operator situational awareness, training scenarios, task validation, and pre-operation assessments. This module includes two key components:

The **VR Scene Repository** serves as a centralized library for virtual representations of the RH system's environment, devices, and workflows. These 3D models and dynamic scenes reflect the physical assets and tasks, ensuring realistic and reliable simulations.

The **VTD Interpreter** processes structured task descriptions outlined in VTDs. These documents, ideally developed according to the RH ontology discussed earlier in this chapter, define the sequence of operations for a specific RH operation. The VTD Interpreter uses this information to generate virtual simulations of the tasks, enabling the detection of potential issues such as sequencing errors, equipment conflicts, or environmental limitations before actual execution. By simulating the operation in a digital environment, it ensures the task is optimally planned, identifying and rectifying faults at an early stage.

8.4.2 Physical architecture

The physical architecture presented here complements the logical design from the previous section by focusing on hardware, topology, and physical connectivity. This proposal involves certain conditions and assumptions since it provides a concrete design based on expected system requirements, such as the final number of devices, system users, and space allocations. While these details are not yet fully defined within the project, the following key assumptions form the basis for an initial, realistic proposal:

1. The system will include 30 RH devices, each equipped with a dedicated cubicle housing the control electronics for its associated tools.
2. These RH devices will be distributed across three zones: the Accelerator, Lithium, and Test Systems. The cubicles will be grouped in dedicated rooms near these zones.
3. The RH Control Room will feature 13 workstations, 3 telemanipulators, and 2 video walls to support operators and enhance situational awareness.
4. The Interlock and Safety networks will share the physical medium with other RH system traffic, provided the maximum required bandwidth, high network availability, and bounded latency are ensured.

The proposed architecture leverages TSN as the foundational technology for the network design. The network will be structured into two primary layers: a core layer and an access/distribution layer.

The core layer will utilize a redundant 10G ring topology composed of TSN-enabled switches connected via fiber links. This layer will incorporate two separate rings. The first ring will be located in the Main Access Building, interconnecting the control room, the servers of the RH HLCS, and the Main Building. The second ring will be situated in the Main Building, linking all cubicles across the three RH zones with the Main Access Building.

The access/distribution layer will consist of 1G TSN switches and copper links. In the Main Access Building, a ring topology will connect the three work cells to ensure efficient data routing. Similarly, in the Main Building, there will be three distinct rings, one for each RH zone. TSN switches within this layer will be responsible for traffic de-tagging so that endpoint devices do not require specialized TSN hardware, simplifying their design and reducing cost.

High availability in this topology will be achieved using Frame Replication and Elimination for Reliability (FRER). FRER is an essential mechanism for enhancing TSN network reliability by transmitting identical frames in parallel along two disjoint paths and eliminating duplicates at the destination node [128]. This approach ensures the system remains robust against single-point failures, providing a reliable and deterministic communication backbone for the RH Control System.

The Emergency Stop signals will have a dedicated network connecting all push buttons in the RH Control Room to the RH device cubicles.

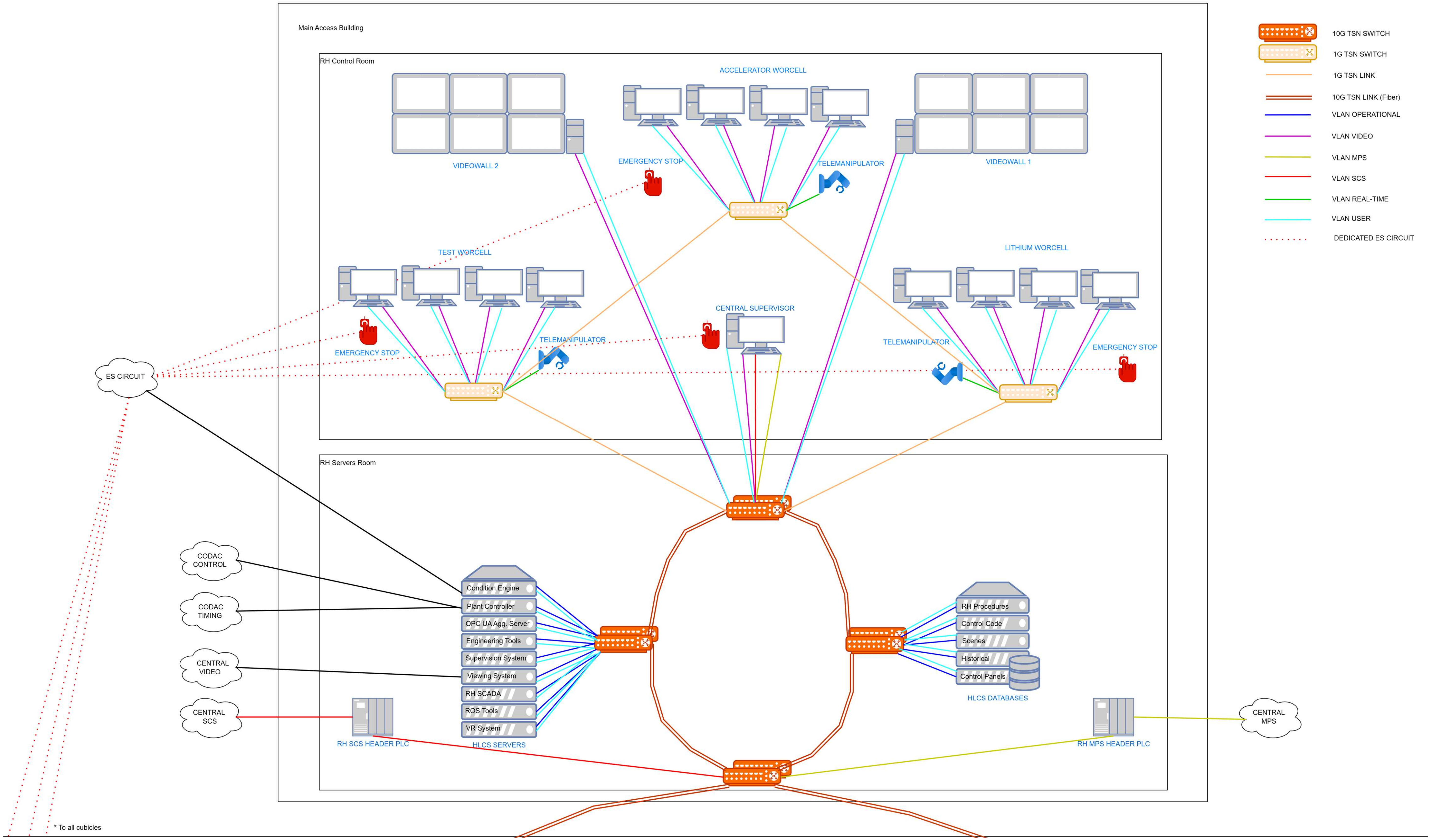


Figure 124: Physical architecture of the enhanced RH Control System (1/2)

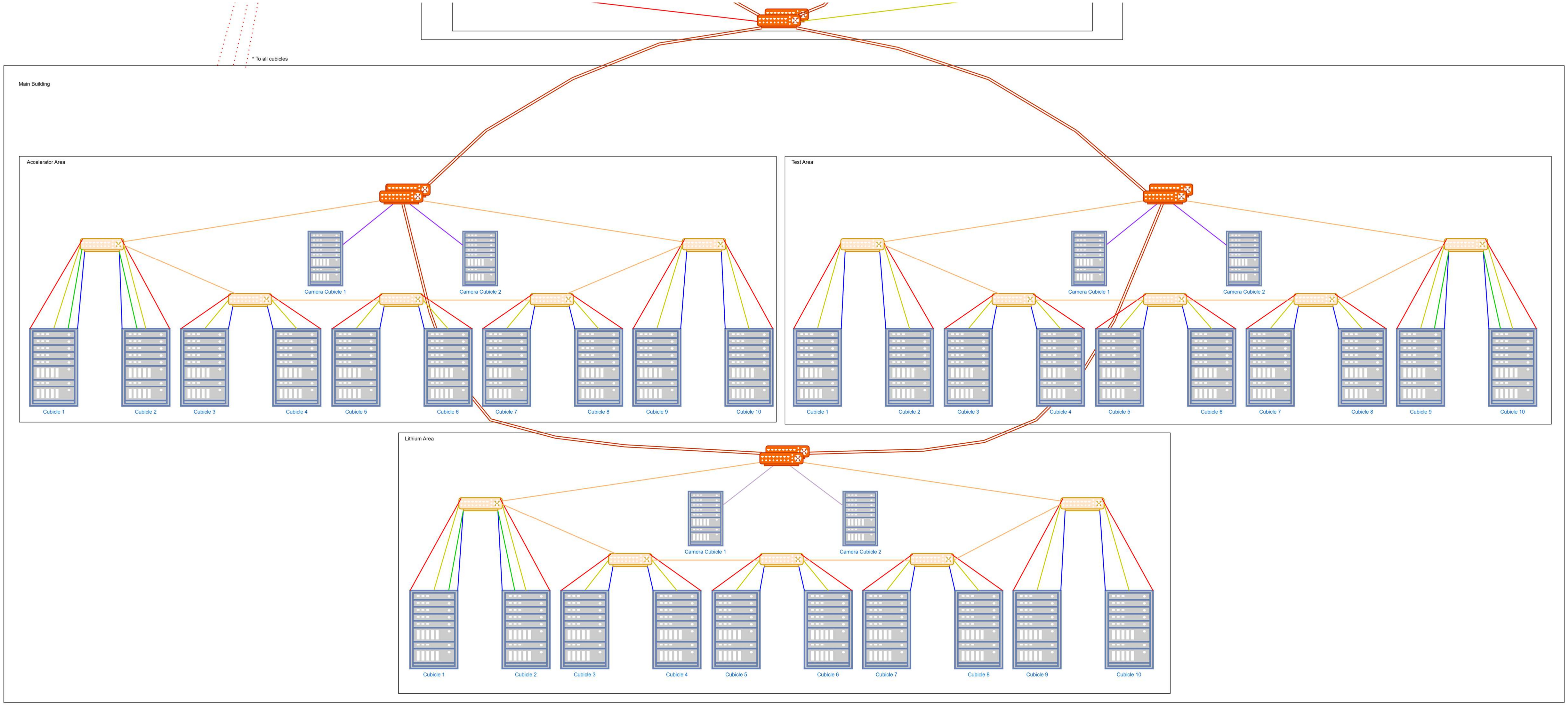


Figure 125: Physical architecture of the enhanced RH Control System (2/2)

8.5 Conclusions of Chapter 8

This chapter builds on the foundational framework of the reference RHCS architecture introduced in Chapter 4, offering a comprehensive and detailed view of an enhanced design that addresses both current operational demands and future scalability. The logical architecture proposed prioritizes modularity, semantic interoperability, and integration of cutting-edge technologies like OPC UA and TSN. Each module has been revisited to incorporate the learnings and conclusions drawn throughout this thesis, with significant advancements in their definitions and functionalities.

Key innovations such as the inclusion of AI-enhanced ROS tools, the structuring of a formal RH ontology, and the integration of Digital Twin capabilities highlight the forward-thinking approach of this enhanced architecture. The ontology ensures semantic clarity and reusable knowledge representation, while ROS-based tools provide the adaptability and computational power needed for complex RH operations. The VR System further underscores the system's operator-centric design, offering unprecedented training and situational awareness capabilities.

The physical architecture complements this logical framework by focusing on reliable, scalable, and high-performance network infrastructure. Leveraging TSN with FRER ensures deterministic communication and high availability, crucial for RH operations in a high-stakes environment like IFMIF-DONES. This emphasis on reliability is further enhanced by the design's redundancy, addressing single points of failure and maintaining operational integrity.

Together, the logical and physical architectures exemplify a holistic approach to addressing the challenges and opportunities within IFMIF-DONES. By bridging theoretical frameworks with practical implementation strategies, this enhanced design not only fulfills the project's immediate requirements but also sets a new benchmark for RH systems in fusion research facilities. Its alignment with broader goals, such as setting a technological roadmap for DEMO and similar projects, underscores its value as a forward-looking and adaptable solution. These contributions strengthen IFMIF-DONES's position as a leader in innovative RH technologies while providing a robust foundation for future advancements.

Chapter 9
Summary and discussion

This chapter summarizes the work presented in the thesis and its **contributions** to the development of the RHCS for IFMIF-DONES. Each chapter addressed key aspects of RHCS design, from foundational requirements to advanced technologies, offering a **comprehensive framework tailored to the challenges of fusion facilities**.

The RHCS design evolved from a reference architecture covering essential functionalities to an enhanced system integrating advanced tools such as AI, TSN, and digital twins. **Experimental validation** in the UGR-DONES laboratory confirmed the **feasibility** and effectiveness of these solutions, while practical insights from collaboration with leading facilities like JET, CERN, and DTP2 strengthened their applicability.

This research demonstrates how industrial standards and modular designs can address the unique demands of RH environments. Despite the challenges of working in conceptual stages and scarce references, the thesis sets a **new paradigm for RH control systems**, aligned with global advancements in fusion research. **Future work** includes refining RH ontologies, developing training facilities, and expanding automation to further enhance RH capabilities.

9 Summary and discussion

This thesis explores the design and validation of a control system for RH equipment in IFMIF-DONES, a pivotal facility within the EUROfusion roadmap. Through seven chapters, the work systematically develops a comprehensive framework tailored to the unique demands of RH in fusion environments.

Chapter 1 introduces the EUROfusion roadmap and IFMIF-DONES, emphasizing the critical role of RH systems in maintaining fusion-related facilities. It outlines the motivations and objectives driving this research, highlights the inherent challenges in RH operations, and presents the framework and structure of the thesis.

Chapter 2 reviews the state of the art in RH, focusing on key aspects such as RH system applications in similar facilities, control system frameworks, industrial networking advancements, and HMIs. This exploration of existing technologies and methodologies provides a foundation for the proposed control system.

Chapter 3 narrows the focus to the specific context of IFMIF-DONES, analyzing project requirements and operational needs. The chapter establishes the functional and integration requirements that guide the design of a customized RH control architecture for the facility.

Chapter 4 details the design and validation of the IFMIF-DONES RHCS. Key distinctions between the RHCS and the CICS are outlined, emphasizing the modularity and flexibility needed for RH operations. A reference architecture, comprising multiple modules, is proposed.

Chapter 5 validates the reference architecture on a real scenario using the UGR-DONES Control Laboratory. Experimental results demonstrated the feasibility of the architecture and revealed areas for improvement.

In Chapter 6, RH processes are analyzed to define workflows, user roles, and interactions within the system. This chapter emphasizes the significance of the Supervision System in process control and coordination between the LICS and CICS. A workflow diagram illustrates the complexity of RH maintenance campaigns and provides actionable insights for improved system coordination.

Chapter 7 addresses data flow and networking, evaluating the applicability of TSN to the RHCS. Experimental results validate TSN's deterministic capabilities, showcasing its potential to simplify network management, enhance efficiency, and ensure reliable performance under challenging conditions.

Finally, Chapter 8 integrates findings from earlier chapters to propose an enhanced RH Control System. Key design principles are defined, highlighting the importance of RH ontologies and operator assistance technologies. The enhanced architecture is detailed from both logical and physical perspectives, offering a scalable, reliable, and future-proof solution for IFMIF-DONES.

This thesis has followed an incremental approach to tackling the design of a complex system of systems. The heterogeneity of RH systems, their operation in unstructured and radiated environments, and the necessity of integrating humans into control loops add a layer of complexity rarely encountered in industrial settings. Nevertheless, the research demonstrates that adapting industrial standards and technologies to such systems improves performance, reduces costs, and outperforms traditional ad hoc solutions typically employed in similar facilities. The result is a new paradigm for RH control systems, aligned with technological trends that pave the way for standardization and enhanced system efficiency.

On a personal level, this project has presented extraordinary challenges. Working on the conceptual design of a unique scientific infrastructure requires embracing a high degree of uncertainty, as many aspects of the broader system remain in preliminary stages or subject to change. This lack of concreteness is particularly pronounced in RH systems, which must accommodate unfinished designs of the systems they maintain and operate on.

Another challenge has been the scarcity of available literature and information about RH control systems, procedures, workflows or the general system functionality in similar facilities. In response, much of the insight for this thesis came from collaborating with experts and engaging with facilities such as the Divertor Test Platform 2 (DTP2) in Finland, RACE and JET in the UK, and CERN in Switzerland. These experiences provided invaluable firsthand knowledge and deepened my understanding of the practical and theoretical aspects of RH systems.

In summary, this journey has been both demanding and rewarding. It has emphasized the importance of adaptability and interdisciplinary collaboration while highlighting the central role that RH systems play in advancing scientific and industrial innovation.

9.1 Claims

This section presents the main claims of this thesis, highlighting how they contribute to addressing the objectives established in Section 1.6. Each claim is linked to specific objectives, providing a clear perspective on the advancements made and their relevance to the overall goals of this research.

O1. Demonstrate the feasibility of using industrial systems for RH operations

C1. Validation of industrial test bench: A test bench using industrial mechatronic devices and control units demonstrated the feasibility of employing commercial off-the-shelf (COTS) solutions. Experimental results from Section 5.5 showed precise task execution in semi-structured environments, leveraging industrial standards for reliable performance.

C2. Adoption of industrial standards and tools: Technologies like TSN (presented in Section 7.3) and OPC UA (Section 4.4.5) were proved to be adaptable to the unique requirements of RH systems, validating the integration of standardized industrial protocols in fusion-related facilities.

O2. Achieve high availability through industrial solutions

C3. High-availability network design: The network design presented in Section 8.4.2 incorporated redundancy mechanisms such as FRER, ensuring continuous operation despite single-point failures.

C4. Resilient communication under load: TSN was validated experimentally in Section 7.5, achieving packet delivery of critical interlock signals even with high network congestion, ensuring uninterrupted RH operations.

O3. Evaluate the application of real-time networks

C5. Real-time networking integration: TSN demonstrated the capability to unify RH system communications integrating the different data flows identified in Section 7.2. The aplication of TAS as discussed in Section 7.5.3, provides predictable and reduced latency, reducing from 27µs to 20µs the maximum value with respect to the use of priorities (IEEE 802.1Q standard).

C6. Optimized network topology design: The physical and logical network layers presented in Sections 8.4.1 and 8.4.2 were designed with TSN as the backbone, achieving robust and scalable communication that meets the demanding requirements of RH operations.

O4. Design the reference architecture for RH systems

C7. Modular RHCS framework: A modular design approach was presented in Section 4.4. Based on that, an enhanced version was further developed in Section 8.4 to enhance scalability, flexibility, and ease of integration with emerging technologies and operational expansions.

C8. Scalable reference architecture: The enhanced logical and physical RHCS architectures from Section 8.4 align with IFMIF-DONES's long-term operational needs, setting a foundational blueprint for future fusion facilities like DEMO.

O5. Integrate emerging technologies

C9. AI-ready architecture for enhanced operations: AI is ready to be integrated in the proposed architecture by using ROS2 interfaces as described in Section 8.4.1.9 to support predictive maintenance, task guidance, and object recognition. This aims to improve operator efficiency and reduce cognitive workload.

C10. Digital Twin for risk-free simulation: Digital Twin capabilities are discused in Section 8.3. This approach can provide immersive training environments and enabled pre-operational task validation, significantly improving proficiency and situational awareness, reducing human error and operational risk.

O6. Evaluate knowledge management approaches for RH

C11. Ontology-driven knowledge framework: The RH ontology proposed initially in Section 6.2, and later extended in Section 8.2 provided a reusable structure for semantic task definitions, facilitating interoperability and effective knowledge transfer across facilities.

C12. Supervision System as a knowledge hub: The RH Supervision System was studied in Section 6.4, providing a detailed description and mockups of the different interfaces according to user roles. Its goal is to capture and structure operational insights, optimizing workflows and providing a repository for procedural knowledge. Section 6.6.1 shows how to model a real RH procedure using YAWL, an open source BPM tool.

O7. Provide a scalable blueprint for future facilities

C13. Adaptable system design for future facilities: The proposed RHCS architecture prioritizes scalability, adaptability, and alignment with global trends, making it a transferable model for similar projects. The similarity of the proposed architecture with other relevant facilities like the ones discussed in Section 2.1, and the application of widely used standards and technologies, makes it a suitable candidate for other future projects.

O8. Experimentally validate RH control systems

C14. Validation of proposed architectures: Each component of the RHCS, including networks (Section 7.4), supervision systems (Section 6.6.1), and general functionality (Section 5.5), was experimentally validated at the UGR-DONES Control Lab, proving its robustness and effectiveness in operational scenarios.

C15. Benchmarking experimental results: The experimental results provided quantifiable metrics and validation through the execution of representativa RH procedures in a real setup, confirming the viability of the proposed solutions.

9.2 Publications

- E. Valenzuela , A. Cano-Delgado , J. Cruz-Miranda , M. Rouret , G. Miccichè , E. Ros , F. Arranz , J. Diaz : "The IFMIF-DONES remote handling control system: Experimental setup for OPC UA integration". Fusion Engineering and Design 192 (2023) 113776. 10.1016/j.fusengdes.2023.113776
- Micciché, Gioacchino; Arranz, Fernando; Mittwollen, Martin; Malloulli, Mariem ; Redondo Gallego, Violeta; Ferre, Mamuel; Garrido, Jesus; Varga, Kornel; Rouret, Martin; Valuenzela, Elio; Barranco, Francisco; Cano Delgado, Abel ; Cammi, Antonio; Benzoni, Gabriele; Tripodo, Claudio; Wang, Yan; Zsakai, Andras; Dezsi, Tamas; Tadić, Tonči; Hoic, Matija; Siuko, Mikko; Rainio, Kari; Mitchell, George; Else, Chris: "Remote maintenance in IFMIF-DONES: current status and future

development program". Article reference: NF-107529 (under review by Nuclear Fusion 24/12/2024). To be published.

- J. Cruz-Miranda, M. Cappelli, E. Valenzuela, M. Damas, J. Diaz: "A Comparative Study of industrial and open-source SCADAs to support the design of control systems for the IFMIF-DONES Plant". To be published.
- V.Vazquez, C. Megias, E. Valenzuela, F. Barranco: "A case study of TSN application to Remote Handling systems". In preparation.

9.3 Future work

Building on the findings of this thesis, several promising avenues for future research and development have been identified to further enhance the RHCS of IFMIF-DONES:

1. **Development of an RH Ontology:** Developing further a comprehensive and modular ontology for RH operations, as proposed in Chapter 6. This ontology would standardize the semantic representation of knowledge across devices, processes, and roles, paving the way for improved interoperability and automation within the RHCS.

2. **Supervision System Definition:** Designing a Supervision System that integrates CMMS or other industrial tools capable of supporting the proposed RH Ontology. This system should leverage industrial standards, such as OPC UA Companion Specifications, to ensure interoperability and streamline RH maintenance processes.

3. **Implementation of a Training Facility/Replica Control Room:** Establishing a dedicated training facility with a fully functional replica of the RH Control Room. This would enable operators to practice complex RH operations in a controlled environment, validate procedures, and provide a backup for RH operations in case of failures or emergencies.

4. **Advanced Automation:** Expanding the application of Artificial Intelligence (AI) and Machine Learning (ML) techniques to enhance RH operations. Specific areas include real-time decision-making, predictive maintenance to prevent failures, operator guidance systems, and improved teleoperation systems leveraging AI for high-quality 3D scanning and object recognition.

5. **Expanded Networking:** Extending the implementation of TSN to larger-scale networks and leveraging advanced configuration tools, such as Centralized Network Configuration (CNC). Monitoring emerging technologies like OPC UA Field Exchange (FX) for field-level communication could also provide insights into achieving more reliable, scalable, and high-performance RH networks.

Each of these areas represents an opportunity to further innovate and enhance the RHCS, ensuring its scalability, reliability, and compatibility with future advancements in industrial automation and fusion research. By pursuing these avenues, IFMIF-DONES can continue to lead the way in Remote Handling technologies and contribute to shaping the roadmap for future fusion-related facilities.

Appendix A: Automation in Remote Handling Systems

In Chapters 4 and 5, the concept of “automatic” and “manual” actions are widely used. The majority of remote handling systems incorporate a human in the control loop (HITL approach), as they are typically deployed in unstructured environments that necessitate the capacity to interpret a highly diverse range of situations. Such systems may exhibit varying degrees of automation, which can either facilitate or reduce the operator's decision-making responsibilities. However, the necessity for human involvement remains. In the absence of a requirement for human intervention, the term "autonomous system" is employed. These systems operate independently, making decisions and executing actions based on preprogrammed algorithms, artificial intelligence, or machine learning, without requiring the supervision or direct intervention of a human operator.

NUREG-0700 [25] is a technical document published by the U.S. Nuclear Regulatory Commission (NRC) entitled "Human-System Interface Design Review Guidelines." This document provides comprehensive guidelines for the design and evaluation of human-system interfaces in nuclear power plants and other critical environments. The objective is to ensure that interfaces are safe, efficient, and effective for human operators, thereby minimizing the likelihood of human error in the control and monitoring of nuclear systems. This document establishes five levels of automation as shown in Table 22. The purpose of it is to provide support for the work of operators rather than to replace it.

Level	Human/Machine interoperability
1 Manual Operation	No computer-based assistance; the operator makes all decisions and performs all actions.
2 Shared Operation	A combination of manual and automatic operations.
3 Operation by Consent	Automatic performance when prescribed. The operator provides close monitoring of the system, approves actions, and may intervene via supervisory commands.
4 Operation by Exception	Computer-operated unless specific scenarios are encountered. Operators must approve critical decisions and may intervene if necessary.
5 Autonomous Operation	Computer-based operations that cannot normally be disabled, but may be initiated manually. Operators monitor system performance and perform backup operations when needed, feasible, and permitted.

Table 22: Automation levels described at NUREG-0700

There are several definitions in the literature in which these levels are adapted to the specific needs of each system. In [129] the proposed automation levels for self-driving vehicles, flight systems or light water reactors (LWRs) are analyzed. The study concludes that increased levels of automation enable higher performance in terms of cost and safety, but requires substantial effort to analyze the legal and licensing implications that need to be considered in this industry.

The study presented in [130] refers to the concept of human-centered Level Of Automation (LOA). Table 23 describes the 5 levels established by the authors:

Level	Description
Action Support (AS)	At this level, the human generates and executes a container-processing plan using a controller (SpaceBall) to move the telerobot and perform specific tasks. Human intervention is necessary to select and control actions, with restrictions on distance and device operation, providing limited joint human/computer control.
Batch Processing	The human generates a plan and selects tasks to be executed through a graphical interface menu. The telerobot automatically implements the selected tasks, allowing full automation of the execution phase of the process.
Decision Support (DS)	Both the human and the computer generate processing plans. The human decides which plan to use, whether their own or the one generated by the computer. The selected plan is automatically implemented by the computer, combining human and automated plan generation with automated implementation.
Supervisory Control (SC)	The computer controls all functions, automatically generating and executing plans. The human can intervene and take control if the computer is not operating safely or efficiently. This level represents primarily automated control with the possibility of human intervention.
Full Automation (FA)	The computer performs all functions, including plan generation, task selection, and execution. Human intervention is not allowed; the human can only observe the system.

Table 23: LOAs for Telerobotic Control in Nuclear Materials Handling

The study illustrates that elevated levels of LOA enhance operational performance under normal operating conditions, thereby increasing throughput and reducing the subjective workload. In contrast, lower LOA levels have been demonstrated to promote higher operator situation awareness and enhance human manual performance during system failure modes. A similar conclusion is reached in [131] and [132], which argue that even when complete automation is a viable option, it can be detrimental to optimal performance across both normal operational conditions and failure modes.

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