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# Digital-Twin based development of Remote Handling facilities for fusion reactors from design to operation

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## Abstract

Remote Handling (RH) systems are vital for maintaining highly activated fusion reactor components. Because of their complexity, customization, and stringent accuracy and reliability requirements, they must be extensively tested, validated, and commissioned in dedicated RH facilities. These facilities also need to qualify man-in-the-loop robotic telemanipulation procedures and provide effective training for human teleoperators. This thesis addresses the full-cycle development of RH facilities by proposing a digital-twin, model-driven workflow spanning concept design to operations. The workflow transfers Industry 4.0 and MBSE approaches, specifically the V-model with RFLP approach, to fusion, using a PLM platform, such as 3DEXPERIENCE by Dassault Systèmes, to unify requirements traceability, 3D CAD design, robotics simulation, maintenance planning, and procedures execution, monitoring and optimization. The method is demonstrated on the Divertor Tokamak Test (DTT) RH Facility, where the V-model is applied iteratively along the hierarchical architecture to guide subsystem design and contractor engineering/manufacturing, while synchronized robotics simulations support verification, integration, and operator training. This digital-twin-based approach improves design iterability and traceability, helping meet tight project schedules and reducing the risk of costly late modifications. To strengthen the digital-twin fidelity, the thesis advances a digital-physical calibration solution developed within the VR Structural Simulator of ITER RH Control System, introducing measurement-driven virtual joints that replicate real structural behavior. This improves trajectory accuracy and operator confidence while meeting computational requirements (13 Hz update rate vs. 2 Hz required). Overall, the work delivers a scalable, transferable workflow for RH facility development, with future extensions toward tighter Digital-Twin and PLM platform interfaces with control system, robust data governance, Machine-Learning-assisted calibration, and deviation compensation.

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# List of Acronyms

**AR** Augmented Reality

**CAD** Computer Aided Design

**CAE** Computer Aided Engineering

**CBDM** Cloud-Based Design and Manufacturing

**CC** Central Cassette

**CCEE** Central Cassette End Effector

**CMM** Cassette Multifunctional Mover

**COTS** Commercial Off-The-Shelf

**CTM** Cassette Toroidal Mover

**DEMO** DEMOnstration Power Plant

**DMU** Digital Mock-Ups

**DoF** Degree of Freedom

**DT** Digital Twin

**DTT** Divertor Tokamak Test

**ECH** Electron Cyclotron Heating

**F4E** Fusion For Energy

**FAT** Factory Acceptance Test

**FOAK** First Of A Kind

**FW** First Wall

**GCS** Global Coordinate System

**HMI** Human-Machine Interface

**HYRMAN** HYper Redundant MANipulator

**ICH** Ion Cyclotron Heating

**IFW** Inner First Wall

**IMU** Inertial Measurement Unit

**ITER** International Thermonuclear Experimental Reactor

**MBSE** Model-Based Systems Engineering

**MRR** Manufacturing Readiness Review

**NBI** Neutral Beam Injector

**OFW** Outer First Wall

**PBS** Product Breakdown Structure

**PFC** Plasma Facing Components

**PLM** Product Lifecycle Management

**POZ** Plant Operating Zone

**R&D** Research and Development

**RFLP** Requirements, Functional, Logical, Physical

**RH** Remote Handling

**RHCS** Remote Handling Control System

**RHS** Remote Handling System

**SAT** Site Acceptance Test

**SC** Second Cassette

**SCEE** Second Cassette End Effector

**SCM** Software Configuration Management

**SS** Structural Simulator

**StC** Standard Cassette

**StCEE** Standard Cassette End Effector

**TFW** Top First Wall

**TRR** Test Readiness Review

**V&V** Verification and Validation

**VR** Virtual Reality

**VV** Vacuum Vessel

**WBS** Work Breakdown Structure

# 1

# Introduction

## 1.1 INTRODUCTION TO FUSION ENERGY

Global energy services are set to expand for decades as populations grow, living standards rise, and end-uses electrify (transport, heat, industry, computation). Long-run scenarios foresee robust electricity growth under diverse socioeconomic pathways, with higher demand and additional upward pressure from warming-induced cooling loads [1].

Equitable development requires universal access to reliable, affordable, modern energy. Closing the access gap with developing countries demands large increases in supply and grid reach, not just household connections, and electrification scenarios to be tailored to spatial density and ability to pay. Energy access strongly correlates with improvements in health, education and income, making it a development as well as an energy-system priority [2].

Despite rapid growth in low-carbon technologies, global CO2 emissions caused by energy production from fossil sources have remained at or near record levels. The Global Carbon Budget 2024 (Earth System Science Data) documents that emissions and atmospheric concentration continued increasing through 2024/2025, underscoring the need for structural decarbonization of energy supply rather than cyclical declines [3].

Existing low-carbon options are indispensable, yet system-scale constraints complicate a straight path to net-zero:

- Once their rate in the power mix becomes large, variable renewables energy (wind/solar) experience declining market value and rising integration costs (balancing, transmission, storage), which must be mitigated by grid expansion, flexibility and firm capacity [4].

- Demand for critical metals increases under net-zero pathways, with concentration risks in mining and refining that call for diversification, substitution and recycling [5].
- Lifecycle Assessment of energy systems show all major low-carbon sources are far cleaner than fossil power, but differ in materials intensity and land use, factors that system planning must manage [6].

These factors, together with the intrinsic volatility of variable renewable energy sources, determine the need for more stable, reliable, large-scale exploitable energy sources, such as nuclear ones. Nuclear power can deliver low-carbon electricity at scale, contributing to system reliability; persistent hurdles include costs, schedules, finance and social acceptance. The scenarios depicted by the International Energy Agency (IEA) retain or expand nuclears contribution in pathways aligned with climate goals [7].

Meanwhile, fusion is advancing from plasma science to integrated technology demonstration, proposing a more efficient and safer solution with respect to fission. Large devices (e.g., ITER) target burning-plasma operation with a net gain factor around Q≈10 for hundreds of seconds, while recent JET Deuterium-Tritium (D-T) campaigns established record fusion energy yields. Developments in Inertial Confinement Fusion (ICF) could also positively impact research on civil application of fusion [8].

Nuclear fusion is the process by which light nuclei combine to form heavier nuclei, releasing energy from the difference in nuclear binding energy. In the deuteriumtritium (DT) reaction, the present focus for power applications, one deuteron and one triton fuse to produce an alpha particle and a neutron with a total energy release of 17.6 MeV (3.5 MeV carried by the alpha, 14.1 MeV by the neutron). This exceptionally high specific energy, together with an effectively inexhaustible deuterium supply and tritium that can be bred from lithium inside the reactor, underpins fusions appeal as a long-term, low-carbon energy source. Sustained fusion power requires simultaneously achieving high fuel temperature ($\approx$ 1020 keV, 100 million °C, for DT operation, much higher than the internal temperature of the sun), sufficient particle density, and adequate energy confinement time, often summarized by the Lawson triple product. In Magnetic-Confinement Fusion (MCF), strong toroidal and poloidal magnetic fields confine the plasma in a torus while external heating (neutral beams, radio-frequency systems) and self-heating by fusion-born alpha particles sustain the temperature.

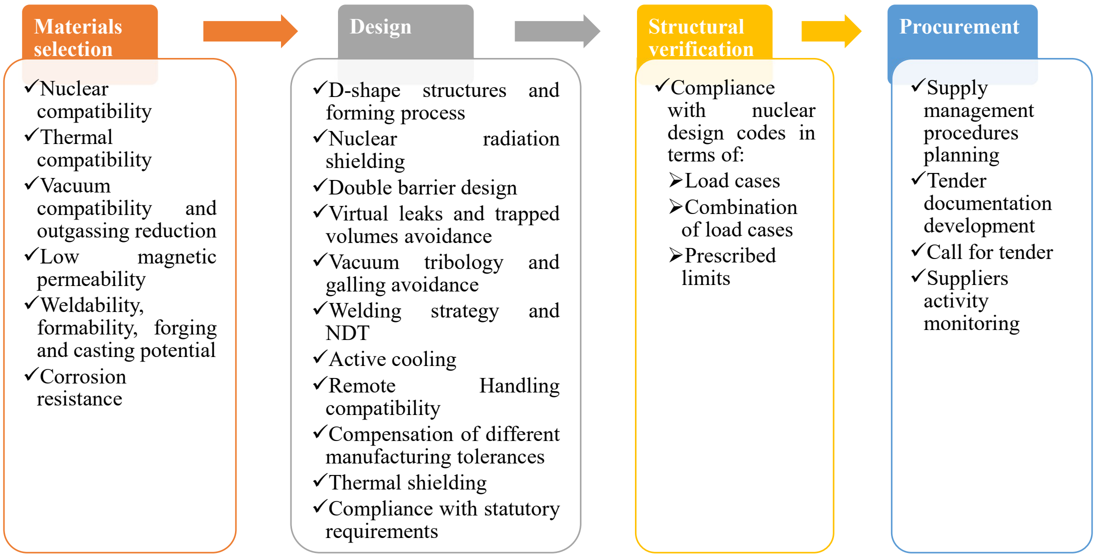


Figure 1.1: Engineering concerns challenging the design process of a tokamak [11]

From a technology standpoint, MCF devices employ: superconducting coils for steady, high-field operation; actively cooled plasma-facing components and divertors to exhaust heat and particles; tritium fuel cycle systems and breeding blankets for fuel self-sufficiency; radiation-resistant structural materials; and fully remote maintenance for activated in-vessel components, all of which are central engineering challenges on the path to power plants. The power-exhaust problem at the divertor and the qualification of low-activation materials under 14 MeV neutron fluxes are particularly critical for DEMO-relevant operation [9, 10]. Among the different configuration options for MCF devices, that are tokamak, stellarator, or reversed field pinch, the tokamak configuration is considered the most promising.

Engineering concerns challenging the design process of a tokamak have already been discussed as part of the initial in-depth studies of the present doctoral research [11]. These are shown in Figure 1.1, with reference to the different stages of the tokamak design flow. Possible solutions to each of these concerns are also shown in [11].

Compared to fission, a single U-235 fission releases $\sim$ 200 MeV versus 17.6 MeV for a fusion D-T event, but the energy density of the base mass of the fusion fuel is still extreme because nearly all the mass participates in the reaction. From the radiation protection side, fission relies on a controlled chain reaction;

loss of reactivity control can lead to prompt criticality and core damage. Fusion plasmas, by contrast, are self-limiting: any off-normal event cools and terminates the discharge. Dominant safety issues in fusion are tritium management and activation of materials by 14 MeV neutrons; designs aim to limit radioactive inventories and ensure that even severe accidents remain within site boundaries [12, 9]. Fission produces high-level, long-lived radiotoxic waste requiring geologic disposal. Fusion produces mostly low-to-intermediate level activation waste with design targets for disposal or recycling within $\approx$ 100 years through use of low-activation alloys [12].

Fusion has been studied as potential energy source for more than half-century. Joint European Torus (JET), one of the oldest and most historical tokamaks, has been the workhorse for DT physics, scenario optimization, and integrated plasma-wall research since its first experiments in 1983. In its final DT campaign (DTE3) in October 2023, JET set a world record of 69 MJ fusion energy in a single pulse of 5.2 seconds, validating models and operational regimes relevant to ITER. JT-60SA (JapanEU satellite tokamak), is the largest superconducting tokamak currently in operation, achieving first plasma in October 2023 [13]. Divertor Tokamak Test (DTT) facility, under construction in Italy, is instead a high-field superconducting tokamak dedicated to the study of the power-exhaust challenge testing several advanced magnetic configurations and divertor shape and materials (including liquid-metal concepts) at DEMO-relevant edge conditions [10, 14]. ITERs mission is to demonstrate burning-plasma physics with gain factor $Q \geq 10$ at $\approx$ 500 MW of fusion power; the machine uses superconducting coils and a large double-null divertor. Following component quality issues and replanning, the updated baseline proposes a consolidated assembly with an initial deuteriumdeuterium operations phase in 2035 prior to full-power operation [15]. As the first device connected to the grid in the European roadmap, DEMO instead aims to deliver net electricity and demonstrate tritium self-sufficiency with power-plant-like availability. Current work addresses the still present technological challenges, like plant architecture, breeding blankets, materials qualification (even in dedicated facilities, such as IFMIF-DONES), safety, and licensing frameworks [16, 9]. In summary, fusion is not a near-term substitute for todays mitigation energy sources, but it is increasingly a credible complement for mid-century decarbonization and energy security if key technology gaps close: steady-state plasma control and high-Q operation in reactors; tritium self-sufficiency via breeding blankets; high-heat-flux materials resistant to neutron damage; efficient, maintainable power-plant systems; and robust, affordable supply chains. ITER provides the integrated physics/technology step, EUROfusions DEMO targets first electricity, and national programs are expanding the option set. Participation to fusion projects from the private sector (industrial companies, start-ups) is also increasing, even if further efforts are needed to close the still present gap. Given the scale of long-term electricity demand and the limitations of any single pathway, advancing fusion alongside renewables, fission, grids, storage, efficiency and CO2 management is a pragmatic hedge that could materially improve the achievability, resilience and equity of net-zero energy systems.

## 1.2 MAINTENANCE IN FUSION REACTORS

Plasma Facing components (PFCs) in tokamaks operate under an extreme multi-physics envelope. Divertor targets are designed for steady heat fluxes of order $\sim 10\ \mathrm{MW\,m^{-2}}$, with short transients up to $\sim 20\ \mathrm{MW\,m^{-2}}$, driving thermal fatigue and dictating periodic refurbishment or replacement of high-heat-flux tungsten monoblocks making up the Plasma Facing Units (PFU) [17]. Disruptions and vertical displacement events induce large electromagnetic loads via eddy and halo currents, challenging blanket/first-wall structures and supports [18]. In parallel, 14 MeV neutron irradiation causes swelling, hardening and embrittlement in structural alloys, degrading fracture and fatigue performance over time [19, 20]. These mechanisms jointly make PFC requiring periodic maintenance for replacement of PFU during the fusion plant lifecycle.

After shutdown, prompt neutron fields vanish but Shutdown Dose Rate (SDR) is dominated by decay $\gamma$ radiation from activated materials in in-vessel components such as first wall, blanket, divertor and port-plug structures. Quantification relies on coupled neutronicsactivation analyses that combine Monte Carlo transport with inventory solvers to generate time-dependent dose maps for maintenance planning [21, 22]. Such analyses allow to understand the activation levels in in-vessel components and environment after plasma operation, providing a solid background to take informed decision regarding the necessity of remote maintenance systems.

International radiological protection benchmarks set the occupational effective-dose limit to 20 mSv/y averaged over five years, with no single year normally exceeding 50 mSv [23, 24]. These limits often exclude hands-on in-vessel work and require the use of remote maintenance technologies, as well as of decay-time management and shielding.

In ITER, radiological protection assessments report absorbed-dose rates inside the vacuum vessel of order $10^2 - 10^3\,Gy/h$ ($\sim 10^2 - 10^3\,Sv/h$ assuming gamma-dominated field) during early post-shutdown periods. Consequently, only radiation-tolerant robotics are viable inside the vessel and sensor/camera lifetimes must be explicitly budgeted [25, 26]. Component-level ITER analyses likewise show in-vessel/contact shutdown dose rates well above hands-on thresholds, reinforcing the need for fully remote maintenance strategies [27].

For DEMO, EUROfusion analyses anticipate substantially harsher SDRs, with $\sim 10^3\,Sv/h$ in front of PFCs eight weeks after shutdown, constraining camera/sensor lifetimes, and implying intervention by radiation-hardened robotics with a fully remote maintenance system [26].

In JET, following DT operation, background in-vessel dose rate at the start of the shutdown were on the order of a few $\sim 4.5\,mSv/h$, as well preventing manned entry and leading to fully remote systems [28].

DTT activation studies also foresee significant activation of PFCs and set requirements for remote maintenance. Inside the vessel high activation is expected after medium and high performance plasma phases ($3.3 \times 10^9 Bq/kg$ and $197\,mSv/h$)[29], therefore in-vessel Remote Handling (RH) is mandatory and an ad-hoc temporary repository for dismounted activated components should be planned. RH for components outside of the DTT cryostat is not needed (access controlled) but accurate planning of maintenance, intervention and dismounting operations during and at the end of the high-performance phase is required [29].

The As Low As Reasonably Achievable (ALARA) optimization principle is embedded in fusion facility design and maintenance planning, as demonstrated by safety strategies usually adopted: shielding and segregation to create hands-on zones, engineered decay time before access, minimization of airborne contamination, and operation sequences that reduce door-open time and streaming. ITER-focused radiological protection studies explicitly frame remote maintenance scenarios as ALARA problems that combine design, scheduling, and procedural controls.

Remote Handling (RH) technologies to execute periodic maintenance of fusion facilities are therefore essential, for three main reasons:

1. Apply the ALARA principle.

2. Maximize the availability of the fusion device for plasma operations (low shutdown time for maintenance).
3. Obtain a higher cost-effectiveness than manual maintenance.

Typical baseline RH systems, such as the ITER's one, include Blanket RH, Divertor RH, Neutral Beam RH, and Cask-and-Plug/Transfer systems for removal, transport and refurbishment in a dedicated radio-protected repository (called Hot Cell) of first-wall panels, blanket shield blocks, divertor cassettes, port plugs and cryopumps [30, 31]. Operations combine heavy transporters/positioners with dexterous, bilateral force-feedback telemanipulators for fine tasks, controlled from a remotely located control room. The JET articulated booms deploying the twin-arm, force-reflecting MASCOT servo-manipulator has accumulated extensive operational hours and remains a reference for complex maintenance under radiation and limited-view constraints [32]. DEMO concepts scale this approach with large casks, vertical maintenance schemes and fully remote Hot-Cell recovery paths [33]. EUROfusion's Roadmap to achieve nuclear fusion highlights the need for RH test facilities (hereinafter referred to as RH facilities only) in which to develop, test, and validate RH technologies, demonstrating their reliability and efficiency for baseline implementation in a future pilot fusion plant such as DEMO [9].

## 1.3 The challenges of Remote Handling (RH) in fusion reactors and the need for RH test facilities

Deployment of RH systems in fusion reactors faces many technological challenges. Optimization of spaces, plasma control efficiency, and material usage limit the in-vessel environment available for access and operation of RH robotic systems. However, these systems are required to handle heavy-weight, huge components in a cantilevered way. Therefore, they are also generally characterized by a massive cantilevered structure that shall be able to navigate in the tortuous operational environment, while guaranteeing a millimeter accuracy in the handling operations and strict reliability, as unforeseen failures and contamination cannot be accepted in the activated in-vessel environment. In addition, these operations shall be executed through complex telemanipulation techniques, in which trained human operators move the equipment through advanced controllers and haptic devices with force-feedback (such as master-slave arms), relying on robust control system and communication infrastructure, and assisted by visual information and telemetry data coming from both on-site sensors and cameras, and virtual software such as 3D CAD, Virtual Reality (VR) and Augmented Reality (AR). Factors such as the constraints of the operational environment and tasks, the high accuracy required, the radiation-hardness requirements to electronics, sensors and cameras, and the weight and dimensions of the components to be handled, determine that RH systems cannot consist of industrial robots. Customized systems are instead designed specifically for the tasks to be executed. The same applies for the control system, based on a demanding man-in-the-loop concept and made of customized software modules.

Due to the high required reliability and dependability (zero tolerance for operation error), as well as complex interactions with environment (component handling, cutting/welding, etc.), the verification process of this hardware and software infrastructure cannot rely solely on virtual prototypes and simulations. Instead, proof-of-concept of customized robots and control system modules shall undergo a detailed phase of physical test campaigns in dedicated RH test facilities. This phase is fundamental to validate, accept and commission the RH hardware and software systems before employment in the stakeholder fusion reactor. Moreover, human operators shall complete an extensive period of training and obtain the required certifications before starting the actual teleoperation procedures. The training shall be carried out by first telemanipulating equipments digital twin only, and then the real systems. RH facilities also provide the proper environment for human teleoperators training, being equipped with a control system within a control room designed for next application to the stakeholder fusion project, too.

In fusion projects, design development methods, concepts and frameworks typical of Model-Based Systems Engineering (MBSE) are still not completely internalized and applied, remaining strongly linked to the industrial sector only. However, fusion projects would widely benefit of the application of this kind of precepts and tools, due to their intrinsic complexity, the large time-span of their development, and the geographically wideness of the design contributors spectrum, factors that may undermine the correct traceability of requirements and design parameters. In particular, RH facilities could represent an ideal framework for application of design workflows centered around digital twin models managed over cloud-based Product Lifecycle Management (PLM) platforms, and driven by MBSEs typical frameworks and design practices. In fact, RH facilities can be assimilated to industrial facilities, being characterized by one or more work areas in which robotic systems carry out autonomous handling operation.

In industrial factories design, adoption of digital twin technologies has spread after the significant growth both of MBSE concepts application, and of Internet of Things (IoT) hardware capabilities. These factors have determined the advent of the so-called Fourth Industrial Revolution, mostly known as Industry 4.0. Industry 4.0 digitizes and automates manufacturing with IoT, cyber-physical systems, cloud/edge, and analytics to maximize efficiency, quality, and flexibility. Industry 5.0 is instead more focused on human factors, promoting concepts such as human-centrality, sustainability, and resiliency: people co-create with AI/cobots, with design focused on wellbeing, inclusivity, and skills. 4.0 optimizes the factory; 5.0 optimizes socio-technical systems and value chains (circularity, resource/energy use, risk & continuity). Practically, 5.0 layers mass personalization, responsible/secure-by-design governance, and adaptability to disruptions onto 4.0s digital backbone.

Focusing on Industry 4.0, it shifts the core of the industrial plant development from the physical equipment to its digital twin. The possibility to model, collect, monitor, manage, analyze and optimize huge amount of operational data, in near-realtime, granted by the development of communication and IoT technologies, enables engineering and management teams to shift the focus on the digital representation of systems and products, instead that on the real physical one. This allows to easily and quickly perform iterative cycle of design, planning, modification and optimization of both systems and procedures in virtual environment, without the need to execute time and cost wasting on-site tests on the physical equipment, often requiring to stop the operations. A group of digital twin models makes up a Digital Work-Cell and, in turn, a group of Digital Work-Cells makes up a Digital Factory, virtual representation of an industrial plant within the Industry 4.0 context that supports its lifecycle from the early design to the final operation and decommissioning phase. PLM platforms provide the software environment to store and manage the huge amount of data embedded in the Digital Factory and its digital twin models. Built around typical MBSE frameworks, such as the V-model in RFLP (Requirements-Functional-Logical-Physical) paradigm, these platforms provide the project design and management teams with a comprehensive set of applications capable of developing the design and managing the entire lifecycle of product and facilities, guaranteeing application of Systems Engineering principles such as iterative design and verification, and requirements traceability. This wide set of applications covering multiple subjects fits with multi-disciplinary projects, like fusion projects. Since they are generally built on a cloud-basis, meaning that are centered around on-cloud portal and database, these platforms facilitate access to and modification of project data for design contributors coming from geographically spread locations, such as in the case of fusion projects. However, differences between automated industrial facilities and RH facilities are not missing. The main ones can be depicted in the following points:

- The presence of a complex man-in-the-loop based control system enabling telemanipulation procedures in RH facilities.
- The high-grade of customization and specialization of RH systems compared to industrial robots.
- The different operation rate between industrial and RH facilities: industrial robotics facilities work full-time, with often considerable operations' speed, to satisfy volume production; instead, robotic test procedures in RH facilities occur with lower frequency because of the time needed between each one to set-up the environment, analyze results, etc., and, moreover, they are generally executed at very low speed due to the high-accuracy required compared to the tight operating spaces.

However these discrepancies do not represent a limitation to application of an industry-like digital-twin based development workflow. Instead, digital twin models could coexist and support the RH control system by providing efficient tools for RH procedures design, organization, management, simulation, and visualization (even with VR/AR applications), also during operation, as well as for storage of project data.

## 1.4 Introduction to the Case Study of the Divertor Tokamak Test (DTT) Remote Handling Facility

### 1.4.1 An overview of the DTT project

The proposed method for digital-twin based design, development and operation of RH facilities for fusion reactors is supported by the application to the Case Study of the Divertor Tokamak Test (DTT) RH Facility, which provides the proper example to show an approach extendable to any other similar facility.

Table 1.1: Main parameters comparison between DTT, ITER, and DEMO

| | **DTT** | **ITER** | **DEMO** |
|---|---|---|---|
| $R$ (m) | 2.19 | 6.2 | 9.1 |
| $a$ (m) | 0.7 | 2 | 2.93 |
| $A$ | 3.1 | 3.1 | 3.1 |
| $I_p$ (MA) | 5.5 | 15 | 19.6 |
| $B$ (T) | 6 | 5.3 | 5.7 |
| Heating $P_{\text{tot}}$ (MW) | 45 | 120 | 460 |
| $P_{\text{sep}}/R$ (MW/m) | 15 | 14 | 17 |
| Pulse length (s) | 95 | 400 | 7600 |

The DTT RH Facility is aimed at testing the RH equipment, procedures, and control system for DTT fusion reactor, as well as training human operators for future telerobotics tasks.

DTT is an experimental tokamak under construction at ENEA Research Center in Frascati, Italy. Its development has been established as part of the EUROfusion roadmap to achieve nuclear fusion [9]. Therein, one of the key missions identified to achieve nuclear fusion is to cope with the problem of power exhaust in fusion reactors, by studying the optimal plasma scenario and divertor configuration, material and technologies, among several possible ones. Within this context, the development of an experimental fusion facility to test several divertor configurations and plasma scenarios has been required. DTT has been commissioned to meet this demand.

To achieve its scopes, DTT is designed as a compact, high-field tokamak capable of achieving plasma conditions comparable to those of ITER and DEMO in steady state plasma operation. By means of substantial external heating power (up to 45 MW), it can also reproduce the divertor heat loads expected in ITER and DEMO ($20\,\mathrm{MW\,m^{-2}}$), even if in a far more compact device, as shown in Table 1.1.

Flexibility is a key requirement for DTT, which is conceived to investigate a wide range of magnetic configurations under extreme conditions (high heat fluxes and strong electromagnetic loads) and with different divertor test configurations, while ensuring high reliability and availability, with 100 operational days per year. Figure 1.2 shows the interaction between the plasma in the three reference scenarios and the DTT divertor, as it is in its first test configuration [14].

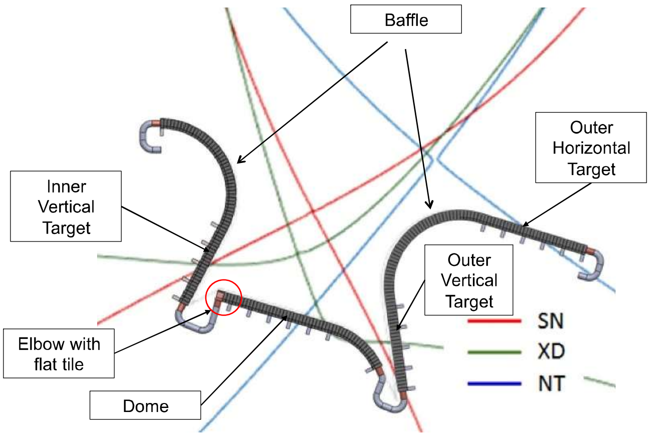


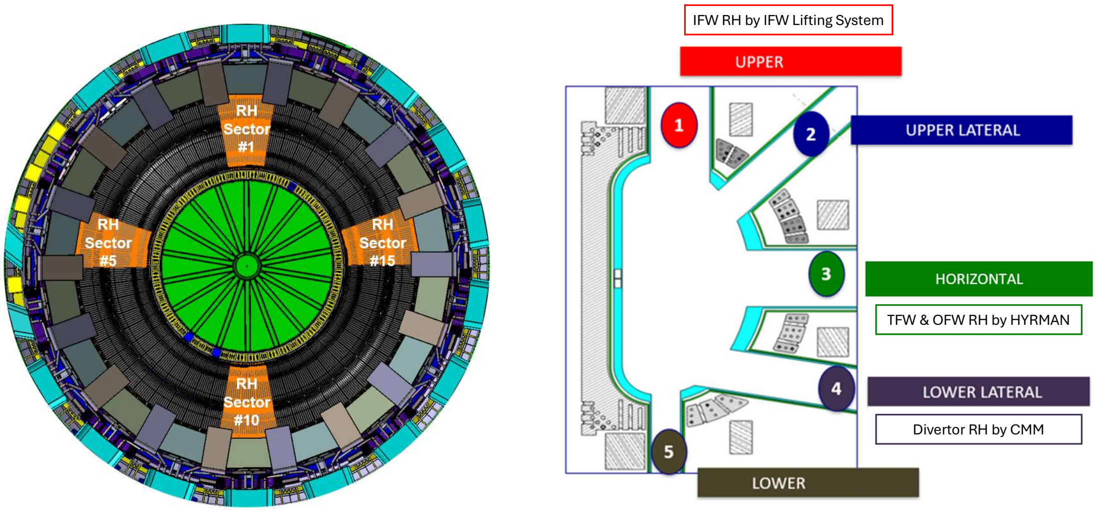
Figure 1.2: Poloidal shape of first DTT divertor and position of strike points in the three reference plasma scenarios [14]

Calculations of the equivalent gain factor for the simulation of the baseline full power Deuterium-Tritium scenario indicate values in the range of $Q_{DT} = 0.3$ [14]. DTT realization has started, with many systems awarded for supply and under construction. The target for first plasma operation is 2029. An association named DTT Scarl has been set up in 2019 to construct and operate the DTT facility, conceived by the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA). Most of the DTT design activity is made through specific tasks assigned to the DTT shareholders and through external engineering services [14].

DTT tokamak includes several subsystems, among which the most important ones are: superconducting magnet system; power supply system; Vacuum Vessel (VV), in-vessel and out-vessel components; plasma facing components; RH system; diagnostic system; heating and current drive systems (ECH, ICH and NBI system).

The DTT VV and in-vessel components feature modular axial symmetry with 18 sectors of 20-degrees toroidal width each. As will be further discussed later, 4 sectors are allocated for RH, placed at intervals of 90 degrees (sectors #1, #5, #10, #15), as shown in Figure 1.3a. Each sector is equipped with 5 ports connecting the in-vessel with the out-vessel environment (Figure 1.3b).

The most relevant in-vessel components are the Plasma Facing Components (PFC), as they must meet the technological requirements to face the high thermal, neutron and electromagnetic loads coming from the plasma. They are grouped in:



(a) (b)

Figure 1.3: Distribution of RH sectors (a) and ports per sector (b) for the DTT machine

- First Wall (FW) modules, covering the internal surfaces of the VV. They are further grouped in:
    - Top First Wall (TFW), covering the upper surfaces of the VV.
    - Inner First Wall (IFW), covering the inner lateral surfaces of the VV
    - Outer First Wall (OFW), covering the outer lateral surfaces of the VV.

  Each sector features 2 TFW modules, 2 IFW modules and 5 OFW modules. In each sector, the IFW modules are divided in one Standard module (in which the cooling pipes are coated with tungsten plasma spray) and one Limiter module prominent to define the plasma edge (in which tungsten monoblocks are welded on the cooling pipes).

- Divertor cassettes, covering the lower part of the VV. Each sector features 3 divertor cassettes, with 54 cassettes in total. The cassettes belonging to each RH sector are divided in one so-called Central Cassette, which is in front of the lower lateral port #4, and two Second Cassettes (SC), which are at the sides of the port, while the cassettes belonging to the other sectors (i.e., the ones placed in-between consecutive RH sectors), are called Standard Cassettes (StC). Each cassette has a stainless steel cassette body that supports three main target subsystems in direct contact with the plasma (Figure 1.2): Inner Vertical Target (IVT), Outer Vertical Target (OUT) and Dome. Each target is made of several Plasma Facing Units (PFU), that are tungsten monoblocks embedding the cooling pipes.

PFC may need periodic maintenance during DTT lifecycle, due to the high fluxes and neutron loads they undergo during DTT plasma operation (neutrons production rate of up to about $1.5 \cdot 10^{17}\,\mathrm{n\,s^{-1}}$ [14]). More in detail, they need to be handled and removed from the in-vessel and delivered to a hot cell for PFU replacement. DTT nuclear design [29] has demonstrated that a RH system is mandatory for DTT in-vessel components maintenance, as well as a Hot Cell, as significant activation of PFC materials is expected after medium and high-performance plasma operation phases, with estimated activity and contact dose rate level in PFC tungsten one day after the end of DTT operations of $3.3 \times 10^9$ Bq/kg and 197 mSv/h. The same results indicate that there is no need for RH outside of the cryostat, even if during and at the end of the high performance phase the access to the torus hall should be controlled and maintenance operations accurately planned, to ensure that the annual dose limit for exposed workers of 20 mSv is not exceeded, to comply with the Italian regulation [34].

### 1.4.2 DTT Remote Handling System (RHS)

The current, final, design of the DTT Remote Handling System (RHS) architecture and strategy is the result of a detailed process of concept generation and selection [35, 36].

DTT RHS can be divided into two key groups of robotic systems that enter the Vacuum Vessel (VV) through the ports #1 (upper), #3 (equatorial) and #4 (lower lateral) of the sectors allocated to RH (#1, #5, #10 and #15):

- RH in-vessel systems, made of:
  - HYper Redundant MANipulator (HYRMAN), in charge of entering the tokamak through the equatorial port #3 of RH sectors and handling the FW modules. TFW and OFW modules are handled by HYRMAN from the in-vessel environment to the out-vessel environment through the equatorial port #3, where they are then placed in a cask for next transportation to the Hot Cell. IFW are instead handled by HYRMAN within the in-vessel environment only, as they are then delivered to another RH system, the IFW Lifting System, in charge of their transportation from the in-vessel environment to the out-vessel environment through the upper port #1. Beyond nominal maintenance operations, HYRMAN may also be used for assistance to the other RH equipment, inspection of the VV environment, rescue purposes, tasks related to diagnostics and heatings [37].
  - Divertor handling system, in turn made of:
    - Cassette Multifunctional Mover (CMM), in charge of entering the tokamak through the lower lateral port #4 and handling the divertor cassettes belonging to RH sectors (central Cassettes - CC - and Second Cassettes - SC).

    - Cassette Toroidal Mover (CTM), a robotic carrier which has to be placed on the in-vessel toroidal rails by the CMM and move toroidally to reach and handle the divertor cassettes in-between consecutive RH sectors (Standard Cassettes - StC). In the StC removal procedure, for instance, these are then released onto the in-vessel toroidal rails by the CTM and removed by the CMM as the other cassettes (CC and SC). The installation procedure is exactly the opposite [38]. Use of CTM is not foreseen during DTT initial operational phases, as all lower lateral ports #4 will be employable for CMM access to in-vessel environment. Then, when lower lateral ports #4 of non-RH sectors will be equipped with in-vessel diagnostic and additional services, they will not be employable for CMM access to in-vessel environment anymore and CTM operation will be required.

- RH out-vessel system, made of:
  - Inner First Wall (IFW) Lifting System, a robotic platform whose primary goal is to enable the IFW modules transportation from the inside to the outside of the VV, and vice-versa, through the upper ports #1. The IFW modules removal procedure, for instance, foresees that Hyrman unlocks and handles the IFW module from its operative location to the lower area of upper port #1, where it then delivers the module to the IFW Lifting System for its lifting along the port and removal from the in-vessel to the out-vessel environment. The installation process is the equal opposite.
  - Additional RH systems for service operations, like Cutting & Welding tools and robotic arm for cooling pipes manipulation. In fact, PFC cooling pipes shall be cut before start of maintenance operations to allow the removal of FW modules and divertor cassettes. Then, they have to be welded again after completion of maintenance operations. Removal of PFC cooling pipes may also be required, to free the space internal to the port and allow easy handling of components, like in the case of the divertor Central Cassette cooling pipes [39].
  - Casks system, which are rad-hard and dust confinement containers for transporting the handled components from the vessel area to the Hot Cell.
  - Hot Cell systems, including all the robotic systems for manipulating the handled components inside the Hot Cell.
  - RH Control System, including all software and hardware equipment and frameworks ensuring proper control, monitoring and management of RH procedures.

The preconceptual design of the DTT RH in-vessel systems and procedures is more widely described in [37] and [38]. The architecture of the DTT RH in-vessel system is represented in Figure 1.4.

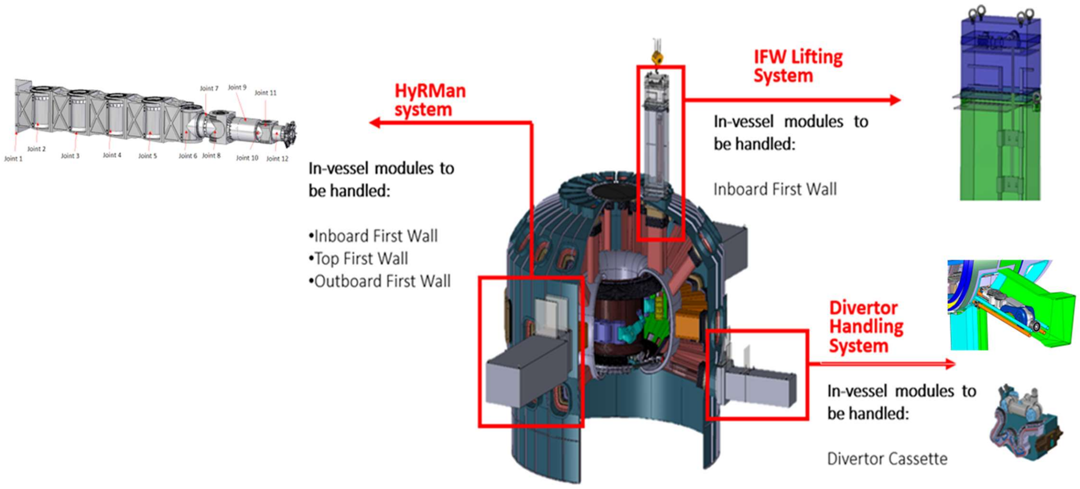


Figure 1.4: Architecture of the DTT RH in-vessel system

### 1.4.3 The DTT Remote Handling Facility

As part of the RHS design process, the DTT project team has commissioned the realization of an RH facility, aimed at verifying and validating the RH robotic systems, control systems, and procedures, as well as training operators for tele-manipulation tasks, prior to their application in the DTT experiment. Given the complexity of the systems and procedures, such as the tele-manipulation of huge robots handling heavy cantilevered loads in very tight environment with limited visibility, verification and training solely based on the use of virtual tools has not been considered sufficient. Therefore, the need arose for a physical facility capable of integrating and testing not only the RH control system to be adopted in DTT (software, communication channels, controllers, haptic devices, VR/AR devices), but also the actual robots of the DTT RHS, by providing a mock-up of the operational environment, namely the in-vessel environment, too. The proper realization and operation of the DTT RH Facility represents a key milestone for the correct future execution of the RH procedures in the real DTT reactor, as well as for their optimization, with the ultimate goal of minimizing device shutdown time for maintenance and hence maximizing its availability for plasma operation and experimental campaigns.

The DTT RH Facility will be constructed within the campus of University of Naples Federico II (Figure 1.5), after agreement with ENEA and DTT Scarl. The completion of the facility is foreseen for 2026.

As already described in [40], the DTT RH Facility aims at achieving the

Figure 1.5: DTT RH Facility site at University of Naples Federico II

following global missions:

- **Completing acceptance tests and commissioning of baseline RH equipment, tooling, control hardware and software**. The final version of the RH robots that will operate in the DTT device will be first delivered to the DTT RH Facility for acceptance tests and commissioning. The DTT RH Facility has hence the primary aim of verifying that the systems meet all technical requirements, are able to perform all prescribed functions, and have been designed in compliance with best practices and design standards. The customized, first-of-a-kind solutions developed shall be comprehensively Verified & Validated prior to application in real DTT device environment, where risks of unrecoverable failures are not acceptable.

- **Testing, validating and optimizing the control framework.** The RH control system employed in DTT will be the exact replica of the one used for the DTT RH Facility, except for the interface with the central CODAC system. Therefore, the DTT RH Facility shall provide the environment to test, validate and optimize the developed control system and framework before application to real DTT case.

- **Testing, validating and optimizing normal and off-normal RH procedures.** RH procedures shall be tested, validated and optimized prior to their execution in real DTT reactor, including both normal and off-normal (rescue and recovery operations) procedures. Test campaigns executed in the DTT RH Facility will ensure the proper completion, optimization and update of the Maintenance Management Plan, allowing for estimation of maintenance procedure times and, therefore, reactor downtime.

- **Training the operators about RH procedures and equipment.** The human operator should receive a full training (theoretical and practical) before gaining the required certification about the RH procedures. The facility shall offer to the novel operators the possibility to get certified, by assisting to the procedures and subsequently conducting themselves in first person. The operator shall be able to navigate within the virtual simulation of the tokamak machine, familiarize with the environment and interact with it, without any risk for his own safety or for damage to the real mock-ups, before moving to the tele-operation of the real physical equipment.

- **Support the development and testing of new RH procedures, equipment, tooling and control devices.** The DTT RH Facility shall provide support for developing, designing and testing new RH procedures, equipment, tooling and control devices that may be developed during the machine lifecycle, possibly without requiring modification to the facilitys structure and its mock-ups.
- **Support the investigation, development and testing of further technologies, systems and processes for the DTT device, beyond RH.** Since the DTT RH Facility will feature a fully equipped mock-up of a toroidal portion of the DTT VV and in-vessel environment, it shall also act as a support laboratory to investigate, develop and test processes, systems, and technologies relevant to the DTT device, even not related to RH.

All the DTT RH in-vessel system will be delivered and tested at the DTT RH Facility, except for the CTM system, due to immaturity of design and lower priority considering the already mentioned possibility of in-vessel access through all the lower lateral ports during DTT initial operational phases. Therefore the FW and divertor CC and SC handling procedures will be validated at the baseline of the facility lifecycle. Anyway, the facility shall be either reconfigurable or upgradable to allow for their testing in future operation phases during the lifecycle.

The DTT RH Facility have the wider mission of representing a reference in the current global landscape of similar facility for fusion and, more in general, for robotics and telerobotics. This mission is intended to be achieved thanks to three main innovations, as already discussed in Section 2.4:

- The Facility will be one of the first to test almost all the RH equipment and procedures of the stakeholder reactor in the same environment, providing an in-scale mock-up of a toroidal portion of the entire DTT tokamak.
- Real DTT robots, not mock-ups, will be tested in the facility before being sent to DTT site for actual RH operations.
- The Facility will be centered around the role of the human operators, focusing on their proper training by providing them all the necessary information to take aware decisions. To achieve this goal, the control system shall have a fundamental role in the facility's architecture, and all the data and visual information to be sent to and consulted by the operators shall be properly collected and managed. That is the reason why the facility appears suitable to be employed as a case study for the application of the digital-twin based development process presented in this thesis work. A centralized digital twin model, uploaded and manageable on-cloud over a PLM platform, represents the most effective way to store and transfer a substantial amount of data and visual models (3D CAD, AR/VR) to the operators in the control room, providing them with as

much information as possible and relying on the interface with the control system to ensure adequate real-time connection between digital twin and physical counterpart. The control room will therefore represent the core of the facility, where both physical equipment and digital twin models can be accessed and controlled through the use of advanced devices, such as VR/AR devices, haptic devices with force feedback, large monitors and controllers. In this way, human operators in the control room will have at their disposal a complete and cutting-edge framework of control hardware and software equipment for the proper and aware execution of teleoperation procedures. The facility control system framework and control room set-up shall be developed and tested at an advanced stage valid to be then equally replicated in the DTT facility.

The development of the DTT RH Facility has started in 2023 and its realization is expected to be completed within 2026. The engineering design of the facility's subsystems is currently under finalization, and the manufacturing is starting.

## 1.5 RESEARCH OBJECTIVES AND WORKFLOW

As discussed so far, development of RH facilities is fundamental to achieve completely validated RH systems, technologies, and procedures for fusion projects, thereby enabling efficient and cost-effectiveness maintenance that minimizes time-cycles and risk of failures, and therefore maximizes the fusion device's availability for plasma operations. However, a comprehensive pattern to enable reliable and efficient management of RH facilities and systems throughout their lifecycle is not currently established.

The present doctoral research has the main objective of defining a workflow for the development and lifecycle management of RH facilities supporting fusion projects, based on concepts, frameworks, and tools well established in the industrial sector and typical of Industry 4.0, however not yet fully implemented in research projects such as fusion reactors. The suggested workflow is validated on the case study of the DTT RH Facility, through application, test, and optimization from design and procurement follow-up experience. The proposed workflow is intended to be possibly extended to any kind of similar facility supporting the fusion mission, not only RH ones.

The research objectives of the present doctoral thesis can be expanded in the following points:

- Contribute to the development and comprehension of RH systems, technologies, and procedures.

- Contribute to and foster the development of RH facilities for fusion.
- Shape a robust, efficient, reliable, and replicable workflow for the development and lifecycle management of RH facilities, based on the digital twin concept and employing, among the frameworks and tools widely adopted in highly-automated industrial plants within Industry 4.0 context, the ones suitable to the needs of the RH facilities.
- Validate the proposed workflow by application to the Case Study of the DTT RH Facility, that aims at becoming one of the most advanced and comprehensive RH facilities in the current global scenario.
- Study, deepen and propose a solution to the problem of calibration between digital-twin models and real world scenario.

The proposed workflow is based on a digital twin concept, that embed project data and drive development choices from the early design stages of requirement engineering to the final real-time management of operations. The digital twin is supported by a PLM platform, able to store the huge amount of related data and offer a wide set of tools to cover the entire development and lifecycle management process, implementing and allowing for application of typical MBSE's frameworks. Among them, in particular, the V-model embedding the RFLP (Requirements-Functions-Logical architecture-Physical architecture) paradigm is identified as the most valuable instrument to drive the design of RH facilities and ensure design and verification iterability, and requirements traceability. The proposed workflow is validated through application to the case study of the DTT RH Facility. The digital twin based workflow is applied to the DTT RH Facility throughout its development, since the first stages of design, with the aim of providing a massive support in the future phases of operation and lifetime management as well. The DTT RH Facility's digital twin is built, developed and managed over the PLM platform 3DEXPERIENCE by Dassault Systèmes, whose both on-cloud and on-client applications allow to apply the MBSE's V-model embedding the RFLP paradigm for the design development. The V-model is iterated multiple times to carry out first the Facility's Architectural Design, allowing to identify its high-level requirements, functions, and logical architecture representing a first Product Breakdown Structure (PBS), then the subsystems' Concept Design, also making up a virtual Physical Architecture acting as Concept Design for the entire Facility, and finally the Engineering Design, developed by manufacturing companies after tenders award and enabling next manufacturing. After a lessons-learned analysis over similar RH facilities already operational, the potentialities of the digital twin as tool for the operational lifetime management of RH facilities are also introduced, as well as its limits. Among them, the digital-physical calibration problem is deepened, with a solution proposed for the calibration of the digital twin's kinematic and VR models for the robotic systems. The solution is developed through application to the test-case of the ITER Remote Handling Control System's kinematic and VR models, and is intended to be replicated in future to the Case Study of the DTT RH Facility.

The present doctoral thesis research is structured as follows. Section 2 provides a review of the role and objectives of RH facilities for fusion projects, of the current scenario of RH facilities already developed worldwide and of their achieved results, as well as of the State Of The Art regarding the application of digital-twin based development methods for products and facilities, from the industrial sector to the nuclear and fusion ones. Section 3 describes the proposed workflow for the digital-twin based development of RH facilities, able to drive its entire lifecycle from design to operation. Section 4 goes into the detailed description of the proposed workflow, with application to the Case Study of the DTT RH Facility from design to manufacturing phases. Section 5 provides a review of the experience gained from the operational lifetime of similar RH facilities, first of all those supporting ITER RH system development, and shows the benefit and limits of using a digital-twin based approach in the lifecycle management of RH facilities. In this section, the proposed solution for the digital-physical calibration problem is also introduced and described, with application to the kinematic and VR models of the ITER Remote Handling Control System (RHCS). It consists in developing a Structural Simulator tool to support the ITER RHCS' VR module, based on the concept of Virtual Joints. Then, a summary outcome of the application of the proposed digital-twin based development method to the DTT RH Facility Case Study, and the results of the virtual-joints based solution for the digital-physical calibration of the ITER RHCS' models are discussed in Section 6. Possible further developments both to the overall digital-twin based workflow and to the specific calibration problem, deriving from their still remaining limits, are also analyzed. Finally, conclusions are provided (Section 7) to outline the activities performed, the results achieved and the possible future works.

# 2

# State Of The Art: the role of RH facilities for fusion reactors and the concept of Digital Twin

*This section surveys the role and objectives of Remote Handling (RH) facilities in fusion projects, maps the global landscape of existing RH facilities and their demonstrated outcomes, and summarises the state of the art in digital-twin based development methods for products and facilities across industrial, nuclear and fusion domains.*

The design and deployment of Remote Handling Systems (RHS) are highly complex engineering challenges. They involves not only the deployment of robotic manipulators and tools compatible with the nuclear fusion environment but also the integration of control architectures, operator interfaces, safety strategies, rescue and recovery procedures. As the RH systems must handle large and heavy components in narrow and low-light spaces, the verification of systems compliance with design requirements becomes a major challenge. Moreover, due to the uniqueness of the environment and procedures, RH systems are generally customized first-of-a-kind robots whose behavior is not easy to predict and model. Although digital simulations and virtual prototyping are indispensable for reducing design costs and time, they cannot substitute physical validation for such complex systems. Therefore, physical RH facilities are essential to achieve complete validation of RH equipment and procedures, as well as to train human operators.

The role of RH facilities is to provide a controlled environment where these complex systems can be developed, validated, and optimized before being deployed in the actual reactor. Virtual simulations, though powerful, cannot by themselves account for critical aspects such as the compliance of manipulators under heavy loads, the tolerances of docking mechanisms, or the cumulative errors in multi-step procedures. For this reason, RH facilities act as testbeds where full-scale mock-ups and prototypes are employed to reproduce the environment of the fusion reactor as faithfully as possible.

The realization of RH facilities to support the development of remote maintenance technologies is also required by the EUROfusion roadmap toward DEMO and toward the achievement of nuclear fusion, under Mission 6 "Integrated DEMO design and system development" [9]. There, it is pointed-out how a well-developed RHS is necessary for DEMO to maximize the overall plant availability, minimizing the downtime for maintenance.

The present section describes the State Of The Art regarding RH facilities for fusion projects, by analyzing their role and objectives, and presenting an overview of the RH facilities already developed worldwide. These subjects have already been addressed as part of this doctoral research in [41] and are revisited in the present thesis work. Finally, the scientific topic of digital-twin based design and development of product and facilities is reviewed, by also analyzing its state of application in the fusion sector.

## 2.1 Objectives of Remote Handling Facilities for fusion reactors

Remote Handling (RH) facilities are fundamental to support the development cycle of RH systems, enabling safe, reliable and efficient reactor maintenance, therefore minimizing machine downtime.

The strategic objectives of RH facilities can be summarized in the following five global missions:

1. **Verification and Validation (V&V) of customized concepts and procedures.** RH operations are highly constrained by the tight environment of the vacuum vessel, the size and weight of components, and the flexibility limits of manipulators. First-of-a-kind robotic devices specifically designed to operate in these challenging conditions can be tested, verified and validated in RH facilities. Integration tests with other systems and surrounding environment can be conducted, as well as deep and realistic failure analyses. Moreover, facilities allow researchers to validate

trajectory plans, test the feasibility of complex operations, and ensure that procedures can be carried out with the required accuracy and within operational safety margins.

2. **Acceptance and commissioning of equipment.** Before deployment on an experimental device or reactor, manipulators, movers, and tools must be tested in realistic conditions. RH facilities provide representative mock-ups of reactor components, enabling acceptance tests and early identification of weaknesses. Alongside RH hardware and procedures, a reliable RH control and supervisory system shall be developed. The RH control system software is also generally fully custom-developed and implemented to control the specific hardware, therefore requiring a number of debugging tests that can be executed in test facilities [42]. As part of this process, calibration of the models embedded in the control system software and in the digital twin can also be performed in RH facilities, by setting the optimal operating parameters for as-built RH devices considering the effect of flexibility and manufacturing tolerances.

3. **Operator training and human-machine interaction validation and optimization.** Due to the complexity of the tasks, RH control systems are generally based on a man-in-the-loop concept where RH tasks are only partially automated, while, for specific high-precision movements, human operators must take direct control of equipment in tele-operation mode. Human operators shall undergo an intense phase of training before manipulating the real equipment in the real environment, where errors cannot be tolerated. Facilities provide a safe training environment where operators can gain experience and optimize workflows, both "off-line" with connection to the digital models only and not to the real ones, and "on-line" with connection to the real equipment. As part of this process, the Human Machine Interfaces (HMI) and the whole control system can be tested and optimized in the facility. The HMI layout, the tools provided to the operators (screens, joysticks, haptic devices with force-feedback, VR/AR systems, and more), the organization of operators, tasks and authorities, the degree of automation of procedures, the data acquisition and exchange systems, are among the components which can be tested and optimized prior to application to the real procedures [43, 44].

4. **Maintenance Management Plan (MMP) and recovery strategies validation.** RH facilities allow testing and validation of both planned procedures and possible unexpected tasks. Planned procedures are generally organized in a Maintenance Management Plan (MMP), a fundamental instrument to set the procedures time schedule and verify its compliance, in order to correctly estimate the timescales for RH campaigns and machine downtime. RH facilities allow to test, update and optimize the MMP to achieve the best procedures organization for the real machine. As for unplanned events and failures, they are unavoidable in a real reactor. RH facilities enable the development and validation of recovery procedures, such as the removal of stuck components, emergency sealing, or the retrieval of failed tools, before they are needed in a nuclear environment.

5. **Technology qualification and scientific development.** Facilities are also used to test novel tools, radiation-hardened components, and new materials, supporting the long-term innovation pipeline required for DEMO and future power plants. Similar facilities allow for development and optimization of automatic and teleoperated robotic procedures whose results can have a wider impact on further application fields in the scientific area of robotics, robotic teleoperation and human-robot interaction, such as:

    - Robotic telesurgery.
    - Remote diagnosis and tele-rehabilitation.
    - Space telerobotics and planetary exploration robotics.
    - Remote industrial robotics and teleoperated manufacturing.
    - Military telerobotics and explosive ordnance disposal (EOD) robots.
    - Remote reconnaissance robotics in hostile scenarios.
    - Underwater telerobotics and remotely operated vehicles (ROVs).
    - Extreme environment telerobotics (e.g., volcanoes, mines, radiation zones).

    Currently, one of the most important scientific obstacles to be overcome regards the correct calibration between digital and physical mock-ups. Further development are needed regarding the virtual representation of deflections of cantilevered systems both during trajectory planning and during handling operations, to overcome the current limitations mainly caused by the too high computational weight required to solve real-time multi-body dynamic simulations of flexible structures. The same concern regards the matching between the virtual assembly forces and the actual ones during testing of mounting/dismounting operations, important to provide teleoperators with exact force-feedback through the haptic-devices [45, 42]. These and further scientific topics can be investigated and deepened in RH facilities, where digital models embedded in the control system software can be linked with and optimized in function of the real twins.

In essence, RH facilities serve as a bridge between design and operation. They are laboratories for innovation, training centers for operators, and safeguards for the reliability of fusion reactors.

## 2.2 THE CURRENT GLOBAL SCENARIO OF RH FACILITIES FOR FUSION

Since the early 1990s, a number of RH facilities have been established worldwide, each serving specific fusion programs. As this research aims at defining a framework for the development of RH facilities for fusion, it is crucial to provide an exhaustive background regarding facilities globally developed which have been operative for years or are still operating. Together, they form a lineage of infrastructures that have progressively advanced RH technology. Significant lessons can be learned from the experience of these facilities, both for the design of similar ones and for their operation.

The first generation of facilities was constructed in support of JET and the early ITER design activities, as shown in next paragraphs.

### 2.2.1 Remote Handling facilities at JET

The Joint European Torus (JET), for many years the largest, most advanced, and most powerful nuclear fusion experiment worldwide, underwent decommissioning in 2023 after decades of operation. Throughout its lifetime, JET extensively employed Remote Handling (RH) both for routine maintenance and for major upgrades [46]. Over thirty years and thousands of hours of RH operations enabled the development of dedicated tools and the accumulation of significant expertise, which have proven essential for understanding the challenges of RH in future devices. This experience also allowed the establishment and testing of training procedures and work organization methods for operators. Indeed, JET has the credit of introducing the man-in-the-loop concept for fusion RH control systems, that breaks autonomous robotic processes to add in-between telemanipulation operations, thereby enabling intentional, informed, and experienced corrections from human operators. Telemanipulation procedures testing and human operators training are among the most relevant activities of JET intensive work on RH technologies, based on testing delicate tasks using bilateral, force-feedback manipulators operated from a remote control room. At JET, articulated booms equipped with the twin-arm, force-feedback MASCOT servomanipulator have accrued extensive operating hours and still represent a benchmark for complex maintenance under radiation and limited-visibility constraints [32].

A summary of the main lessons learned is presented in [47], which emphasizes the importance of dedicated test and training facilities to ensure the success of RH operations.

Comprehensive operator training and procedure validation were initially carried out at the full-scale In-Vessel Training Facility (IVTF, Figure 2.1), located near the JET machine. The IVTF houses mock-ups of in-vessel components that

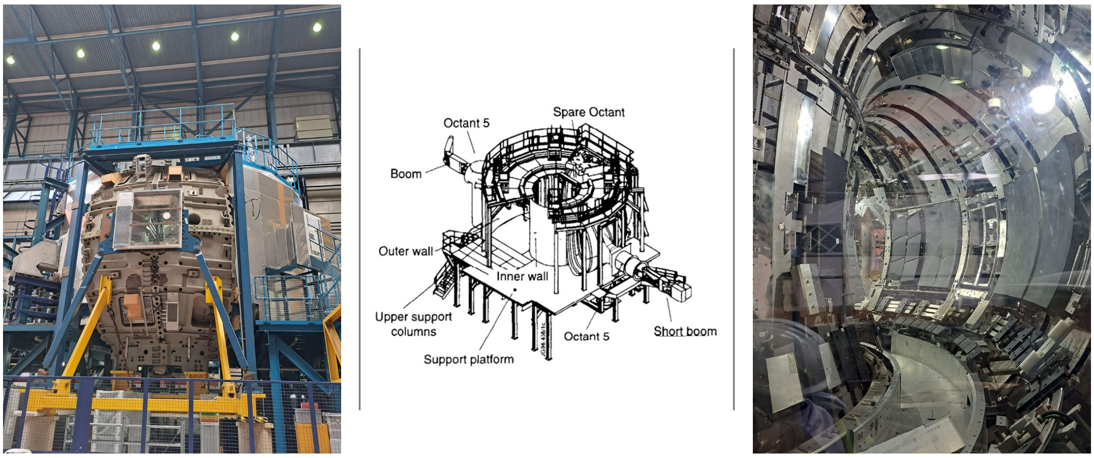


Figure 2.1: Layout and pictures of the In-Vessel Training Facility (IVTF) for JET project

reproduce the originals in size, weight, shape, and surface finish, and, where possible, also includes spare components. This facility proved invaluable for verifying tasks, validating procedures, and training operators for both planned and unforeseen activities. It also demonstrated recovery strategies for equipment failures and provided realistic estimates of task duration, accounting for operator fatigue [48].

In 2014, the Remote Applications for Challenging Environments (RACE) facility (Figure 2.2) was established to further support JETs RH procedures and to capitalize on the expertise accumulated over decades. Since then, RACE has expanded its activities through collaborations with industry, academia, and research organizations in diverse fields such as particle accelerators, nuclear fission, petrochemicals, space exploration, construction, and mining. Through these initiatives, RACE has provided technical consultancy, operational support, and has contributed to advancing the broader knowledge base in robotics and teleoperation.

### 2.2.2 REMOTE HANDLING FACILITIES IN SUPPORT OF ITER PROJECT

In the huge ITER project, several components, like divertor cassettes, blanket modules, neutral beam components and in-port parts and diagnostics, can require more or less regular refurbishment due to different levels of sputtering, erosion, and deposition after interaction with plasma, while others may need to be replaced due to unexpected failure [14-15]. Complete procedures planning

Figure 2.2: Outside picture and Control Room of RACE facility

and assessment, as well as a well-executed phase of training for operators who will control real Remote Handling Equipment (RHE), have always been considered necessary in ITER. During the last decades, a number of dedicated facilities have been realized in support of ITER RH:

- **ITER Divertor Test Platform (DTP, Italy, 1995)**

  One of the first RH facilities developed for ITER project was the Divertor Test Platform (DTP) (Figure 2.3), developed at ENEA Research Centre in Brasimone, Italy. This facility acted as a full-scale test-bed for divertor RH equipment suited to the ITER98 design [49, 50].

  DTP included [51]: 1) mock-ups system comprising a 72-degrees portion of the tokamak divertor region; 2) prototypes of main and auxiliary RHE; 3) test equipment for monitoring and controlling RHE (sensors, data acquisition, supervisory and control system, viewing system). In DTP virtual reality models for both on-line monitoring of RHE and off-line trajectory planning already appeared [52]. All mock-ups were made of steel with main dimensions, assembly tolerances, mass distribution and structural characteristics as close as possible to those of the real components. The most relevant RH interfaces were made with the same materials foreseen for the real components. The procedures for divertor cassette replacement were tested both considering positioning and manufacturing tolerances of ITER components (nominal conditions) and deviations from initial tolerances, resulting from deformations of components or misalignments between handling equipment and cassettes (limit conditions). The assessments were conducted in several test campaigns and allowed to: demonstrate the basic feasibility and repeatability of divertor cassette removal/installation, with the acceptance tests showing that RHE fulfill the basic requirements of ITER divertor maintenance scheme, even in limit conditions; validate the re-mote compatibility with the DTP test equipment; optimize the operation procedures; estimate the time required to remove/install all the cassettes; carry out a Failure Modes and Effects Analysis (FMEA) to identify possible accidents and consequences during the procedures and modify, if necessary, the design of movers and components; assist the procurement and testing of new hardware; evaluate an innovative rad-hard laser in-vessel metrology/viewing system; carry out

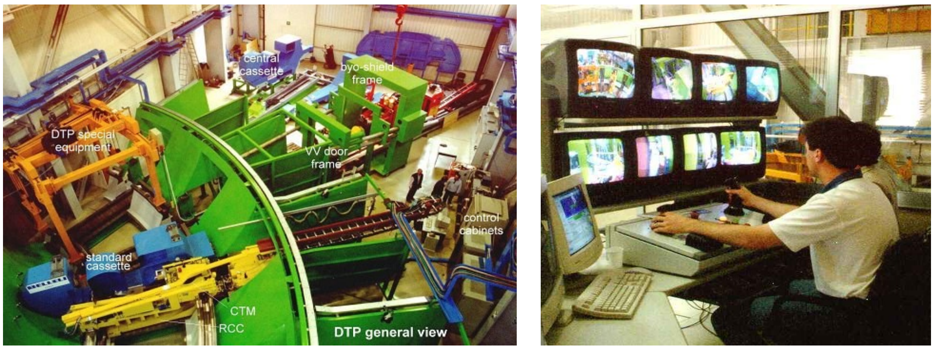


Figure 2.3: DTP Facility: layout and control room

a set of technological tests to qualify, under relevant environmental conditions (vacuum, temperature, radiation), special materials and components for the cassette locking systems and for the handling equipment [51, 53].

- **Divertor Test Platform 2 (DTP2, Finland, 2008)**

  In moving to the ITER 2001 design, the overall reduction in space determined modifications to divertor RH equipment, which has thereafter been composed of two main cantilevered systems: the Cassette Multi-functional Mover (CMM), moving radially to remove cassettes near RH ports, and the Cassette Toroidal Mover, moving toroidally inside the vessel to remove cassettes distant from RH ports. For the testing of these new movers a new RH mock-up facility has been designed and constructed at VTT Research Centre of Finland in Tampere, called Divertor Test Platform 2 (Figure 2.4) as it substituted the decommissioned DTP [49]. DTP2 was launched in 2008 and is still operational. Originally conceived to validate both CMM and CTM operation, DTP2 has been built and used to only demonstrate CMM functioning so far. Its design includes: a Divertor Region Mock-up (DRM), reproducing a 27-degrees portion of the lower vessel region; a prototype of CMM; a cassette space-frame mock-up [43, 54]. The design of the mock-up structures has only been focused on those geometrical and physical features that directly affect the design of the RH equipment and/or on the execution of RH procedures. A second major design driver has been to maximize the modularity of the mock-up structures to allow for easy modification in the event of ITER component design changes and for future extension of the facility [55]. DTP2 activity has been divided in three main phases: 1) integration and calibration of systems; 2) prove of concept for RH equipment and procedures; 3) control system usability and reliability tests. Thus far, the main achievements of DTP2 have been: confirmation of design and technology choices for the divertor RH equipment and their interfaces with ITER Plant; feasibility and controllability verification within safe operational limits of the second cassette cantilever transportation and deployment by the CMM, with cycle times assessment; development and testing of a reliable control and supervisory system to be replied for real ITER RHS [56, 57]. In the DTP2 Control Room two operators and one supervisor cooperate. Operations can be either automatic, with the op-

Figure 2.4: DTP2 facility: layout and control room [43]

erators just intervening if necessary, or teleoperated, with the operators controlling the robots by means of joysticks and haptic devices with force feedback [58]. Each operator has one or two screens on the desk in addition to a common power wall where to show visual information and data, with the possibility to choose which to visualize and discuss during the procedure. The information coming from the real images collected by the on-site cameras are complemented with a calibrated virtual model, which is updated in near real-time. In this regard, DTP2 has played a groundbreaking role, due to the massive implementation in the viewing system of digital mock-ups and VR/AR technologies to enhance the operators perception of the environment and provide them the necessary information to make aware decisions, while reducing the required number of on-site cameras [59, 57]. All that finally results in a reduction in the integration and commissioning times, an improvement and smarter updating of RH procedures, and an easier way to train future ITER RH operators [60, 30]. However, this is only possible if a correct calibration between the 3D virtual model and the physical mock-ups is ensured, also considering, as much as possible, deflections of cantilevered components during handling [61, 62]. DTP2 has also allowed to develop an optimized staff organization for a RH test facility, defining user groups with different accesses to sub-systems functionalities, in order to hide the irrelevant ones from the control room's operators and hence reduce unintentional actions [44]. Finally, in DTP2 several processes have been explored and practiced to be later applied to real ITER project: procurement with subcontractors, testing ITER Product Lifecycle Management (PLM) system; combination of PLM and Software Configuration Management (SCM) systems in the development and maintenance of RHS [63]; preparations of maintenance period; organization of operator guidance during maintenance procedure; handling of unexpected events; comparison between manual and automatic procedures to set their correct calibration and respective levels. To completely exploit in future the experience gained in the DTP2 facility and provide useful responses for real ITER maintenance processes, as much data as possible have been recorded and analyzed during its whole operation [43].

- **ITER Divertor Refurbishment Platform (DRP, Italy, 1998)**

  Once removed from the vessel, the divertor cassettes are placed in the ITER Hot Cell, where they undergo remote maintenance and refurbishment (i.e., the set of operations necessary to bring the cassette to the conditions for a new cycle in reactor). The DRP (Figure 2.5) facility has been commissioned at the end of 1998 to assess these operations, simulating the features of the Hot Cell environment [52]. It is located at ENEA Brasimone Research Centre in Italy and is still operating.

Figure 2.5: Divertor Refurbishment Platform (DRP)

In DRP a number of operations (Plasma Facing Components and Cassette Locking Systems replacement, cooling pipes cutting/re-welding/inspection, metrology survey) are simulated by means of teleoperated RHE, with the main objectives of confirming or modifying the design choices and increasing safety and reliability during refurbishment operations, as well as minimizing their duration. The DRP includes the following sub-systems [30]: 1) hot cell area handling equipment; 2) full size ITER divertor cassette mock-up, made of steel (except for the most relevant RH interfaces made with the same materials of real components) with main dimensions, weights, assembly tolerances and structural characteristics as close as possible to those of the real components. 3) Metrology equipment. 4) Plasma Facing Components (PFC) handling and replacement tools. 5) Test equipment and operating area, initially equipped with control panels, video monitors with a video matrix for camera view selection and control, and a large screen for display of sensor data to the operator [52]. Throughout its operation, the DRP has been allowing to: execute acceptance tests for ITER divertor refurbishment and metrology equipment and operations; improve and optimize refurbishment procedures; execute technological tests under ITER relevant environmental conditions; simulate accidents and test rescue operations; assistance for procurement of new hardware. For each test operation, most significant logged data have been retrieved and analysed, to get a deep understanding of the behaviour of equipment and mock-ups under test. All the major abnormal situations occurred during the tests, and the countermeasures taken accordingly, have been log-booked, in order to build a database usable for addressing the final design of the real ITER RHE [51]. The optimized re-design of the PFC to the cassette body attachment system, obtained through the large number of tests executed at DRP, is a practical example of the strong aid provided

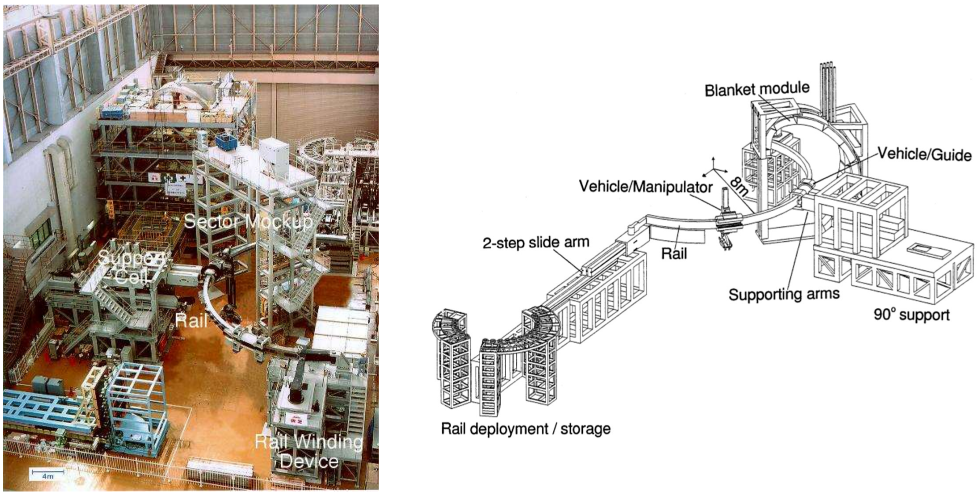


Figure 2.6: Architecture and layout of Blanket Test Platform (BTP) [64]

by a test facility in the design process of RH systems and procedures [52]. In the decades of continuous operation, DRP has proven to be a facility able to update and modernize, guaranteeing the possibility of testing both upgraded and completely new equipment and procedures.

- **ITER Blanket Test Platform (BTP, Japan, 1998) [64]**

  Beyond divertor RH, complex RH procedures are also required for ITER blanket modules replacement [65]. These have been tested and validated in a dedicated full-scale test platform called Blanket Test Platform (BTP, Figure 2.6), developed and fabricated during 1998 at Naka facility of Japan Atomic Energy Research Institute (JAERI), reproduces the physical environment of a 180-degrees in-vessel region of ITER, including the associated RH ports, maintenance cell, mock-up structures and full-scale required RH equipment/tools. A test and measurement system is installed in the BTP to evaluate the performance of RH equipment/tools for blanket module replacement, composed of a number of sensors (position, speed, force, acceleration, etc.) installed on the RH equipment/tools and mock-up structures and feeding the Data Acquisition System (DAS). A number of systems are linked to the DAS and to each other through a supervisor system: console system for DAS management, monitoring system for data real-time display, VR system and on-site cameras for environmental visual feed-back, robot controllers, and a database system to store all the obtained data [64]. Even in BTP2 a new control scheme was developed to suppress the dynamic deflection of the manipulator during sudden load transfer, based on its prediction and compensation. BTP facility allowed to demonstrate the effectiveness of the blanket module handling, including the most critical operations. In addition, the proof of principle of the use of the auxiliary equipment and tools has been also demonstrated, including the development of radiation hard components [65].

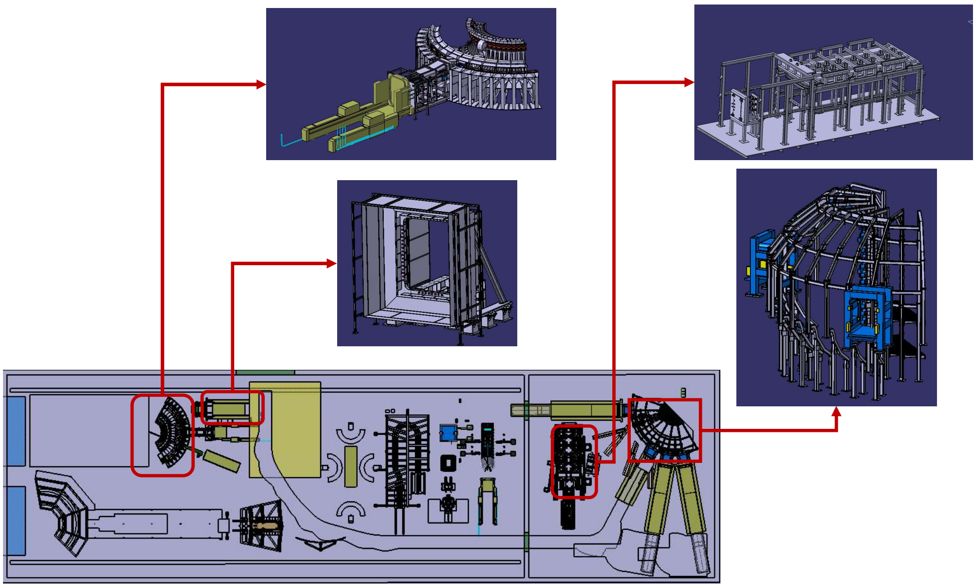


Figure 2.7: Conceptual layout and mock-ups of the ITER Maintenance Test Facility (IMTF) [67]

- **ITER Maintenance Test Facility (IMTF, France, 2025)**

  The maturation of ITER project has prompted the realization of new infrastructures, such as the ITER Maintenance Test Facility (IMTF). Located within the ITER site in Cadarache, France, it will host several large-scale mock-ups for ITER RH blanket and divertor procedures testing. Each procedure will therein be tested separately in a dedicated mock-up and area, as it can be seen from the facility's layout shown in Figure 2.7. The Preliminary Design of the IMTF has been completed at the end of 2023, and International Tenders will be launched soon [66, 67].

### 2.2.3 Remote Handling test platform for Chinese CFETR project

Another operative RH test platform in Asia is the Comprehensive Research Facility for Fusion Technology (CRAFT), which is a large-scale R&D platform for the China Fusion Engineering Test Reactor (CFETR), an independent Chinese project aimed at testing and verifying the engineering and technical feasibility of future fusion reactors. The CRAFT consists of 20 different facilities which address most of the key technologies and systems of CFETR. In the CRAFT RH platform (Figure 2.8), several RH procedures are tested in different test stages: a first stage of Component Test is executed to individually validate single components and tools design; then, a second stage of Sub-system Test validates

Figure 2.8: The RH test platform within the Comprehensive Research Facility for Fusion Technology (CRAFT) for the China Fusion Engineering Test Reactor (CFETR)

whole sub-systems design; finally, the third and last stage of United Test, validate planned and unplanned handling procedures, as well as procedures of cooperation between multiple robotic sub-systems.

## 2.3 Concluding remarks about the current global landscape of RH facilities for fusion reactors

RH Facilities for fusion projects have been developing for about 30 years, each contributing in its own way to the improvement of RH and robotic teleoperation technologies.

A summary of the described facilities is provided in Table 2.1. A timeline spanning their development over the last 30 years is instead provided in Figure 2.9, while Figure 2.10 shows their geographical distribution worldwide.

Collectively, these facilities have enabled fundamental advances: validation of divertor and blanket maintenance strategies; development of auxiliary tooling such as welding/cutting equipment and transfer casks; testing of Human-Machine Interfaces and staff organization strategies; testing of man-in-the-loop concept for RH control systems adding human telemanipulation operations to robotic autonomous tasks; human operators training for telemanipulation tasks; and introduction of VR/AR techniques to compensate for visibility limits.

Yet, their limitations are equally significant. Most facilities are specialized, focusing on divertor or blanket operations only, and do not integrate the full range of in-vessel maintenance tasks. ITER strategy has also foreseen the distribution of the RHS testing in separated facilities, each involving only a part of the procedures and equipment. Collaboration between multiple operators on a shared digital twin of the reactor environment is still absent. Furthermore, there is no RH facility already built capable of testing various RH systems within the same mock-up environment; a decentralized approach is instead generally preferred, with different testing areas, each hosting the mock-up of a specific portion of the stakeholder fusion device and testing specific RH equipment.

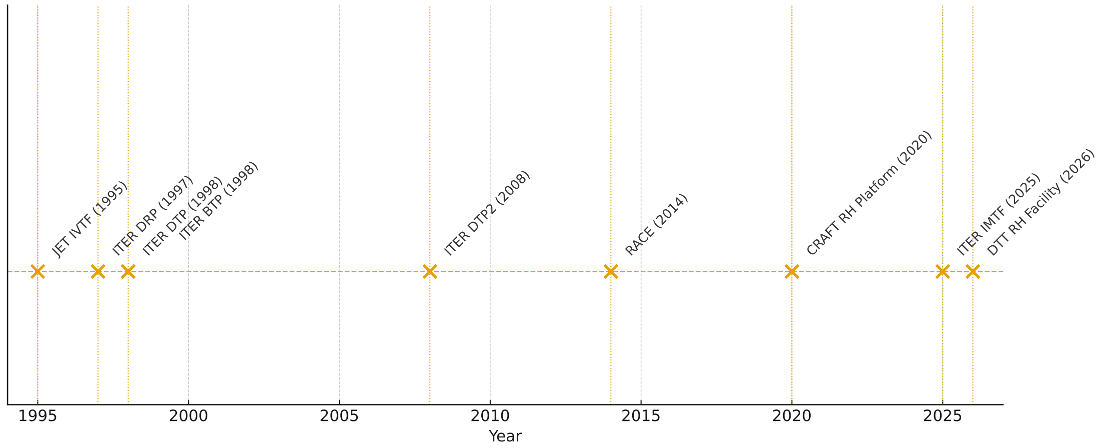


Figure 2.9: Timeline of RH facilities developed for fusion reactors worldwide (1995-2025)

## 2.4 The innovations of the DTT RH Facility

The analysis of existing RH test facilities for fusion reactors highlights the absence, at least in Europe, of a comprehensive infrastructure capable of supporting the validation of all devices and procedures of the reactor's RH system, including operations across different in-vessel regions and components. A notable exception is represented by the IMTF, that is planned to cover the testing of all ITER RH equipment, however in separate test areas empploying different mock-ups, as already mentioned. The forthcoming RH Facility for the Divertor Tokamak Test (DTT) project is intended to address this gap by providing an integrated mock-up environment for the validation of RH procedures and equipment for the entire tokamak [35, 68, 37]. In addition, the DTT RH facility is

Table 2.1: Global RH Facilities: scope and major contributions

| Facility | Location | Year | Focus | Key Contributions |
|---|---|---|---|---|
| JET IVTF | UK | 1995 | FW Tiles exchange, Divertor operations, training | Operator training; recovery procedures; procedure timescales. |
| ITER DRP | Italy | 1997 | Divertor refurbishment | Validation of cassette refurbishment operations. |
| ITER BTP | Japan | 1998 | Blanket operations | Auxiliary tools (transfer casks; cutting/welding); rad-hard components. |
| ITER DTP | Italy | 1998 | Divertor acceptance tests | Acceptance tests; auxiliary procedures (vacuum door; rails). |
| ITER DTP2 | Finland | 2008 | Divertor testing | Digital mock-ups; AVR to overcome camera limitations. |
| RACE | UK | 2014 | Manipulator testing | Support to JET/ITER/ESS; systems integration. |
| CRAFT RH Platform | China | 2020 | Blanket/divertor/ NBI | Multipurpose platform; intelligent control. |
| ITER Maintenance Test Facility (IMTF) | France | ~2025 | ITER blanket/divertor | Full-scale mock-ups at ITER site. |
| DTT RH Facility | Italy | ~2026 | Full RH with Digital Twin | Comprehensive test and training hub for DTT and beyond. |

conceived as a human-centered environment, designed to support operators by supplying extensive information through data, images, and virtual renderings, thereby facilitating decision-making and teleoperation tasks. At the heart of this facility lies a digital twin, which links real equipment with its virtual counterparts within the control system. Data from multiple subsystems, including physical and digital mock-ups as well as actual DTT robots, will be integrated within a cutting-edge control room. The control room will serve both as the

Figure 2.10: Global distribution of Remote Handling facilities for fusion

hub for executing procedures and as a platform for gathering data to enable subsequent analyses and future developments.

The main innovations of the DTT RH facility can be summarized in the following points:

- Comprehensive Architecture: the DTT RH facility will include a single mock-up assembly that replicates a 100° sector of the entire DTT vacuum vessel, including the vacuum vessel structure with dedicated RH ports, first wall and divertor modules, as well as placeholders for additional in-vessel components.

- Deployment of real DTT robots: unlike the majority of earlier platforms that relied on simplified manipulators, the DTT RH Facility will employ the actual DTT RH equipment. They will first be tested, validated and commissioned in the facility and then transferred to DTT site for operation. This configuration ensures one-to-one correspondence between test environment and reactor operation.

- Integration of digital twin and VR/AR Technologies: digital twin technologies will play a primary role in the development and operation of the facility, and integration with VR/AR systems will be fundamental to provide humnan operators with as much comprehension of robots and operative environment as possible. The physical equipment will be coupled with virtual models to allow real-time alignment between digital and physical states. This integration will provide operators with additional information beyond sensor feedback, such as structural deflections, vibrations, and collision risk alerts.

- Operator-Centered control room: the control room is conceived as the heart of the facility. Equipped with multi-screen visualization, immersive head-mounted displays, and haptic interfaces, it will allow operators to seamlessly go through three control modes: **offline mode**, training and procedure rehearsal in a safe virtual environment; **teleoperated mode**, direct robot control via master-slave systems; **supervisor mode**, oversight of automated procedures, with intervention capability in case of anomalies. Operator training is a cornerstone of DTT RH Facility mission. New operators will gain experience in both the virtual environment and the physical mock-ups before obtaining certification. The ability to train in VR will allow repeated practice of procedures without risk to equipment, enhancing preparedness and reducing the probability of human error.
- A European hub for Remote Handling innovation: the facility will also be able to host acceptance tests for novel RH equipment and tooling, beyond those foreseen for DTT. It has thus the aim to become a European hub for innovation in the sector of RH in fusion reactors, potentially serving DEMO and further future projects.

The global evolution of RH facilities reflects the progressive maturation of fusion technology. Early platforms provided proof-of-principle demonstrations; ITER-oriented facilities refined equipment and procedures, and VR/AR technologies began to enhance operator support. However, none has yet achieved a fully integrated approach capable of testing the entire spectrum of RH tasks within a single mock-up environment.

In this regard, the DTT RH facility represents a significant step forward: by combining a single full-scale mock-up assembly, real robots, advanced digital twin technologies - managed over a centralized PLM platform - and dedicated operator training infrastructure, it will contribute to reduce the gap between design and reliable operation of RH systems.

## 2.5 STATE OF THE ART ANALYSIS ABOUT DIGITAL-TWIN BASED DEVELOPMENT OF PRODUCT AND FACILITIES

The establishment in the industrial production of Model Based Systems Engineering (MBSE) methodology [69], with the development and spread of Product Lifecycle Management (PLM) platforms [70] and Cloud-Based Design and Manufacturing (CBDM) approach [71], are leading the transition to the so-called "Industry 4.0". This evolution finds its foundations on advanced technological concepts as Internet of Things (IoT), Artificial Intelligence (AI), cloud computing, cyber-physical models, Intelligent Manufacturing Systems (IMS) and robotics, which allow for digitalization and efficiency of productive processes [72]. These concepts have developed during last years thanks to the fast growth of computer, servers, data network and communication channels technologies, which enable the flow and storage of huge amounts of data. This is the most important factor to achieve three key aspects of modern Smart Factories:

- The complete interconnection of humans, machines and systems.
- The storage of all data in on-cloud software frameworks accessible from everywhere and for everyone endowed with the appropriate rights.
- The digitalization of all products and processes, represented by a digital twin.

Digital twin concepts allows for digitalization, interconnection and integration of models, processes and products, representing the virtual objects where to store all the reference data of the physical correspondents during their whole lifecycle. This is valid for both products and facilities, such as industrial factories or experimental test facilities. The digital twin becomes the core of the product/facility development full-cycle, from early stages of market evaluation and requirement engineering to the final real-time monitoring, management, and optimization of operations. The digital twin has the role of storing and integrating all the models which are continuously produced during the development of the product or facility, at the same time linking them to the physical correspondents and the embedded actuators/sensors for equipment control and monitoring, through communication channels.

*M. Grieves and J. Vickers* (2016) introduced one of the foundational conceptualizations of the digital twin as a means to address the challenges of emergent, often unpredictable behaviors in complex engineered systems [73]. The authors argue that traditional modeling and simulation approaches, while useful, are insufficient to anticipate undesirable outcomes that arise from the nonlinear interactions of subsystems. In their formulation, the digital twin is defined as a dynamic, virtual counterpart of a physical asset, continuously updated through bi-directional data flows across the systems entire lifecycle. This architecture enables predictive analysis, what-if scenario exploration, and the mitigation of risks before they manifest in the physical domain.

The digital twin has been adopted as a conceptual basis in the astronautics and aerospace area in recent years, where the cost of failures and the safety requirements demand advanced predictive capabilities. One of the earliest formalizations of the digital twin paradigm in aerospace engineering was provided by *Glaessgen and Stargel* (2012) [74, 75], who defined it as an integrated multiphysics, multiscale simulation of a vehicle or system, continuously updated with sensor data from its physical counterpart. Their work, developed within NASA and the U.S. Air Force context, emphasized the potential of digital twins to transform both design and sustainment of complex aerospace vehicles by enabling real-time performance assessment, structural health monitoring, and predictive maintenance. In this view, the digital twin is not a static model but a living digital entity, evolving in parallel with the physical system across its lifecycle, thereby supporting decisions on safety, repair, and mission readiness. The authors also identified the major scientific and technological challenges associated with this paradigm, including the need for high-fidelity multiphysics modeling, robust data assimilation techniques, and high-performance computing infrastructures. Although ambitious, their framework positioned the digital twin as a disruptive approach to reduce reliance on costly physical testing, extend service life, and enhance operational reliability in aerospace systems, setting a precedent for its subsequent adoption in other engineering domains.

NASA has widely used the digital twin concept in their technology roadmaps. The concept has been proposed for next generation fighter aircraft and NASA vehicles [74, 75], along with a description of the challenges [75] and implementation of as-builts [76]. At NASA, digital twins were conceived not only as design and testing tools but also as operational companions to physical spacecraft and aircraft, allowing continuous monitoring, anomaly detection, and system optimization. This early institutional commitment by NASA significantly contributed to the dissemination of the digital twin concept, framing it as both a design methodology and a lifecycle management strategy for complex, high-risk systems. The high-level of customization, specialization, and complexity, as well as the strict operational requirements, make NASA's systems even closer to RH systems for fusion devices than industrial robotic systems, as application cases for digital-twin based design, development and lifecycle management.

A digital twin is typically structured around three core elements: the physical asset, its virtual model, and the data connections that integrate the two domains [77]. The physical entity provides the operational context, while the virtual counterpart consists of multi-physics and data-driven models capable of simulating the behavior of the physical entity. The bi-directional data link ensures real-time synchronization, enabling the digital twin to evolve with the physical system. This structure is visible in Figure 2.11. Extended frameworks

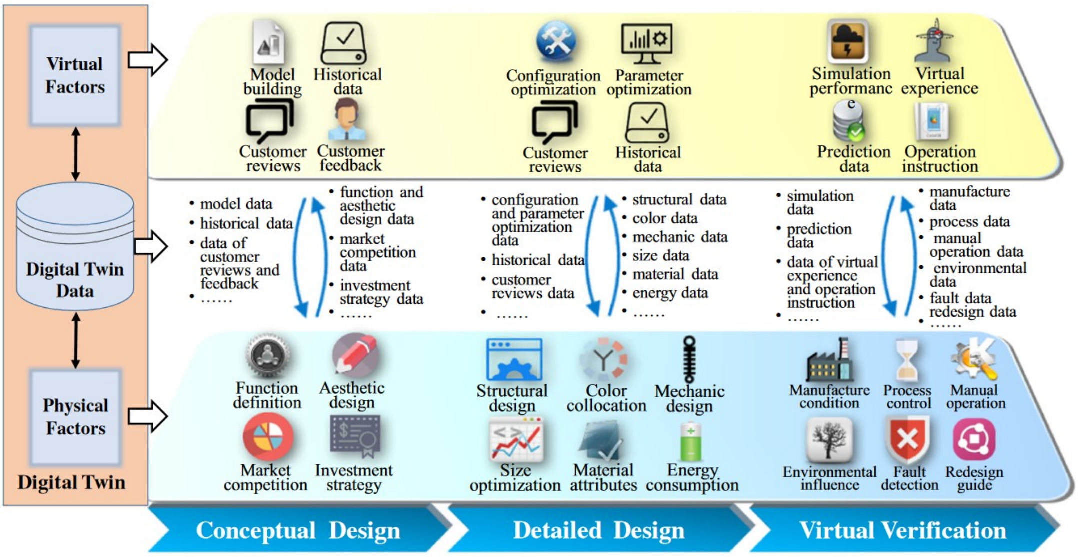


Figure 2.11: Schematic view of the core elements of a digital twin along the whole product development cycle [79]

also include service layers and humanmachine interfaces, which allow stakeholders to leverage the digital twin for monitoring, prediction, and optimization [78].

Broadening the scope to plant and processes, rather than to individual products, the concept of digital twin can also be referred as Digital Factory or Smart Factory or even Digital Twin Shop Floor. The concept of the Digital Factory represents a comprehensive, digitally integrated system that leverages advanced technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), machine learning, big data analytics, and digital twin models to design, simulate, monitor, and optimize manufacturing processes and production systems. It enables real-time data exchange, enhanced automation, predictive maintenance, and agile manufacturing operations, thereby improving efficiency, productivity, and flexibility in the manufacturing lifecycle. Digital models of products, processes, and resources are continuously synchronized with their physical counterparts through real-time data exchange, a paradigm enabled by the IoT. This dynamic coupling allows not only the simulation and optimization of manufacturing workflows before physical implementation, but also the continuous monitoring and adaptive control of production systems during operation. As highlighted by *Tao et al.* in their work on digital twin-driven manufacturing [79], the Digital Factory provides the foundation for lifecycle integration, linking product design, production, and service phases through data-driven in-

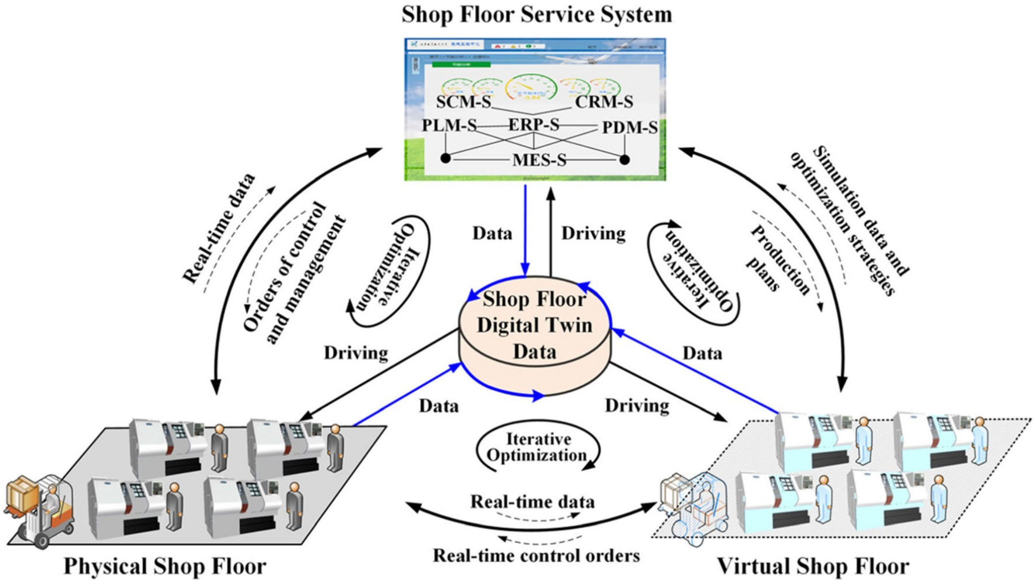


Figure 2.12: Schematic view of the core elements of a Digital Factory or Digital Twin Shop Floor [81]

telligence. At the same time, *Xu et al.* [80] emphasize the enabling role of the Internet of Things (IoT), which provides the pervasive sensor networks, communication infrastructures, and big data analytics necessary to ensure that factories can evolve towards higher levels of flexibility, efficiency, and responsiveness. Consequently, the Digital Factory emerges not only as a technological advancement, but as a strategic enabler of Industry 4.0, supporting the transition from traditional manufacturing systems to adaptive, intelligent, and service-oriented production ecosystems. Although typical of new technologies related to Industry 4.0, Digital Factories still provide the foundation for plant development and management after Industry 5.0 coming, that instead focuses on socio-ethical factors and value chains rather than technological innovations. Figure 2.12 depicts the core elements of a Digital Factory or Digital Twin Shop Floor, similar to those previously identified for the product's digital twin: the Physical Shop Floor, the Virtual Shop floor and a Shop Floor Service System constantly share real-time data through the Shop Floor Digital Twin, enabling continous iterative optimization of systems and processes.

This is a concept that can be extended to several other domains, not only within the industrial sector. One may consider, for instance, the ongoing development of Smart Home [82] or Smart City [83, 84] projects. The underlying principle remains the same: the focus shifts from the physical entity to its digital counterpart, which becomes the core of the system, serving as the central hub for monitoring and control. Therein, all data are stored and managed, while ensuring a continuous exchange of information between the physical subsystem and its digital twin.

Challenges to the large-scale adoption of digital twins in the development and management of complex products and facilities still remain and are mainly related to ensuring interoperability across heterogeneous platforms, validating models against complex real-world behaviors, and addressing issues of scalability and data governance, which continue to be active areas of research [85].

### 2.5.1 Product Lifecycle Management (PLM) platforms for managing Digital-Twin based projects

The large amounts of data centered around the Digital Twin or Digital Factory need wide software frameworks to be managed. These are offered by Product Lifecycle Management (PLM) platforms [86] [87]. PLM platforms are centralized platforms allowing for managing the entire development process of a product or facility, keeping in constant integration the different design stages as prescribed by the MBSE paradigms.

PLM enables effectively management of products and processes throughout their entire lifecycles, from the initial idea to their retirement and disposal, by providing in the same platform the tools to carry out several design phases, from requirements engineering to optimization during operation, passing through Verification & Validation by means of virtual simulations [79].

Product Lifecycle Management (PLM) platforms have progressively evolved from datacentric repositories into enterprise-scale infrastructures that integrate product information, processes, and decision-making across the full lifecycle, from design to service and end-of-life [88, 89]. Early formulations conceptualized PLM as a means to close knowledge loops ensuring that information generated at each stage is captured and reused [89], while more recent approaches emphasize closed-loop PLM, where operational and IoT data are continuously fed back into engineering to enhance designs and maintenance strategies [90]. Case studies in aerospace demonstrate that PLM platforms, when deployed as enterprise backbones rather than isolated tools, enable concurrent engineering, iterative design, digital mock-up practices, and certification-ready digital threads, improving efficiency and reducing lifecycle costs [87, 91]. The integration of digital twins within PLM platforms, supported by big data analytics, further strengthens this paradigm by maintaining synchronized virtualphysical representations of assets and processes, as shown in applications such as machine tool twins and Industry 4.0 demonstrators [79, 92]. Cloud-native PLM extends these benefits to distributed supply chains, lowering entry barriers and enabling scalable collaboration, though challenges remain regarding interoperability, twin governance, and data security [93]. Overall, PLM platforms are emerging as the backbone of digital transformation in complex industries, providing the necessary framework to integrate digital twins, foster continuous improvement, and operationalize the digital thread across the entire product lifecycle.

PLM platforms leverage the possibility of moving to the cloud all the information via the concept of Cloud-Based Design and Manufacturing (CBDM). CBDM is defined as a computing and service-oriented manufacturing model developed from existing advanced manufacturing models (e.g., application service providers, agile manufacturing, networked manufacturing, manufacturing grids) and enterprise information technologies under the support of cloud computing, the Internet of things (IoT), virtualization and service-oriented technologies, and advanced computing technologies [71]. Leveraging the potentiality of the cloud technologies, eases the burden of integrating large agents in big science projects, like fusion reactors. CBDM approach relies on the storage of all data, models, documents and any type of information regarding products, processes and facilities over an on-cloud database. CBDM enables seamless access to all this information for each design team member and contributor, regardless of the geographical location. The concept of file system disappears, and therefore also the need to constantly transfer files among design contributors. On-cloud models are constantly updated and can be branched to carry out specific tests and simulations within the PLM platform without impacting the main design version. For instance, a Finite Element Analysis (FEA) can be performed on a dedicated branch of a components main version, allowing the assessment of specific design changes without affecting the primary model. Once the modification has been validated and authorized, it can then be merged into the main component version. This process eliminates the need to export or import files across different software tools, or to manually transfer data to other team members for simulation purposes, as all models are stored within the PLM platform, accessible to all authorized team member and equipped with the necessary tools to support the entire product development cycle, including simulations such as FEA. In this way, the risk of losing or compromising design information is significantly reduced.

For PLM systems to operate efficiently within a CBDM approach, they must rely on a robust and reliable network infrastructure. Furthermore, user access rights and permissions should be carefully defined and managed across the design team to prevent unintended workflow actions or unauthorized design modifications.

From a technological standpoint, PLM platforms now encompass a wide range of services:

- Model-based definition and design control, linking CAD/CAE models with bills of materials (eBOM, mBOM, sBOM) and requirements management.
- Simulation and test data management, enabling closed-loop validation and verification processes.
- Manufacturing and operations integration, bridging engineering design with Manufacturing Execution System (MES) and Manufacturing Operating System (MOM) systems and in-service maintenance.
- Cross-domain collaboration, increasingly enabled by open standards.

PLM platforms generally provide the tools to apply the principles, methods and frameworks of MBSE.

Model-Based Systems Engineering (MBSE) has been established as a paradigm shift from traditional document-centric practices towards model-driven approaches, aiming to cope with the increasing complexity of modern engineered systems. By relying on formalized models as the central artifact of communication and decision-making, MBSE enables improved consistency, traceability, and cross-disciplinary integration throughout the system lifecycle. Early surveys of methodologies have highlighted its potential to support requirement management, verification, and validation, while reducing design risks and costs [94]. More recently, MBSE has been positioned as a key enabler of digital continuity and as a foundation for digital twin development, since it provides a structured framework to integrate heterogeneous models, simulations, and operational data [95, 96]. In this perspective, MBSE is increasingly seen not only as a systems engineering practice, but also as a cornerstone of the digital transformation of complex industries such as aerospace, defense, and energy.

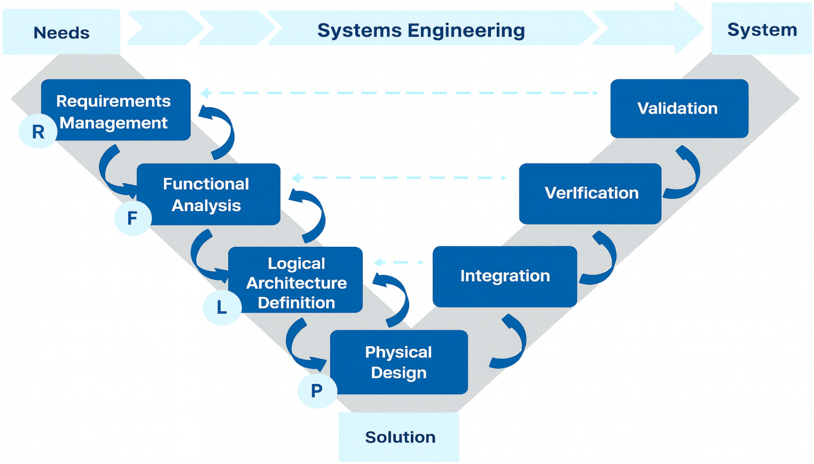


Figure 2.13: V-model embedding the RFLP paradigm

Among the several MBSE's frameworks supporting product design process, the V-Model in RFLP approach is one of the most commonly employed in industrial production.

The V-model and the RFLP (Requirements, Functional, Logical, Physical) approach are two complementary frameworks that structure the development of complex systems. The V-model, widely adopted in systems engineering, emphasizes the correspondence between development phases (requirements definition, architectural and detailed design), representing the left side of the V-model and together intended even as *Specification Stream*, and their associated Verification & Validation stages, representing the right side of the V-model and together intended even as *Testing Stream*, thereby ensuring traceability and reducing the risk of late-stage failures [97, 98, 99]. The RFLP represents the *Specification Stream* placed at the left side of the V-model, by introducing a hierarchical decomposition from requirements to functional, logical, and physical framework, enabling engineers to progressively refine system specifications into realizable designs. When embedded within PLM and MBSE practices, RFLP provides the structured backbone to implement the V-model in a digital environment, linking requirements to verification steps through coherent models across the lifecycle [100, 101]. Together, these methodologies foster digital continuity, systematic validation, and a stronger alignment between stakeholder needs and technical solutions, thus forming the methodological foundation for digital twindriven systems development. The V-model embedding the RFLP paradigm is shown in Figure 2.13

### 2.5.2 Applications of Digital Twin and PLM technologies in nuclear and fusion sectors

Digital Twin technology has rapidly gained relevance in the nuclear sector as a transformative paradigm for bridging physical systems with their virtual counterparts through real-time data integration, multi-physics simulation, and predictive analytics. In nuclear fission, digital twins have been employed for predictive maintenance and lifecycle management of safety-critical components, enabling anomaly detection and fault diagnosis before failures occur [102]. Beyond component-level monitoring, system-wide digital twin frameworks have been proposed to integrate operation, safety assessment, and training in a unified digital environment, offering operators enhanced decision-making support and improved resilience against unforeseen events [103].

The fusion sector, characterized by extreme operational environments and complex system integration, has increasingly explored digital twins as enablers for next-generation plant design and operation. One particularly promising field is plasma control, where Digital-twin based predictive models are coupled with diagnostic data streams to anticipate plasma instabilities and disruptions, effectively creating a cyber-physical loop that augments real-time machine control. At the same time, digital twins have been leveraged for facility-level visualization and integration, supporting the virtual prototyping of reactor subsystems and entire plants. Platforms such as NVIDIA Omniverse have enabled immersive simulation of fusion facilities, fostering collaborative engineering and advanced operator training in realistic environments [104]. These applications underline the growing role of digital twins not only as engineering validation tools but also as strategic infrastructures for digitalized fusion research. *M.I. Battye and S. Perinpanayagam* [105] offer a systematic review of the current state of digital twin development in fusion energy. They highlight how the centralized storage of data and models and the integration of digital twin technology promise to accelerate simulation-based testing and optimization of reactor components, reducing the need for costly, iterative physical testing and paving an efficient pathway to achieving fusion as a reliable energy source.

Among the diverse applications of digital twins in fusion, robotic remote maintenance stands out as one of the most critical. digital twins provide a safe and flexible environment to design, validate, and optimize RH procedures. Early examples in fission demonstrated the feasibility of digital twins for robot navigation and autonomous interaction under hazardous conditions [106], laying the groundwork for fusion-oriented applications. As part of China Fusion Engineering Test Reactor (CFETR) development, *Wan et al.* suggest employing Digital Twin (DT) technology for the CFETRs Multipurpose Overload Robot (CMOR). The CMOR-DT system was developed as a digital replica of tokamak manipulators, enabling the validation of complex trajectories and motion strategies prior to deployment in real devices [107]. Similarly, DT-driven approaches have been applied to specialized tools such as the snake endoscope manipulator, conceived for inspection and repair in narrow vessel regions, reducing reliance on costly and time-consuming physical mock-ups [108].

Building on these foundations, research has recently advanced toward cognitive digital twins, where surrogate modeling and AI-based reasoning are integrated to enhance adaptability under uncertain operating conditions, thereby enabling dynamic optimization of robotic tasks [109]. At a broader level, *Do et al.* [110] propose a set-up to extend the scope of DTs from task-level validation to plant-wide integration, embedding autonomous intelligence into facility maintenance planning and operation. Immersive DT environments have also proven valuable for human-in-the-loop validation, where operators can test procedures, rehearse maintenance strategies, and evaluate safety protocols in highly realistic virtual facilities [104].

Despite rapid advancements, digital twin applications in fusion energy largely remain at a conceptual or laboratory stage, with limited validation under real operational conditions. Real-time synchronization between physical systems and their virtual twins is another critical barrier, constrained by the need to manage substantial data volumes, maintain stringent low-latency communication, and uphold cybersecurity standards [111, 112, 113, 114].

Another challenge is achieving a reliable matching between the digital twins models and their physical counterparts: in fusion reactor's remote maintenance, for instance, efforts are still needed to ensure proper matching between the digital twin Virtual Reality models and the real pose assumed by the robots during operation. The unsolved discrepancies are mainly due to both the structural behavior of cantilevered robots while handling heavy loads and the differences between the as-built equipment version and the nominal model, which are two aspects difficult to accurately predict, model, and represent in real-time. However, the high accuracy required in the robotic equipment movements determine the need for digital twin models to reproduce the real correspondents in an extremely faithful way. To achieve this scope, a process of calibration of digital twin models must be carried out during commissioning of hardware and software RH equipment, to align them to the real as-built configuration. Calibration and compensation of unpredicted errors occurring during operation and deviating the robot configuration from the nominal one is a widely diffuse process in industrial robotics. Calibration of digital twin models has found application in fusion sector during the development activities of the ITER divertor RH equipment, carried out at the DTP2 facility. Interesting and effective solutions have been proposed for model-based calibration & compensation [115], for instance through addition of error models with virtual joints to the kinematic model [62], and deflection representation [61]. However, the implementation of these error models in the digital twin CAD models was partially tested but not completed, and currently nominal CAD models with rigid body kinematics assumption are still used, compromising their reliability during trajectory planning and teleoperation.

In conclusion, digital twin technologies are progressively reshaping the nuclear and fusion domains, spanning applications from plasma control and plant design to immersive training and robotic remote maintenance. While their maturity in fission is approaching industrial practice, in fusion they remain largely exploratory. Nevertheless, digital twins are increasingly recognized as essential enablers for the safe, efficient, and cost-effective operation of future reactors. Their successful deployment will depend on overcoming current barriers in fidelity, integration, and standardization, but their potential impact on the realization of fusion energy is profound.

Broadening the discussion to the use of PLM platforms in nuclear and fusion applications, they provide indispensable support for the governance of complex projects. Fusion facilities are characterized by extreme design complexity, long development timelines, and high regulatory oversight. In this context, PLM enables traceable configuration management and integration of systems into broader plant design, also ensuring that maintenance strategies are validated against consistent digital models.

Today, PLM platforms are increasingly being adopted in the nuclear fusion energy research sector. Start-ups like Tokamak Energy are leveraging the capabilities of Siemens Teamcenter [116], while established research centers such as UKAEA are utilizing Dassault Systemes 3DEXPERIENCE platform [117]. Similarly, ENEA in Italy is implementing the 3DEXPERIENCE for the DTT project

[118]. This strategic shift aims at addressing the challenges posed by integrating multiple contributions within a single extensive project, by consolidating everything from requirements definition to Verification & Validation onto a unified platform, to maximize flexibility and streamline processes.

The ITER project has also progressively deployed a comprehensive Product Lifecycle Management (PLM) infrastructure to coordinate design, procurement and construction across its members, multiple Domestic Agencies and a large industrial supply chain. The PLM backbone is centered on Dassault Systèmes ENOVIA/3DEXPERIENCE platform, tightly integrated with CATIA for 3D design and Digital Mock-Up (DMU) activities. This environment structures the Plant Breakdown Structure (PBS), manages configuration baselines, and links 3D models to engineering data, documents and change processes [119]. A major benefit of PLM at ITER is the creation of a single source of truth for the Tokamak Complex. The 3D master model, hosted and controlled in PLM, supports global DMU to check clashes, interfaces and maintainability for millions of parts and numerous plant systems. The same platform underpins configuration and change management, via formal change control boards and workflows, ensuring that design changes, non-conformities and as-built updates are propagated consistently across the project. For a First Of A Kind (FOAK) nuclear installation, this approach is essential to demonstrate traceability and compliance with regulatory requirements [120].

For Remote Handling (RH) systems, ITER has also explored the combined use of PLM and Software Configuration Management (SCM) tools. Mechanical and hardware configuration is maintained in PLM, while control software and related artifacts are tracked in SCM, with defined links between the two domains [63, 121]. This architecture anticipates a digital thread in which RH hardware, control software and verification & validation (V&V) evidence can be traced across the lifecycle, an important prerequisite for future digital twin implementations.

However, ITERs experience also reveals several criticalities. First, the multi-partner, multi-tool environment makes data exchange and synchronization complex, and achieving uniform modeling and configuration rules requires strong governance. Second, the size of the DMU raises performance and usability issues; large assemblies must be simplified and converted into lightweight models for routine design reviews and RH simulations, adding extra steps to the workflow. Third, the long project timescale has led to solutions based on the coexistence of legacy ENOVIA/MatrixOne and the current 3DEXPERIENCE deployment, with the usual migration overheads and risk of fragmented practices. Finally, PLM usage is uneven across user communities; the system is perceived as powerful but demanding, and shadow practices (local files, spreadsheets) still appear, which may weaken configuration discipline [122].

Overall, PLM at ITER has enabled unprecedented design integration and configuration control for a fusion device, while simultaneously exposing scalability, interoperability and usability limits typical of large FOAK facilities. For the purposes of this thesis, these lessons position PLM not only as a necessary backbone for RH facilities, but also as a starting point for more advanced MBSE and digital twin workflows, which aim to strengthen the digital thread between RH hardware, control software and operational data.

Ongoing research aims at solving several challenges that remain open in PLM adoption for fusion and other complex projects. These include the difficulty of achieving end-to-end interoperability across heterogeneous toolchains [123], the synchronization of engineering and operational data in near-real time [124], and the definition of robust governance frameworks that balance openness and intellectual property protection [111]. At the same time, future directions suggest increasing integration of PLM with AI-driven analytics, knowledge graphs [125]), and sustainability assessment methods [126], expanding their role from product data management to true innovation platforms capable of orchestrating digital twins throughout the facility lifecycle [127].

## 2.6 INNOVATIONS OF THE WORK AND INTEGRATION IN THE SCIENTIFIC CONTEXT

Some key considerations can be drafted out from the state-of-the-art analyses performed:

- Remote Handling (RH) facilities are indispensable to assist and validate the design of RH equipment and procedures, train operators, and achieve efficient and reliable maintenance plan able to minimize the fusion reactors' downtime.
- The current landscape of RH facilities worldwide lacks of an integrated RH facility able to test and validate the whole set of RH equipment and procedures of the stakeholder fusion machine in a unique mock-up assembly, designed to fully reproduce an in-scale toroidal portion of the fusion device.

- Digital-Twin driven design over PLM platforms, relying on MBSE principles and frameworks, is nowadays widely adopted in industrial sector but has not yet been fully established in nuclear and fusion research.

In this scientific context, the present research aims at providing the framework, methodology and workflow for the full-cycle development of RH facilities for fusion reactors in a digital-twin driven approach. At a broader level, the scope is to define a reference in the development and management of RH facilities for fusion reactors, based on the employment of concepts widely settled in the industrial production and in the management of industrial facilities but still only partially and separately used in fusion sector.

So far, the development of fusion projects, and of all the related facilities, has mainly being carried out by research centers, public agencies, consortia and academies, particularly at the earliest stages. Therefore, frameworks and tools typically and historically associated with industrial production have struggled to establish. However, their use would strongly help in facing the development challenges of such complex, multidisciplinary and multi-stakeholder projects.

Therefore, the present thesis proposes a methodology for developing and managing fusion-related RH Facilities based on approaches, tools, and frameworks generally used for industrial factory shop floors, leveraging on multiple specific similarities between fusion RH facilities and industrial factory shop floors:

- One or more automated machines executing predefined tasks.
- End-tools allowing the robots to interface with the components to be handled.
- Components to be handled.
- Limited workspace where the automated machine operate.
- Control station (wider and more articulated in RH facilities due to the presence of complex teleoperation tasks).

In this perspective, as in the case of industrial factory shop floors, the digital twin is intended to drive the facility development process by storing all the related data, models and simulations throughout its lifecycle, benefiting from the use of a PLM platform and following the principles of MBSE and, in particular, of the V-Model framework in RFLP approach.

The methodology proposed in the present work is supported by the application to the Case Study of the DTT RH Facility (more widely described in

Section 1.4), representing an innovation in the panorama of RH facilities for fusion projects, due to the large scale of RH procedures and equipment to test and the advanced control frameworks.

The present work has therefore the wider aim of establishing a method to apply the frameworks of digital-twin based design, development and management of industrial facilities to fusion-related facilities, providing a valuable Case Study application, and to also contribute in this way to bridge the gap between research institutions and industry in fusion sector.

# 3

# Materials & Methods: workflow and tools for the Digital-Twin based development of RH facilities for fusion reactors

*This section presents the digital-twin based workflow for developing RH facilities, guiding the full lifecycle from design to operation.*

## 3.1 DIGITAL-TWIN BASED DESIGN WORKFLOW DRIVEN BY V-MODEL IN RFLP APPROACH

As mentioned, the proposed approach to the design of RH facilities for fusion reactors is centered around a comprehensive digital-twin of the facility and makes use of principles and tools of MBSE, such as the V-Model in RFLP approach, employing a PLM platform built around these paradigms.

The hallmark of a digital-twin based development process is storing all the data, models, and project information on the on-cloud server of the employed PLM platform as part of the Digital-TWin itself, from the earlier stages of Requirements Engineering (RE), to the last stages of operation and processes optimization or even decommissioning of the facility. Around this key principle, the V-model is deployed over all its stages.

The left side of the V-model is represented by the Specification Stream, namely the four phases of RFLP (Figure 3.1):

- ***R****equirements*: what the system should guarantee.
- ***F****unctional Analysis*: which functions the system must provide for.
- ***L****ogical Architecture*: high-level design of the system with identification of the subsystems and draft of the first Product Breakdown Structure (PBS).
- ***P****hysical Architecture*: high-level design of the subsystems.

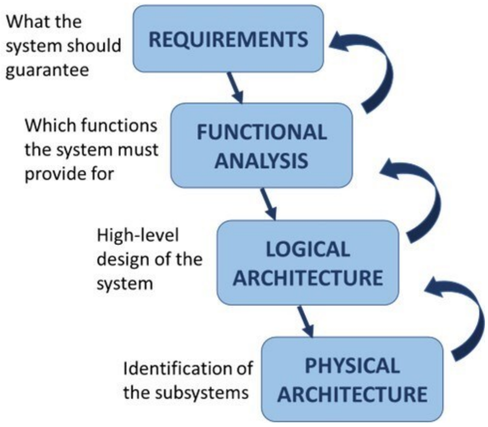


Figure 3.1: Specification Stream on the V-model left-wing: the RFLP paradigm

This process is first carried out for the entire facility. The requirements are directly elicited by the stakeholder fusion project (in the case study, DTT), and derives from some key aspects:

- The main objectives of the facility.
- The RH tasks and equipment to be tested, as well as those that are likely to be tested in future and affect modularity and re-configurability requirements.
- The control procedures and frameworks to be tested.
- The required level of alignment between the tested procedures and the future real ones.

Therefore, the main questions to drive the development of the facility should be: which procedures shall be tested? Which control operations shall be tested? How shall they be tested? How closely shall the test procedures reproduce the actual future operations?

Answering these questions allows to draft requirements models for the entire facility. Then, the functional analysis consists in translating the identified main requirements into functions the facility shall perform. On this basis, it is possible to draft a logical architecture for the facility by breaking it down in a limited number of key subsystems. At this step, it may be already possible to develop a first digital physical architecture for the facility. This means developing 3D CAD models for the identified subsystems, representing the graphical backbone of the facility's digital twin. These models will be constantly updated at each design progress and will be linked to simulation models during the Verification & Validation phase, and to on-site equipment (sensors, actuators, etc.) for real-time connection between physical equipment and digital-twin during the operation phase.

Once the RFLP paradigm has been applied for the entire RH facility, representing the main project system, and the logical architecture defining a first PBS with the subsystems has been established, the process is repeated at a lower level in the PBS and applied to the subsystems. This allows to define the requirements, functions and an architecture for each of the subsystems in which the RH facility has been divided in the previous stage. This approach is aligned with the principle of iterative design, with constant design detail and optimization, which underlies the V-model.

Once the functions and main components of each facility's subsystem have been determined, the digital-twin 3D CAD model can be detailed to represent a first concept design of the facility.

The process of integration and interfaces management among the facility's subsystems also starts at this point, benefiting from the help of the digital-twin 3D CAD model. This involves:

- Integrating in the digital twin on the PLM platform the different subsystems' models developed by the different stakeholders involved in the project.
- For each subsystem, determining internal interfaces and external interfaces, representing its physical boundary.
- Clearly specifying manufacturing requirements for external interfaces (position, tolerance, surface finish).

Once the first concept design has been developed, integrated and implemented in the digital twin on the PLM platform, a first stage of Verification & Validation must be carried out, in accordance with the principles of MBSE and V-model. To achieve this scope, the first simulation models (Finite Element Analysis models, kinematic & dynamic simulation models, etc.) are built within the PLM platform and linked to the digital twin 3D CAD models. At each update of the 3D CAD models, the simulation models can be easily and automatically updated to re-iterate the verification. This step allows to perform a preliminary Verification & Validation of the facility architecture and subsystems, to demonstrate the existence of at least a feasible solution for the project, before proceeding with the Engineering Design and Manufacturing.

All the process described so far could be managed within institutions, research centers, academies and engineering companies generally involved in fusion projects. However, once the Concept Design has been developed, it becomes necessary to include manufacturing companies in the project. Starting from the elicited requirements, represented by the Concept Design, which also demonstrates the feasibility of the project, the manufacturing companies must cover the Engineering Design and manufacturing of the facility's subsystems. The Engineering Design should be a development of the Concept Design, fulfilling the defined requirements and driven by manufacturing purposes, therefore Design For Manufacturing principles become relevant.

The manufacturing development of the facility's subsystems can be awarded to one or more companies, choosing between two alternative approaches:

- **Centralized approach**, in which a single manufacturing company covers the Engineering Design and Manufacturing of all the facility's subsystems through a single contract. It is more easy to be addressed in terms of interface management but may hinder the awarding process, as only large, financially solid, experienced and multi-disciplinary skilled companies may be able to participate to and be awarded the contract.Under this approach, companies may be more oriented to subcontract parts of the supply to other industrial partners more skilled on specific technologies. Therefore, with this approach the development of the facility's subsystem may still be assigned to different companies, but the main contractor company is in charge of their management and integration.
- **Distributed approach**, in which each facility subsystem is managed under a separate contract awarded to a different company. In this case, the challenging task of integration coordination and interface management is in charge of the RH facility design team. However, it allows to divide the delivery of the overall system into smaller supplies, thereby lowering the economic thresholds as well as the experience and skill diversity required for participation in the tender. Moreover, this approach enables each subsystem to be developed by companies with specific expertise in the assigned scope of work, while also fostering a broader network of com-

panies involved in the project. This aspect is particularly significant given the current relevance on increasing industrial involvement in fusion.

At this stage, facility design teams that have developed the Concept Design must prepare technical documentation for tenders, and, when these are awarded, follow-up the work carried out by the companies, ensuring that the requirements are fulfilled throughout the Engineering Design development and manufacturing process. During the preparation of the technical documentation for tender, is extremely important to clearly specify the engineering design requirements to be fulfilled by the company. The role of the Concept Design shall only be to provide the company with a proof of concept better clarifying the requirements and demonstrating feasibility of the project within the budget set for the tender. This approach leaves to the companies the freedom to adopt different design solutions, if they deem it appropriate and if compliant with the design requirements.

During design development by manufacturing companies, if a *distributed* approach is adopted and the facility's subsystems are engineered and manufactured by different companies, RH facility design teams shall also cover the integration and interface management among the subsystems and the companies involved. This is of primary importance to ensure companies properly understand which subsystems are included in their scope of work, avoiding overlays or uncovered components.

The RH facility design teams shall also manage the implementation in the digital twin of the models developed by the companies throughout the Engineering Design. Even in this case, two approaches are available:

- Involving the manufacturing companies members in the PLM platform, granting them proper accesses and authorizations. This approach is more efficient as the manufacturing companies can directly develop and update the digital twin models and simulations within the platform, and the follow-up and verification by the facility design teams is also streamlined. However, it requires manufacturing companies to have or develop specific skills on the usage of the PLM platform adopted by the project, an aspect which can slow down the design development process. In this case, RH facility design teams shall ensure proper authorizations are distributed among the manufacturing companies members involved, to avoid possible mistakes during their work on models stored on the same cloud. Moreover, they have to manage the integration of the updates made by the different stakeholders.
- Not including the manufacturing companies members in the PLM platform, leaving them freedom on the platform to be used for models and

simulations development. This approach is less efficient, as it requires the RH facility design teams to constantly upload and integrate in the PLM platform the models developed by the companies from several different software. However, it may be easier and seamless from the companies' perspective, which can keep employing their preferred software.

As mentioned before, the V-model is executed again for each subsystem for its Engineering Design by manufacturing companies.

Therefore, each manufacturing company has to:

1. Understand the engineering requirements related to the supply.
2. Implement the requirements to obtain the own set of requirements valid for Engineering Design and manufacturing.
3. Further decompose the logical and physical architecture of the awarded supply, if necessary.
4. Cooperate with RH facility design teams for implementation of the developed models in the facility's digital twin and integration with the models developed as part of the other supplies.
5. Verify & Validate the developed Engineering Design for the Manufacturing Readiness Review (MRR) executed by the RH Facility customer design teams. This step shall be carefully reviewed by the facility design teams, and repeated if necessary. If the chosen approach allows the companies to use their preferred software to perform simulations for verification, parallel simulations performed by RH facility design team employing the adopted PLM platform's embedded tools may also be useful to store in the PLM platform Verification & Validation models linked to the digital twin.

Once the Engineering Design has been verified and approved by the RH facility design teams, the companies can proceed with the manufacturing phase. As part of the Verification & Validation process, it is fundamental to include phases of Factory Acceptance Tests (FAT) and Site Acceptance Tests (SAT). The first are the validation tests to be executed on the manufactured equipment at the manufacturer factory, while the second are the validation tests to be executed at the delivery site, that is the RH facility. The RH facility design teams shall be clearly specify the tests to be executed and their requirements in the tender technical documentation. For each RH facility's subsystem, the design teams shall also propose an assembly strategy and specify the logistic requirements for packing, transport and delivery to the site.

The SAT phase marks the transition from the Design & Manufacturing phases to the operational phase of the facility. The on-site commissioning and acceptance tests of the manufactured RH equipment can be considered the first steps

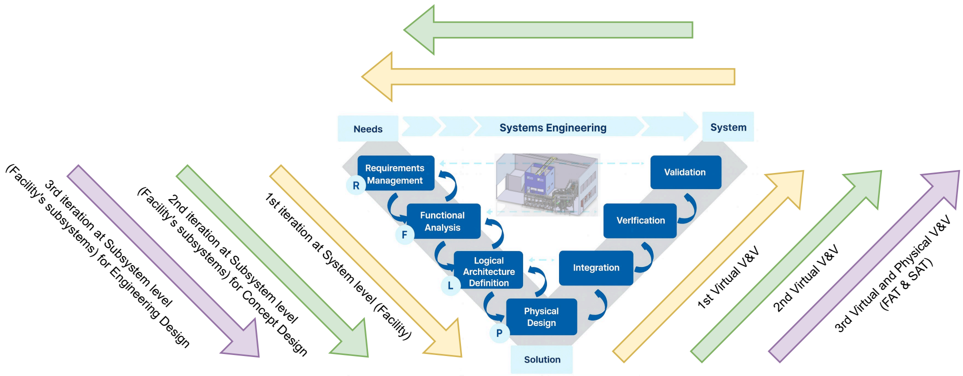


Figure 3.2: Iterative application of the V-model embedding the RFLP paradigm and centered around the digital twin for development of Architectural, Concept and Engineering design of RH facilities

of the operative life of the facility. These stages shall be conducted in cooperation between manufacturing companies and RH facility design teams. The firsts are in charge of planning and performing the SAT in alignment with the tender technical specifications, the second shall verify the fulfillment of the requirements and the correct execution of the SAT. After positive results of FAT and SAT, and commissioning of all RH hardware and software systems, the supply can be accepted and the contract closed.

In Figure 3.2, a diagram shows the iterative application of the V-model embedding the RFLP paradigm for RH facility design and verification at system level for preliminary architecture design first, then at subsystem level for concept design, and finally at subsystem level as well but for engineering design.

During the on-site commissioning and acceptance test phase, the RH facility design teams shall update the digital twin models by implementing the *as-built* models, which reflect the equipment configuration as is after manufacturing. Moreover, the digital-twin as-built models shall be calibrated to align with the real physical equipment. This is a fundamental step to ensure perfect correspondence between the digital twin and the physical counterpart during operation, enabling reliable real-time equipment rendering, monitoring and teleoperation. To guarantee that the digital-twin models properly match the physical ones, dynamic effects occurring during operations and deviating the real equipment from the nominal design of the digital-twin models shall be considered. These are, for instance, flexibility of robot links or compliance internal to robot joints. A strategy to compensate these effects to recover the nominal design configuration may also be developed. These steps are also important during the trajectory planning process, in which digital-twin Virtual Reality models are employed and shall properly match the real ones, to ensure that the configuration assumed by the robot with respect to the surrounding space in VR environment mirrors the real behavior.

## 3.2 PLM PLATFORM EMPLOYED FOR THE CASE STUDY: 3DEXPERIENCE

In the presented case study, the PLM platform employed to manage the digital twin of the facility is the 3DEXPERIENCE platform, developed by Dassault Systèmes. However, the approach, framework, methods and principles herein adopted and defended are applicable through any kind of similar PLM platform. The present research does not in any way intend to promote the products related to the 3DEXPERIENCE platform or Dassault Systèmes, nor to undermine their image.

3DEXPERIENCE has been selected as PLM platform for the digital-twin based development and management of the DTT RH Facility for two main reasons:

- It is one of the most advanced and comprehensive PLM platforms available on the market, with wide application in the industrial sector and specific application cases even in fusion sector [117].

- It has been recently adopted by the entire DTT project for its CAD Configuration Management process. This makes 3DEXPERIENCE the most suitable PLM platform among the most developed and employed in the industrial field. In fact, first of all DTT RH Facility design team members may have already acquired expertise using the platform from previous usage for DTT activities. Then, permissions and accesses can be easily managed among design teams of both DTT and DTT RH Facility project. Last but not least, on-cloud stored digital twin models can easily be shared between the DTT and DTT RH Facility project over the platform, without the need of time-wasting and information-loss-prone process of download/upload and files exchange. This aspect is of fundamental importance given that the integration of the RH equipment into the design process of all the tokamak machine is imperative, as even a minor modification to the RH equipment design can have a significant impact on the entire tokamak design and operation (and vice-versa), and can cause a strong time and money-consuming redesign process. Moreover, the possibility to cooperate and share design information over the same cloud-based platform is especially important for DTT and DTT RH Facility design teams, which involve several geographically spread institutions.

This aspect can be extended to any other application, not only to the case study of the present thesis. In fact, the project of a RH Facility would likely begin when the development of the stakeholder fusion project is already at an advanced stage, meaning that the PLM platform for development, management and operation of the RH Facility project should align to the one employed by the stakeholder fusion project, if employed. This would allow for easier, quicker, and more efficient digital-twin data and models interface, management, and sharing between the main fusion project and its RH Facility project.

Developed by Dassault Systemes as successor of CATIA V5, 3DEXPERIENCE is intended to make a step beyond and qualify as not only CAD modeling and simulation platform, but as a multi-user, collaborative, cloud-based PLM platform providing users with a unified environment for design and management of products, services, activities and entire facilities. Coherently with CBDM approach, the 3DEXPERIENCE cloud-based environment allows for connection of multi-disciplinary and geographically spread project members. Companies, academic institutes and research centres can be equipped with a dedicated space over the platform for storage of all related data, called *Tenant*. Then, these space can be divided in subspaces, called *Collaborative Space*, for subdivision of on-cloud objects among the different projects or activities. These spaces can be accessed from every kind of workstation equipped with network connection, as well as from mobile platforms.

The 3DEXPERIENCE platform is built upon the V-model in RFLP approach [128], integrating within a unified environment the tools required to manage the entire product design process. These tools are provided as a comprehensive suite of embedded applications, replacing the traditional notion of standalone software, each designed to occupy a specific role in the V-modelbased design workflow. The applications are organized into *Web Apps*, accessible from any browser and primarily dedicated to product and resource management, and *Native Apps*, which require local installation and are mainly devoted to design activities (CAx applications). Figure 3.3 shows some of the applications provided by the 3DEXPERIENCE platform to cover the whole V-model-based lifecycle development of a robotic system. The applications that features in their icon a small arrow in the top-right box are *Web Apps*, accesible from any browser, while the others are *Native Apps*, accessible through the software locally installed on-client.

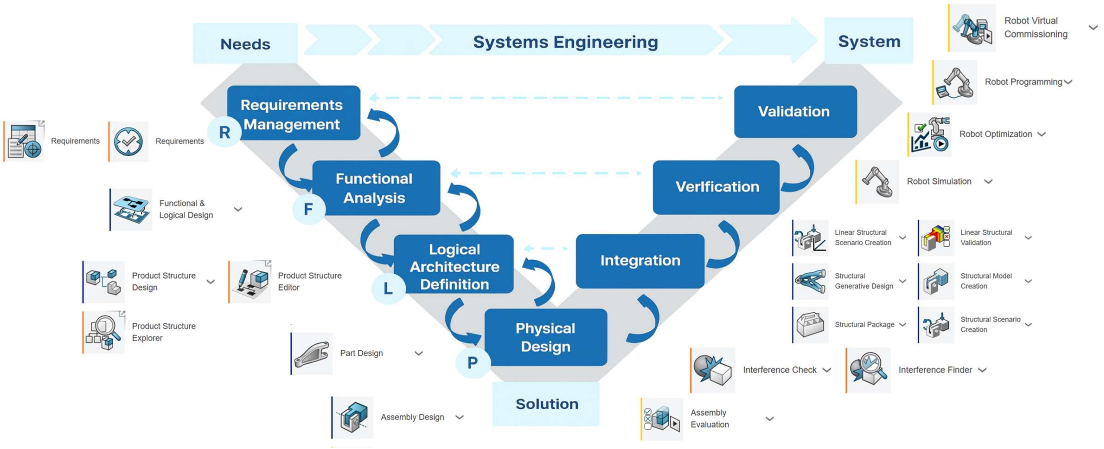


Figure 3.3: 3DEXPERIENCE applications to cover the V-model-based full lifecycle development of robotic systems and facilities

This framework eliminates the need for complex integrations of models developed across heterogeneous software environments and the repeated transfer of data and files, replacing them with a fully automated, model-based, cloud-enabled approach [86, 129]. All items produced during the various stages of the design process, such as documents, CAx models, and simulations, are stored in the cloud as *objects*. Each object can be associated with the digital twin of the product, which itself is represented as an object. In this way, the concept of *object* supersedes that of *file*, and cloud-based storage ensures that designers always work on the most updated version of each item, without the need for external file exchanges and with reduced risk of data loss. Furthermore, this structure enables the automatic propagation of design changes across all related models and results, thereby facilitating the creation of an automated and consistently updated design cycle.

The 3DEXPERIENCE platform is now spreading both in the industrial sector and in the academic and research one, with application in several areas as Transportation & Mobility, Aerospace & Defense, Marine & Offshore, Industrial Equipment, High Tech, Home & Lifestyle, Energy, Constructions, Cities & Public Services and Business Services.

In the next sections, the RFLP stages representing the *Specification Stream* at the left side of the V-model are discussed and applied to the case study of the DTT RH Facility. Each stage is managed through the dedicated apps provided by the adopted PLM platform, in the present case 3DEXPERIENCE (with the apps shown in Figure 3.3.

# 4

# Digital-Twin based design and manufacturing of RH facilities: a Case Study on the DTT RH Facility.

*The present section provides a more detailed description of the proposed digital-twin based workflow for development of RH facilities for fusion reactors, with particular reference to the phases of design development and manufacturing. The remaining phase of facility's operation and the related concerns will be described in next Section 5. The workflow is detailed and applied to the DTT RH Facility case study, employing 3DEXPERIENCE as PLM platform.*

## 4.1 ARCHITECTURAL DESIGN OF RH FACILITIES: FIRST APPLICATION OF THE RFLP APPROACH WITHIN THE V-MODEL

As introduced in previous sections, the digital-twin based development of the RH facility is carried out following MBSE's principles and tools, such as the V-model in RFLP approach. Therefore, after the identification of the adopted PLM platform, in the present case 3DEXPERIENCE, the first stages are those part of the Specification Stream placed at the left side of the V-model, represented by the RFLP (Requirements - Functional analysis - Logical architecture - Physical architecture) paradigm.

### 4.1.1 R-Step of RFLP: Requirements Engineering

The first stage is the Requirements analysis, or even Requirements Engineering (RE), fundamental to clarify what the facility shall fulfill and properly set all the next stages. As already mentioned, the facility's requirements are directly elicited from the main objectives of the facility itself, from the stakeholder requirements and the level of accuracy to be achieved during the test procedures. The main objectives of the Case-Study DTT RH Facility are those presented in Section 1.4.3, while the stakeholder requirements are set by the DTT project. They depend on the RH procedures, test setups, and control frameworks to be tested in the facility to provide the required support for the development of the commissioning DTT project [40].

The requirements are first drafted in a table for the entire facility. The requirements are then uploaded and managed through MagicDraw, the dedicated SysML/MBSE modeling engine embedded into 3DEXPERIENCE platform to ensure that requirements and system architecture are coherently managed alongside CAD, CAE, and PLM data.

The integration between MagicDraw and the 3DEXPERIENCE platform reflects Dassault Systèmes strategy of embedding Model-Based Systems Engineering (MBSE) within a broader Product Lifecycle Management (PLM) framework. Magic now constitutes the SysML-based modeling core of the 3DEXPERIENCE platform. Within this role, Magic provides the semantic system model used for requirements definition, architecture modeling, and behavioral simulation, which can be directly connected to the product data, CAD/CAE models, and enterprise processes managed in 3DEXPERIENCE. The combination of these tools enables full digital continuity: requirements and system models created in Magic can be traced to design and verification data stored in the platform, ensuring consistency across the lifecycle. This integration not only strengthens collaboration among multidisciplinary teams but also supports the construction and governance of digital twins by linking conceptual system architectures to detailed engineering and operational data. In this sense, Magic acts as the MBSE enabler of the 3DEXPERIENCE platform, complementing its PLM and simulation capabilities and moving beyond document-centric practices towards integrated and traceable system development [130] Requirements can be directly modeled and represented using SysML constructs, enabling a structured definition of system needs. The tool supports full traceability by allowing requirements to be linked with system functions, architecture, behaviors, and test cases, thus facilitating impact analysis in case of modifications. This integration ensures consistency between requirements and design artifacts, enhancing the reliability of the development process. In Magic, each requirement is created as SysML requirement element and linked to the corresponding system block through a *satisfy* relationship. The same requirement may also be connected to a test case specifying the load verification procedure via a *verify* relationship. By maintaining these connections, the tool enables to assess whether the system architecture and verification activities remain aligned with the specified requirements, and to immediately identify the ripple effects of any changes.

Starting from the global missions of the DTT RH Facility (stated in Section 1.4.3) and employing the Magic tools, a Black Box Analysis has been performed, providing as output the Facility's high level requirements diagram. This diagram serves as input for the next phase of functional modeling to ensure that the main functionalities of the Facility are constantly taken into account during the next design development stages. The requirements are divided by category and herein reported in Table 4.1:

### 4.1.2 F-Step of RFLP: Functional analysis

Moving to the next step in the V-model's Specification Stream, a *Functional analysis*, F-step of the RFLP paradigm, is carried out, highlighting the main functions the facility must provide for. They are directly derived from the facilitys requirements and are herein reported in Table 4.2. Traceability through establishment of relationships between Requirement and Functional domains is crucial to obtain a consistent system design.

Within Magic tool, requirements are translated in and linked to functions, creating functional block models enriching the digital twin.

### 4.1.3 L-Step of RFLP: from WBS and Digital Maintenance Manual to PBS and Logical architecture of the facility

Once the functions have been determined, tabled, and modeled, the next step in the digital-twin based development of the RH facility is the drafting of

Table 4.1: Main requirements of the DTT RH Facility

| Category | ID | Requirement |
|---|---|---|
| Functional | RF_01 | The DTT RH Facility facility shall make available to operators knowledge, instructions and experiencing of RH equipment functionalities and main maintenance issues, of control system devices (i.e., controllers and HMI) to be used for the Hall operations, of VV structure, modules and access ports/ducts, of the RH system installation and removal procedures. |
| | RF_02 | The DTT RH Facility shall replicate as closely as possible all the RH-relevant functionalities, operations and physical characteristics of the DTT RH systems to be tested. |
| | RF_03 | The DTT RH Facility shall be able to emulate motion capabilities and operations of any subsystem to be tested, independently from the foreseen task and missions. |
| | RF_04 | The DTT RH Facility shall be able to set-up several contingency situations. |
| | RF_05 | The DTT RH Facility must be able to conduct acceptance testing for new RH practices, tools, and equipment that could be developed over the machine's life. |
| Environmental | RE_01 | The environment of the The DTT RH Facility shall be compliant with the one defined for the DTT hall and in any case compliant to the national standards (EU directive) on safety and health at work. |
| Operational | RO_01 | The DTT RH Facility shall be operated outside the Hall. |
| | RO_02 | One training session at a time (of any type) shall be executed using all the required equipment. |
| | RO_03 | The DTT RH Facility shall be available in both switch on and switch off periods and for the entire lifetime of the DTT facility. |
| | RO_04 | The DTT RH Facility shall enable the implementation of digital-twin and control system models able to comprehensively reconstruct the environment, systems and operations |
| Human Factor | RH_01 | Any device and graphics used for environment virtualization shall allow an optimal virtual experience. |
| | RH_02 | Any HMI (Human Machine Interface) has to be designed according to usability and ergonomic standards and rules. |
| Design | RD_01 | Any 3D model for VR use shall be worked starting from the available CAD models of the RH system. |
| Verification | RV_01 | Any model used in the VR environment shall be verified vs real objects for all the implemented issues (e.g. geometric, encumbrances, dynamics, stiffness, etc...). |
| Physical | RP_01 | The DTT RH Facility shall use a 1:1 mock-up of a section of the VV and involved ducts, pipes, ports and internal modules to be handled (Divertor Cassettes, First Wall modules, etc.), including at least two RH accesses. |
| | RP_02 | The DTT RH Facility shall implement the real robots of the DTT facility to test the RH procedures. |

Table 4.2: Main functions of the DTT RH Facility

| Category | ID | Function |
|---|---|---|
| Functional | FF_01 | The DTT RH Facility facility will be based on a dedicated Control Room featuring all the necessary equipment for visualization and interaction between Human Operators (HOs) and robots. The Digital-Twin CAD models and the implementation of VR technologies will allow the HOs to experience the environment in off-line mode, i.e. even without connection to the real equipment, familiarizing with the RH equipment, with the main maintenance issues and procedures, the control system devices, the VV structures and in-vessel components design. |
| | FF_02 | The DTT RH Facility will host an in-scale reproduction of the DTT Tokamak's environment made of mock-ups and real robots, in order to test all the DTT RH operations and procedures. |
| | FF_03 | The DTT RH Facility will be designed to also test rescue operations and be adaptable for the study and testing of new procedures and operative situations. |
| | FF_04 | The DTT RH Facility will guarantee the possibility, in terms of available space and services, to implement new RH equipment for the testing of new RH procedures, which could be developed during the machine's lifetime. |
| Operational | FO_01 | A dedicated space in the The DTT RH Facility building area will be left for the Control Room, such to carry out the operations and the training of the operators outside the Hall. |
| | FO_02 | The DTT RH Facility facility will be a completely separated facility from DTT, realized in a different geographic area; this means that it will be available to operate during the whole lifetime of the DTT facility and even in future, for the test and training of the RH operations related to other nuclear reactors. |
| Human Factor | FH_01 | The Control Room will be based on a well-designed communication and data-exchange system, able to guarantee the required refresh rate, with the lowest possible latency. Specific studies will be conducted to also represent in the virtual environment the flexibility of the robotic equipment, with the aim of taking in account its effects during the execution of the tasks. |
| | FH_02 | Each HO will be provided with a well-equipped work-station, whose usability will be guaranteed by a modular Human Machine Interface (HMI), customizable according to the needs and the role of the user. |
| Verification | FV_01 | Digital Twin's CAD models of the real systems will follow their exact characteristics in terms of geometric encumbrance, stiffness, weight, features. |

| Category | ID | Function |
|---|---|---|
| Physical | FP_01 | The DTT RH Facility will be characterized by a physical reproduction of a portion of the DTT Tokamak, made of in-scale mock-ups. |
| | FP_02 | The robotic equipment operating in the DTT RH Facility will be the same designed for the RH of DTT, which will first be tested in the RH facility and then sent to DTT site for actual operation. |

a Logical architecture, L-step of the RFLP representing the Specification Stream of the V-model. This allows to obtain a first Product Breakdown Structure (PBS) for the facility.

The Product Breakdown Structure (PBS) is a hierarchical decomposition of a product, in this case of a facility, into its constituent elements, ranging from the complete system to progressively smaller subsystems, assemblies, and components. Its purpose is to provide a clear and systematic representation of the product architecture, supporting the allocation of requirements to physical elements and serving as a reference for design, procurement, manufacturing, and verification activities. Unlike the Work Breakdown Structure (WBS), which focuses on the tasks and processes needed to deliver a system, the PBS is strictly product-oriented, answering the question What is the system made of? rather than What work must be performed?. In Systems Engineering practice, the PBS is closely integrated with requirements models and functional architectures, ensuring that each system function is mapped to a corresponding physical realization [131]. This linkage is fundamental in model-based approaches, where tools such as SysML can represent PBS hierarchies through Block Definition Diagrams, enabling full traceability between requirements, design, and verification [132]. A Block Definition Diagram has been created for the Case Study of the DTT RH Facility. The functions have been created as value properties inside blocks. Those blocks define the systems inside the RH Facility. With the requirements on one side and the value properties of the blocks on the other, the creation of an allocation matrix has ensured a precise allocation of requirements to the proper value properties (functions) and thus to the block representing the system. The use of the allocation matrix ensures that no requirement has been left unallocated.

From the functional block analysis a very first logical architecture and PBS can already be drafted. Therefore, the DTT RH Facility system is broke down into the following main subsystems:

- Building & Services: the set of buildings and plant services necessary to perform the facility's functions and achieve the facility's requirements.
- Mock-ups: the set of mechanical prototype structures reproducing the real environment internal to DTT and representing the robots' surrounding working space for reliable testing of RH procedures.
- Robots: the set of RH equipment to be tested, accepted and commissioned in the facility, that allow to test the required RH procedures. In the case of the DTT RH Facility, these are the real DTT robots and not ad-hoc prototypes, unlike the approach adopted in other similar facilities. The DTT robots shall be first tested in the DTT RH Facility and then transported to DTT site for actual operations.
- Control System: the set of hardware and software equipment enabling proper real-time teleoperation, management and supervision of robotic procedures.

However, to draft a more complete PBS and provide a more robust answer to the question "What is the system made of?", it is indispensable to draft a WBS, that in this case is the list of procedures that have to be performed and tested in the facility, answering the question "What work must be performed?".

The analysis of the RH procedures to be tested in the facility allows to further decompose each subsystem and obtain a more robust PBS, determining all the logical blocks in terms of Buildings & Services, Mock-ups, Robots and Control systems necessary to perform the required test procedures.

The RH procedures to be tested in the facility are part or all the procedures planned for the stakeholder fusion reactor, and are stored in its Maintenance Management Plan (MMP), whose validation and optimization is one of the key objectives of the facility.

Three levels of maintenance management specification can be distinguished. At the highest level, the Maintenance Management Plan (MMP) establishes the overall strategy and philosophy of maintenance, defining objectives, responsibilities, scheduling policies and the interface with operations and safety management. At a lower level and building on this framework, the Maintenance Manual (MM) provides a system-oriented compilation of all technical instructions required to apply the strategy in practice, including preventive and corrective tasks, tooling requirements, spare parts and safety constraints. At the most detailed level, the Operations Sequence Descriptions (OSDs) within the MM specify the ordered steps (with preconditions and postconditions) of individual maintenance tasks, ensuring that operators and RH systems can perform each action in a safe and controlled manner. Each OSD is a building block used by the Maintenance Manual, which contains or points to the OSDs for step-by-step instructions. The MM may contain dozens or hundreds of OSDs depending on system complexity. In this way, the MMP defines what must be achieved, the Maintenance Manual translates this into how it must be organized, and the OSDs detail how it must be executed in practice.

In particular, the RH Maintenance Manual in a fusion power plant allows to:

- Define and describe RH systems/components, required tools and spare parts.
- List and describe preventive and corrective maintenance tasks.
- Specify safety preacutions and environmental conditions.
- Point to OSDs for specific operations' instructions for operators.
- Support the design of the whole plant acting as an interface document between RHS and the related plant systems.

A Maintenance Manual is hence a document which has a fundamental role not only during the operation of a fusion facility, but also during the design of the components included in or interfacing the RH system. Therefore, it should be an alive document, easy to be updated and optimized. Moreover, representing an interface documents for surrounding systems, it shall be distributed to and consulted by many multidisciplinary engineers and physicists cooperating to the project. For these reasons, the use of Digital Maintenance Manual is highly recommended instead of paper documentation. A Digital Maintenance Manual is more considerable as a model than as a document. In a digital-twin based development of RH facilities and systems, a Digital Maintenance Manual represent a set of alive, easy-to-be-updated models, that can be linked to the other related models of the digital twin, such as CAD/CAE models. For instance, the Digital Maintenance Manual can be linked to kinematic simulations to have a graphical representation of the actions to be executed. Since it is stored in the on-cloud PLM platform selected for the project, as any other digital-twin model, it can be easily accessed and consulted by any authorized project contributor, from any device (also portable device, if the platform allows it, as the 3DEXPERIENCE does). Moreover, it can be embedded in the Control System, representing a single manual able to be read by both human operators and machines, with no duplication. In fact, its inherently interactive nature, with the linkage to CAD/CAE models, means that it can be connected to the HMI at disposal of each teleoperator to:

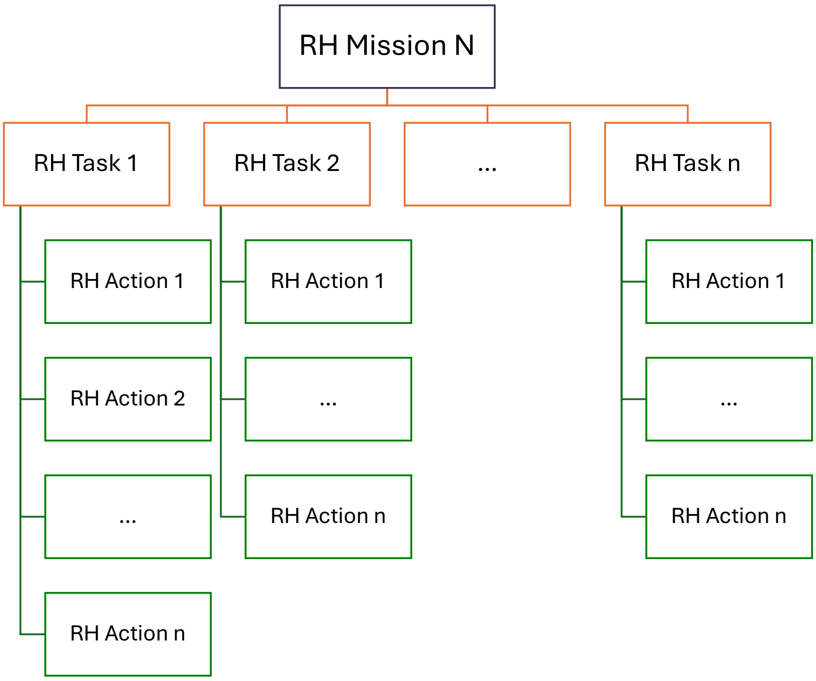


Figure 4.1: Hierarchical structure of an Operation Sequence Description (OSD) document/model

- Display Virtual and Augmented Reality images for more comprehensive visual instructions, as well as any required multimedia information.
- Be controlled by the operator (for instance, the instructions of a task appear only when the operator confirms the correct completion of the previous task).
- Provide the operator with information about the current state of the process. In particular, if real-time connection between digital-twin models and real equipment is enabled, process' states can automatically be updated through the reading of on-site equipment sensors.

Going into the details of the Maintenance Manual, the OSDs hierarchically decompose the RH Procedures (or Missions), in RH Tasks and, in turn, these in RH Actions,as depicted in Figure 4.1. The analysis of each RH Action allows to map:

- The plant components to be maintained, inspected and calibrated.
- The other plant components affected by each RH procedure.
- The tokamak and plants area involved in and to be available for RH procedures.

In the digital-twin development of the RH facility, the Digital Maintenance Manual is fundamental both in the design phase and in the operational phase of the facility lifecycle:

- In the design phase, OSDs within the Digital Maintenance Manual allow to map the procedures to be tested and, in turn, the robots, mock-ups, buildings and services that the facility must feature. In other words, it allows to further breaking down the preliminary PBS previously presented, providing a more robust and branched Logical architecture for the entire facility.
- In the operational phase, the Digital Maintenance Manual assists the operator both in the off-line training process (without connection to the real equipment) and during the on-line test procedures (teleoperating the real equipment).

Therefore, as said, the Logical architecture of the facility is branched through the analysis of the OSDs within the Maintenance Manual and the mapping of the subsystems required to each RH Mission, Task and Action to be tested in the Facility.

Some of the DTT RH Missions have been identified as the most important and enough developed to be tested in the RH Facility. These allow to obtain the WBS of the DTT RH Facility, from which an excerpt is shown below, up to its 2nd-level (RH Tasks level):

- Mission 1 (M1): First Wall (FW) RH
  - M1 - Task 1 (M1-T1): Outer First Wall (OFW) Module #1 Installation
  - M1 - Task 2 (M1-T2): OFW Module #1 Removal
  - M1 - Task 3 (M1-T3): OFW Module #2 Installation
  - M1 - Task 4 (M1-T4): OFW Module #2 Removal
  - M1 - Task 5 (M1-T5): OFW Module #3 Installation
  - M1 - Task 6 (M1-T6): OFW Module #3 Removal
  - M1 - Task 7 (M1-T7): OFW Module #4 Installation
  - M1 - Task 8 (M1-T8): OFW Module #4 Removal
  - M1 - Task 9 (M1-T9): OFW Module #5 Installation
  - M1 - Task 10 (M1-T10): OFW Module #5 Removal
  - M1 - Task 11 (M1-T11): Inner First Wall (IFW) Limiter Module Installation
  - M1 - Task 12 (M1-T12): IFW Limiter Module Removal
  - M1 - Task 13 (M1-T13): IFW Standard Module Installation
  - M1 - Task 14 (M1-T14): IFW Standard Module Removal

  - M1 - Task 15 (M1-T15): Top First Wall (TFW) Module #1 Installation
  - M1 - Task 16 (M1-T16): TFW Module #2 Removal

- Mission 2 (M2): Divertor (DIV) RH
  - M2 - Task 1 (M2-T1): DIV Central Cassette (CC) Installation
  - M2 - Task 2 (M2-T2): DIV CC Removal
  - M2 - Task 3 (M2-T3): DIV Second Cassette (SC) Installation
  - M2 - Task 4 (M2-T4): DIV SC Removal
  - M2 - Upgrade Task 5 (M2-UT5): DIV Standard Cassette (StC) Installation
  - M2 - Upgrade Task 6 (M2-UT6): DIV StC Removal

The Upgrade Tasks are the RH Tasks which shall be tested in a second phase of the facility service life, after a future upgrade. Therefore, the facility shall allow their testing or shall be reconfigurable to test them in future.

In next Table 4.3, the RH Task M2-T1 of Central Cassette installation, within the RH Mission of Divertor handling, is analyzed as an example, allowing to determine the related Mock-up and Robot systems required. Iterating this process to each RH Task, a more detailed logical architecture for the facility can be obtained, representing its first completed PBS, to be further constantly expanded along the design development. It is represented in Figure 4.2.

Table 4.3: Operational Tasks and Requirements for CC Installation

| RH Mission | RH Task | Action No. | Operation | Required Mock-Ups | Required Robots |
|---|---|---|---|---|---|
| Divertor Handling | CC installation | 0 | Environment configuration | VV with interfaces<br>Placeholders: SC Cooling Pipes, CC Cooling Pipes support, DIV Coils, SC-J, SC-r, FW | CMM |
| Divertor Handling | CC installation | 1 | CMM is placed on out-vessel Radial Rails (RR) support frame | Radial Rails out-vessel support structure | Trolley for CMM movement |
| Divertor Handling | CC installation | 2 | CMM grabs CC+DR from a storage location near RR support frame | CC + DR<br>storage location near RR support frame | CMM |
| Divertor Handling | CC installation | 3 | CMM with CC+DR autonomously moves on RR | Bridge for testing of CMM transit from cask/RR support frame to duct<br>Bridge actuation system | CMM |
| Divertor Handling | CC installation | 4 | CMM positions CC in the correct place to be then preloaded (CMM still grabbing CC) | Duct with RR | CMM |
| Divertor Handling | CC installation | 5 | CMM Preloading Unit locks to the duct by means of locking pins | Surrounding components: see operation 0 | CMM Preloading Unit for CC, equipped with limit switch |
| Divertor Handling | CC installation | 6 | CMM Preloading Unit pushes CC inward up to correct insertion of Nose in the corresponding inner-rail slot | Duct interface with CMM Preloading Unit | CMM Preloading Unit |
| Divertor Handling | CC installation | 7 | CMM Manipulator (or equivalent) actuates Dummy Rail locking pins | VV interface to Divertor (Divertor Toroidal Rails)<br>Divertor Interfaces to VV (Nose) | CMM Manipulator or equivalent |
| Divertor Handling | CC installation | 8 | CMM releases CC | Dummy Rail pins limit switch | CMM |
| Divertor Handling | CC installation | 9 | CMM leaves the VV Mock-Up through the duct | Dummy Rail interfaces with CMM Manipulator or equivalent | CMM |

The children blocks of the *Control System* depend on the types of control frameworks and procedures to be tested as also specified in the facility's requirements, rather than on the analysis of the OSDs within the Maintenance Manual. In the case of the DTT RH Facility, the Control System and Control

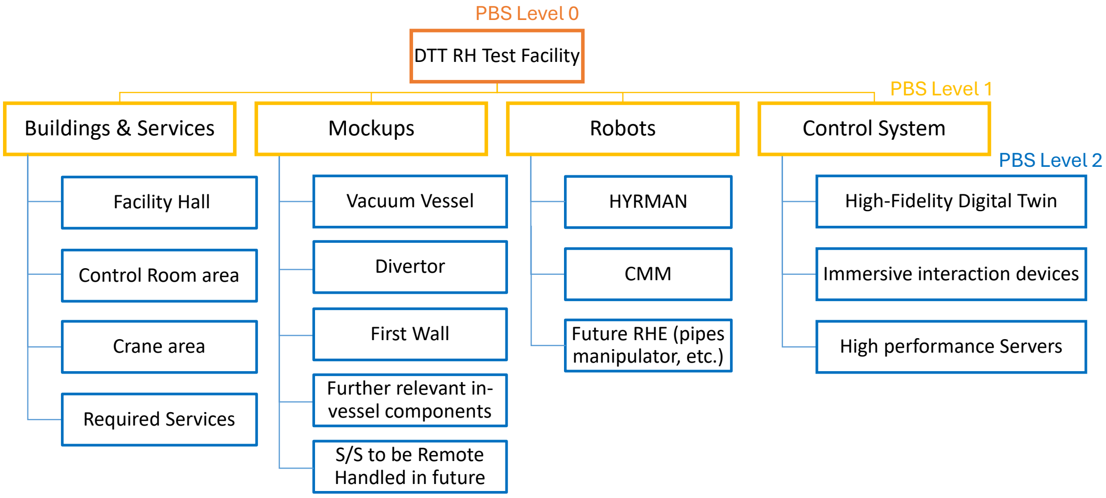


Figure 4.2: Logical architecture of the DTT RH Facility, representing the first version of its Product Breakdown Structure (PBS)

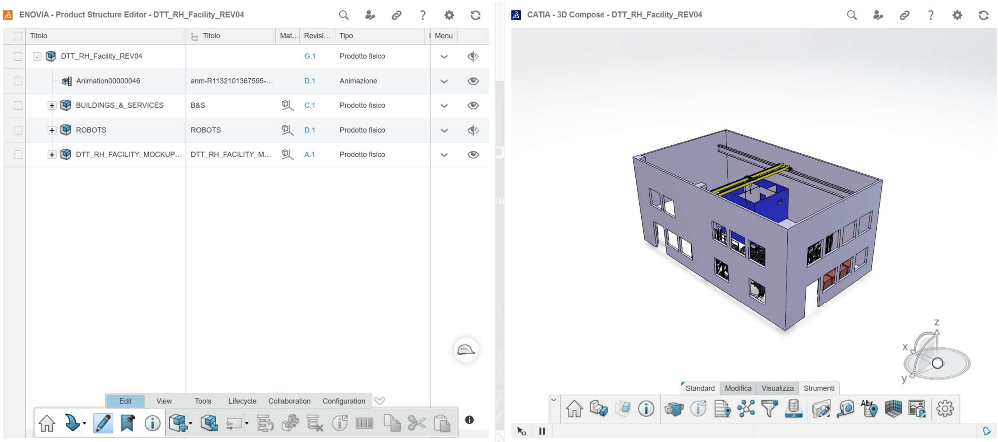
Room shall feature the same hardware & software components, set-up and functionalities of the future DTT RH Control System and Control Room, except for the interface with the central Control, Data Access and Communication (CODAC) system, as also evidenced by the facility's requirements listed in Table 4.1.

The logical architecture is then implemented in the digital twin on the PLM platform. In 3DEXPERIENCE, the on-cloud app *Product Structure Editor* can be used to build the PBS. Empty objects can be created in a hierarchical structure, to be populated with CAD or any other type of model in a later moment. The on-cloud based nature of the *Product Structure Editor* app allows users to access, check and edit the PBS easily and quickly from everywhere and from any device with network connection (Figure 4.3). The PBS will be constantly updated, populated and branched as the design develops.

### 4.1.4 P-Step of RFLP: Physical Architecture

The drafted Logical architecture is then materialized and visual represented in a Physical architecture, as P-Step of the RFLP paradigm. The empty logical blocks of the digital twin PBS begin to be populated with 3D CAD models, data and annex documents.

The main goal of this phase is to assess the space required by each subsystem, which allow to define the area where the facility will be built, as well as its



| Titolo | Titolo | Mat... | Revisi... | Tipo |
|---|---|---|---|---|
| DTT_RH_Facility_REV04 | | | G.1 | Prodotto fisico |
| Animation00000046 | anm-R1132101367595-... | | D.1 | Animazione |
| BUILDINGS_&_SERVICES | B&S | | C.1 | Prodotto fisico |
| ROBOTS | ROBOTS | | D.1 | Prodotto fisico |
| DTT_RH_FACILITY_MOCKUP... | DTT_RH_FACILITY_M... | | A.1 | Prodotto fisico |

Figure 4.3: DTT RH Facility Product Breakdown Structure managed over 3DEXPERIENCE's *Product Structure Editor* on-cloud app

layout, with the support of 2D and 3D CAD modeling tools. For instance, 3DEXPERIENCE platform offers dedicated on-client applications for that scope, such as *Plant Layout Design*, that allows to define the 2D and 3D layout of the facility, allocate resources, reserve space for stock materials and spare parts.

The assessment of the encumbrance of each subsystem derives from the analysis of the facility's requirements, functions and procedures to be tested. For instance, Requirement #RO_01 of Table 4.1 specifies the need of a building or room separate from the facility Hall to host the Control Room. Or even, Requirement #RP_01 specifies the need to "use a 1:1 mock-up of a section of the VV (...), including at least two RH accesses". This means that the Mock-ups subsystem shall reproduce at least 5 sectors (100 degrees) of the real DTT tokamak, where each RH sector is placed every 5 sectors (Sectors #1, #5, #10, #15). This is necessary to ensure reliable test of the RH procedures (Missions) of FW installation & removal in each machine's sector.

Following this process, it is possible to identify the available building to host the facility, or design a new one, and define its layout and necessary plants and services to integrate all the necessary equipment. For the DTT RH Facility, the proper hosting building has been identified within the University of Naples Federico II facilites, also due to its involvement in the DTT project and to the closeness to the ENEA Research Centre of Portici. The building features a Hall and a separate internal pre-fabricated building, identified to host the separated Control Room, in compliance with the requirements. The Hall provides enough space to host:

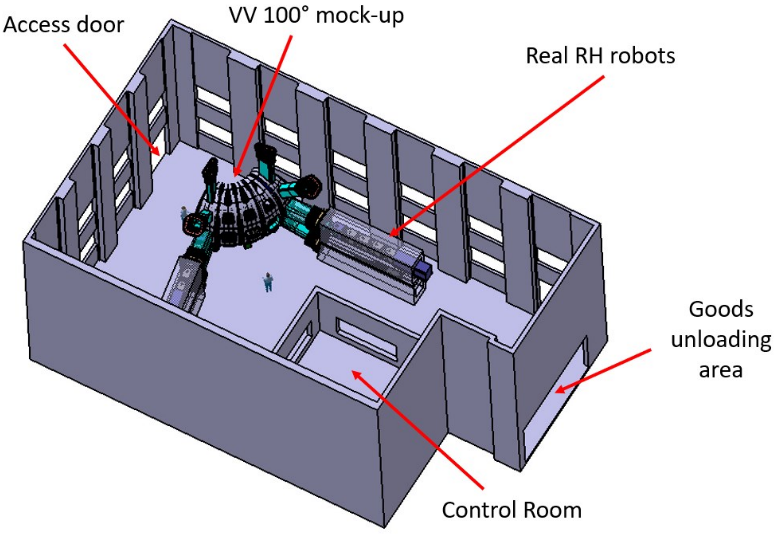


Figure 4.4: First physical architecture of the DTT RH Facility

- An in-scale mock-up of a 100 degrees sector of the DTT Vacuum Vessel (VV) and internal systems.
- Two RH accesses at the end sectors, each equipped with Equatorial Port #3 and Lower Lateral Port #4.
- Spare parts.
- Control cabinets.

The assessment of the compliance of available spaces with required equipment is supported by 3D CAD tools, that allow to model the first virtual physical architecture of the facility, representing the first 3D CAD digital twin model of the facility. 3DEXPERIENCE platform offers on-client apps for 3D modeling (*Assembly Design* and *Part Design*, for assembly and part objects respectively). The 3D CAD model representing the first physical architecture of the DTT RH Facility is represented in Figure 4.4.

The model features:

- Buildings subsystem, which have been modeled starting from the available 2D layout of the facility, also including the prefabricated identified to host the Control Room.
- Mock-up subsystem, in this first version including the same CAD models of DTT VV and in-vessel components, to only assess their encumbrance with respect to the available space and propose its positioning.
- DTT RH robots for FW and Divertor maintenance, i.e. Hyrman and CMM respectively, at concept design version.

The 3D CAD model represents core model of the facility's digital twin, as any other model or document (requirements models, description documents, 2D drawings, simulation models, etc.) can be linked to it and to its sub-assemblies. It will be constantly updated throughout the design development and will be enriched with all new developed models or documents.

After this stage, the RFLP has been completely applied at the highest hierarchical level, that is the main system level of the entire facility (PBS Level 0, as shown in Figure 4.2). The assessment that the defined logical and physical architecture for the facility are able to satisfy each design requirement in compliance with the spaces and services available in the hosting building, performed for the DTT RH Facility, represent the Verification & Validation of the facility's architectural design.

Once logical and physical architectures for the facility have been obtained, the Concept Design for each subsystem can be developed, so as to also detail the Concept Design of the entire facility. To achieve this scope, the V-Model and RFLP paradigm will be applied again, however at subsystem level (PBS Level 1), as prescribed by *Iterative Design* principles of MBSE.

## 4.2 CONCEPT DESIGN OF RH FACILITIES: REITERATION OF V-MODEL IN RFLP PARADIGM AT SUBSYSTEM LEVEL

One of the key principles of Systems Engineering is the application of *Iterative Design* methods. In the V-Model application, the *Iterative Design* is realized through multiple iterations of its several stages, which replaces linear consecutive application of each stage. The V-Model application shall hence be cyclically re-iterated, going inside the subsystems levels of the PBS, as depicted in previous Figure 3.2.

The second iteration of the complete V-Model in RFLP approach at subsystem level allows to produce a Verified & Validated Concept Design for each subsystem, shaping the Concept Design of the entire facility. At this point, it is also important to define the management process of the imminent facility's subsystems development. The approach herein proposed, adopted for the DTT RH Facility development, is to assign the drafting of the Concept Design to the RH Facility design team (which also contributes to the stakeholder fusion project), generally made of contributors from research centers, academies or even companies. Then, the Engineering Design & Manufacturing is assigned to manufacturing companies by means of one or more calls for tender, depending on if a *Centralized* or *Distributed* approach is chosen, as explained in previous Section 3. The decision about the followed approach shall be made as soon as the concept design begins to develop, as it will form the basis for the technical specifications for each subsystem. If a *centralized approach* is selected, the supply of all the subsystems is in charge of the same company under the same contract. This means that a single call for tender is launched and one technical documentation package for the supply of all the subsystems shall be drafted by the RH Facility design team. If a *distributed approach* is instead selected, each subsystem is supplied by a separate manufacturing company. This means that a call for tender is launched for each subsystem and a separate technical documentation package shall be drafted by the RH Facility design team. In the latter case, the RH Facility design team can be distributed in separate groups, each one focusing on the development of the Concept Design and technical documentation package for a specific subsystem. However, keeping constant interaction and exchange of information is fundamental to ensure coherent design and reliable interface management among the subsystems. Moreover, part or all Design Team's members shall be involved in the update and management of the digital twin models. This means that either all Facility Design Team members work on the digital twin models stored on PLM platform on-cloud database, or specific Design Team members are in charge of updating and managing the digital twin. For the DTT RH Facility, a *distributed approach* has been adopted in the subsystems supply's management, and also the subsystems Concept Design has been developed by separate DTT Design Teams, each focusing on a specific subsystem and employing the preferred tools, with a specific group in charge of the digital twin models' management and update. At the end of this process, for each subsystem, the Concept Design and technical documentation package (2D drawings, 3D CAD models, Technical Specifications, Interfaces Sheet, etc.) are drafted and delivered as call for tender's attached documentation for project understanding by potential bidding companies. As mentioned above and proposed in the presented methodology, the V-Model and RFLP application shall be reiterated at subsystem level (PBS Level 1) for developing the subsystems Concept Design. The application of this process to the DTT RH Facility Case Study is described in the present section.

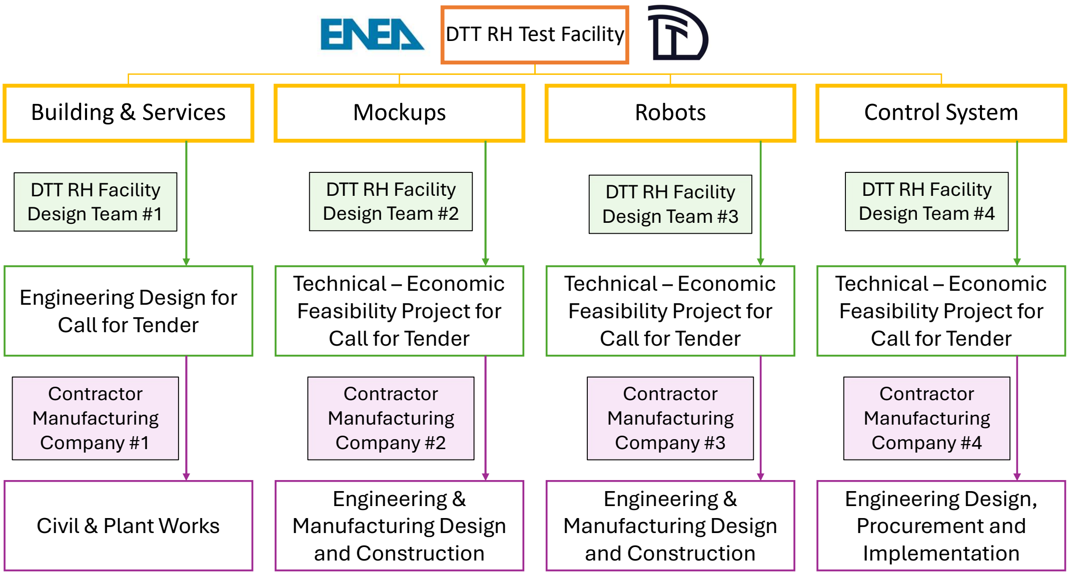


Figure 4.5: Workflow for subsystems design development and manufacturing adopted on the case study of the DTT RH Facility

### 4.2.1 Second iteration of RFLP application for subsystems Concept Design

In line with the principle of *Iterative Design*, the RFLP paradigm is applied again at subsystem level as Specification Stream of the V-Model, to deploy each subsystem Concept Design, that will be integrated with the other subsystems, Verified & Validated in the successive phases. Re-iteration of RFLP paradigm application is fundamental to guarantee requirements integration and tracking at lower design levels.

#### R-Step of RFLP at subsystem level

As carried out at system level for the entire facility and described in the previous paragraph, the first **R-step** concerns the Requirements analysis. Requirements tables are therefore drafted for each subsystem. Subsystems' requirements derive from both the requirements of the entire facility and from the RH procedures to be tested. Facility requirements shall be decomposed into children requirements belonging to each subsystem, while OSDs included in the Maintenance Manuals shall be examined again to instead obtain the required hardware equipment for each subsystem. Requirements of different subsystems can depend on each other. For instance, requirements for the Building & Services subsystem mainly depend on the requirements and functions of the other subsystems. Or, Control System requirements can derive from Robots requirements and vice-versa. Or again, Mock-ups requirements can depend on Robots requirements or even on Robots functions, making the process even more complex. This shows how the RFLP application is also an iterative and concurrent process itself: some requirements may depend on other subsystems' functions or developed design, therefore designers shall constantly control the interface among the different subsystems and be able to come back in the process to adapt requirements, functions or even design to the updated version of another subsystem. In this process, the Robots and Control System subsystems can be identified as the priority ones, being the facility designed for their testing. Therefore, requirements, functions and architecture of Mock-ups and Building & Services shall be flexible to updates if modifications in Robots or Control System configuration occur. A digital-twin based design process, supported by a cloud-based PLM platform, strongly facilitate the process of constant update of and interface management among design requirements, functions, architectures and versions. Indeed, digital-twin models opportunely developed, configured and interfaced within a PLM platform allow to keep interconnection between design parameters related to different development stages and to different subsystems, enabling the automation of parameters tracking and update, as well as of interference analyses after design parameter modification. To perform requirements engineering at subsystems level, requirements of Robots and Control System are first elicited, categorized and tabled. Requirements of Building & Services subsystem are the last to be drafted, as they represent the technological and services requirements to adapt the facility site to the requirements of the other subsystems, from which therefore directly derive. These are, for instance, the electric power required by the robots, the weight of the mock-ups, the cabling route to connect the robots to the control room, the air conditioning requirements in the Hall and in the control room, which lead then the plant and civil works to be performed to adapt the site to the scopes of the facility. Requirements are uploaded and managed on 3DEXPERIENCE Magic tool, to be implemented in the corresponding digital twin models and linked to the system-level requirements (i.e., the requirements of the entire RH facility). In this way, a more detailed requirement diagram is created, including 101 requirements from all the involved systems and obtained by ensuring no duplication

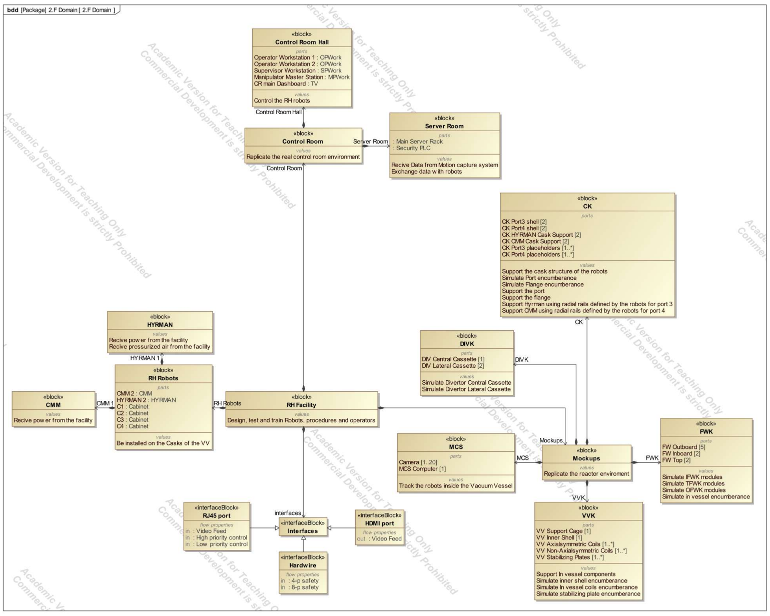


Figure 4.6: DTT RH Facility functional domain

of requirements and proper coordination among each other.

### F-Step of RFLP at subsystem level

A Functional analysis is then carried out to translate subsystem-level requirements into functional blocks employing Magics tool, detailing the Block Definition Diagram already previously drafted at system (facility) level and thus mapping a complete functional domain at subsystem level (Figure 4.6).

### L-Step of RFLP at subsystem level

From the connection of the functional blocks defined at subsystem level, it is possible to further branch the Logical architecture for each facility subsystem, L-Step of RFLP application at subsystem level. Developing subsystems' Logical architectures allows to decompose the PBS of the facility in further, more detailed, levels.

At this stage, the procedures and OSDs included in the Maintenance Manual shall be further analyzed to ensure that each required equipment is implemented in the logical architecture. This is primarily valid for the Robots subsystem and, in turn, for the Mock-ups subsystem. For the robots, the full understanding of each RH Action included in each RH Task allows to opportunely define their

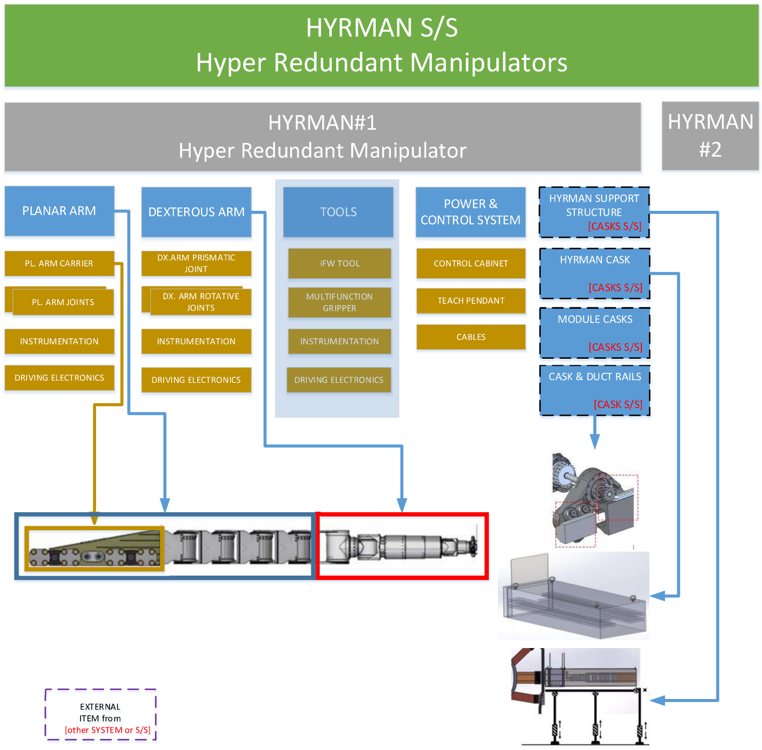


Figure 4.7: HYRMAN Logical Architecture at Concept Design stage [133]

kinematics and, then, to find the proper number and typology of joints and links making up the architecture.

The Robots logical architectures are shown in Figure 4.7 and 4.8, for HYRMAN [133] and CMM [133] respectively, as they are after the several design and verification iteration performed in compliance with the best practices of application of the V-model in RFLP approach.

The main subsystems of the HYRMAN's logical architecture are the following:

- *Planar Arm*, allowing for radial movement along the rails placed on the Equatorial Port #3 walls and for planar movement on the tokamak's equatorial plane to reach the sector where the FW module to be handled is placed.
- *Dexterous Arm*, allowing for movement in the tokamak's poloidal plane to reach the sector's FW module to be handled.
- *Tools*, including all the end-effector components for grasping the several FW modules.
- *Power & Control System*, including all the components of the HYRMAN Low-Level Control System.

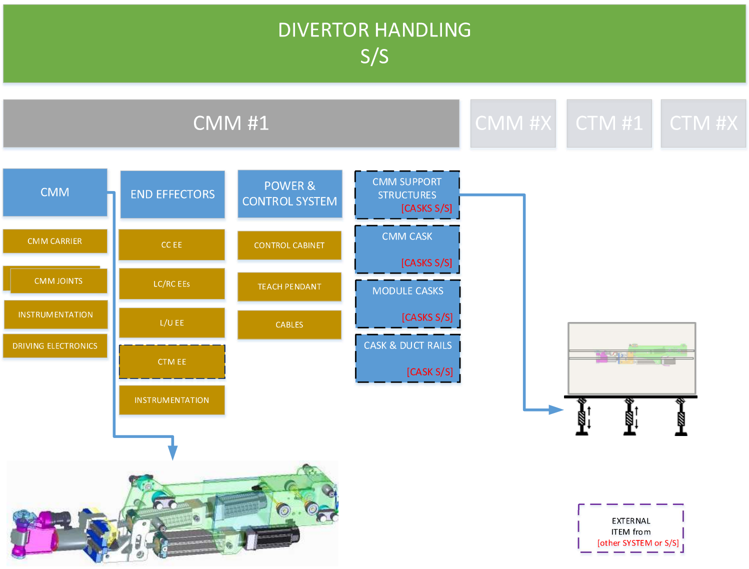


Figure 4.8: CMM Logical Architecture at Concept Design stage [134]

- Additional mechanical structures, such as support structure, casks, and rails.

The main subsystems of the CMM's logical architecture are:

- *CMM* mechanical structure, mainly composed by a carrier for radial translation along the rails placed on the Lower Lateral Port #4, and of the set of joints for handling Central and Second Cassettes.
- *End-Effectors*, including all the end-tool components for grasping the Central and Second Cassettes, as well as the future CTM.
- *Power & Control System*, including all the components of the CMM Low-Level Control System.
- Additional mechanical structures, such as support structure, casks, and rails.

For the mock-ups, the analysis of the procedures and OSDs included in the Maintenance Manual, together with requirements analysis, allows to determine the number and typology of each mock-up component. Mock-ups components can be divided into four typologies:

- Actual *Mock-up* modules, representing the modules which must be handled by the robots during the test campaigns and therefore must faithfully replicate not only the encumbrance (external geometry) of the corresponding real modules, but also the inertial properties, such as weight, Center of Gravity (CoG) position and stiffness. Therefore, their internal geometry may differ from that of the corresponding DTT components as long as the same inertial properties (weight, center of gravity position, stiffness) are replicated, as these affect their handling by the robots.

- *Placeholders* modules, representing the modules which are never handled by the robots and therefore must replicate the encumbrance (external geometry) of the corresponding real component only, while not the intertial properties. They can therefore be made of lightweight, cheaper material and manufactured with less strict tolerance requirements.
- *Interface* components, representing the components that interface with other systems and that, therefore, must replicate the same external geometry, contact properties, such as contact stiffness and surface roughness, and manufacturing tolerances of the corresponding DTT components.
- *Support* components, representing the components that only have structural support function and that, therefore, must only replicate the structural behavior of the original correspondents (structural stiffness).

The draft an extended logical architecture for the Mock-ups subsystem, each Mock-up block is split into children components, quantified and categorized by type [135]. The main components included under each Mock-up block are the result of a selection process carried out following the principles of modularity, reconfigurability, reduction in required materials, weight, costs and manufacturing complexity, with the ultimate main goals of reducing the technological and economic requirements of the next manufacturing process, thus facilitating industrial companies participation to the call for tender, and ensuring possible upgrades and reconfiguration of the facility for future further uses.

The Mock-ups subsystem's logical architecture and included components can broadly be described as follows:

- The *Vacuum Vessel (VV) Mock-up* subsystem includes: all the components necessary to support the Mock-up modules or the structural interfaces (VV Mock-up Support Cage, VV Support Pads and Plates and Port Support Pads); internal interfaces (Toroidal Rails and VV Support Plates) and external interfaces (Radial Rails of Port #3 and Port #4); in-vessel and port placeholders; cask Mock-ups, which must be moved by the crane while hosting the robot, and their support; Regulation System for in-vessel Components (RESC), that is a system designed to act as a regulable interface for the FW Mock-up modules, to vary their position and thus simulate the effect of manufacturing tolerances and/or non-conformities.
- The *Divertor Mock-up* subsystem includes: one unit of Divertor Cassette Mock-up, that must be modular and reconfigurable to be adapted to Central, Second and Standard Cassette configuration; two units of Handable Divertor Cassette Placeholder, light components that, before the start of a RH Task test, shall be manually placed at the side of the Divertor Cassette Mock-up whose handling must be tested; one unit of Walkable Divertor Placeholder, thought as a walkable plate covering the intermediate space between the lateral RH sectors of the Mock-up.

- The *First Wall Mock-up* system includes: one unit of FW Mock-up for each different configuration (Standard and Limiter IFW, five OFW module configurations and two TFW configurations), which can be moved and placed in each of the Mock-up sectors; one unit of FW Placeholder for each of the remaining FW positions (39 modules in total).
- The *Installation Tool* allows for first assembly of Mock-ups and for varying the RH Task test configuration set-up by moving the Mock-ups module among the different possible test positions.
- The *Mock-ups Instrumentation* includes the Motion Capture System needed to measure and reconstruct the robots' 3D motion, and the support pads for the required optical cameras. The presence of a Motion Capture System in the Mock-ups area is of fundamental importance for robots real-time tracking and visual representation to human teleoperators in the Control Room, as well as for calibration of their control and digital twin models.
- Additional tools, like Transportation Tools for transportation of Mock-ups modules before first assembly and Spare Parts.

The conceptual Logical architecture for the Control System [136, 137] is instead shown in Figure 4.9.

It is a Multi-Server, Multi-Client architecture, where:

- The Multi-Clients are represented by both the Machine side (including all the devices located in the mock-up area, such as actuators and sensors), and the Operator side (including all the devices in the Control Room, such as operator workstations and control devices).
- The Multi-Servers are represented by two central servers, the Control Server and the Visualization Server, each featuring specific software modules, and a Data Server:
    - The *Control Server* is responsible of the high-level control and coordination of procedures, manages robot manipulation and control algorithms, runs diagnostic software to monitor system safety, and ensures data synchronization and consistency across operator workstations. The control server also manages intermediate-level control, interfacing with the low-level control on the robot's industrial PC, while operators handle the high-level control. The software modules foreseen in the Control Server are: Motion Planner, Dynamic Simulation Interface, Operation Management, Diagnostic, Authentication & Authorization, Teleoperation Control.
    - The *Visualization Server* runs graphic engine for rendering the High-Fidelity digital twin VR models, considering deformations and vibrations of long-reach flexible robots, and simulates RH operations offline for testing and training, providing VR environment for immersive operator training and real-world task execution. The software modules foreseen in the Visualization Server are: Visualization module (made of a Physic engine, a Graphic engine and a Virtual Reality engine) and Collision Management module.

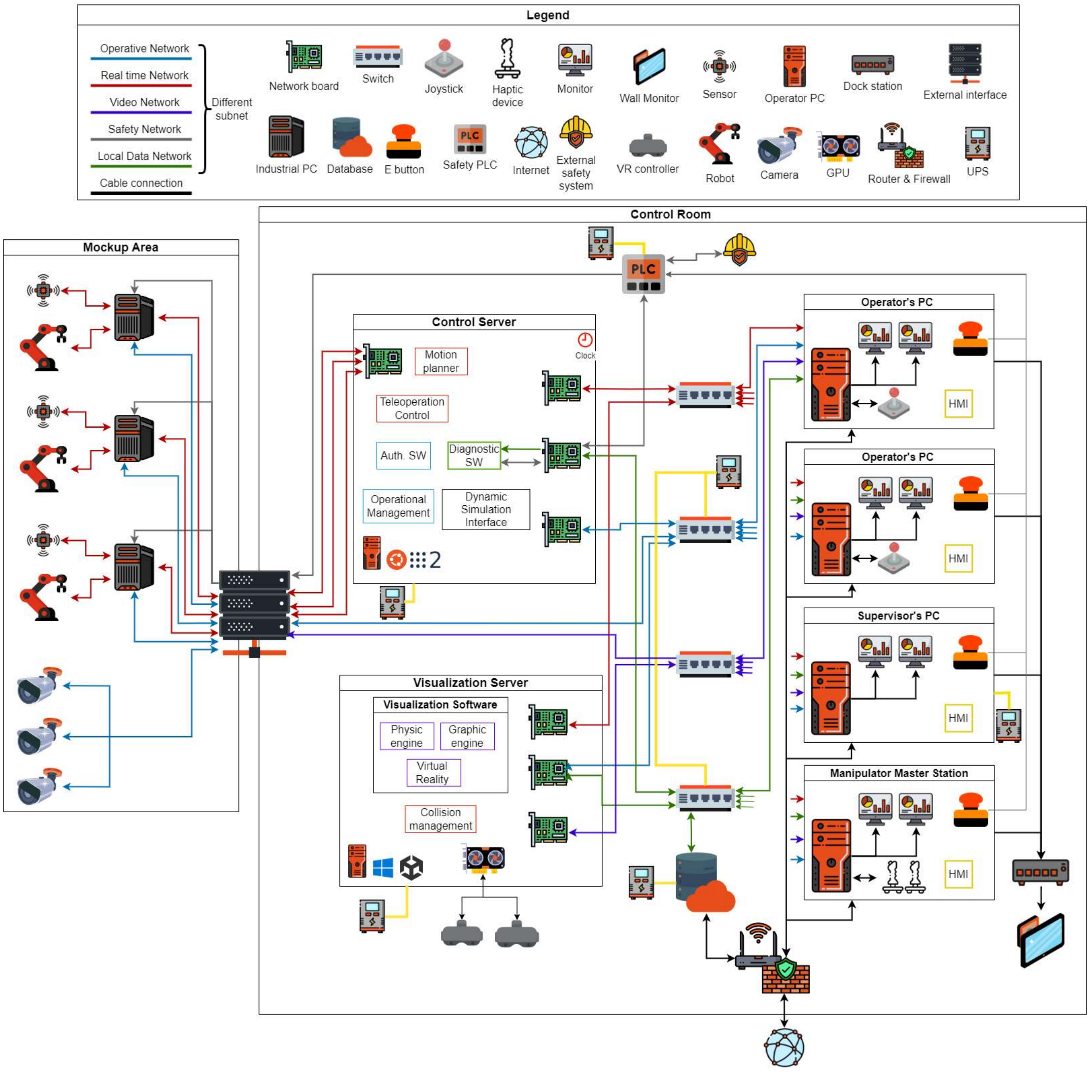


Figure 4.9: DTT RH Facility Control System Logical Architecture at Concept Design stage [136, 137]

  - The *Data Server* stores all data such as 3D models, task reports, and all the information regarding RH procedures. It can be coincident or linked to the digital twin storage, that is the PLM on-cloud database.

In addition, external interfaces facilitate communication and interaction between the control room systems and the systems in the mock-up area, ensuring independence in design and functionality.

The Control System software is intended to be integrated and managed through a framework such as Robotics Operating System 2 (ROS2). ROS2 establishes a structured environment facilitating seamless communication, data sharing, and task execution among different software components of a robot. Compared to its predecessor ROS, ROS 2 introduces a paradigm shift, particularly in terms of modularity, communication protocols, and real-time capabilities. Its distributed architecture, built upon the Data Distribution Service (DDS), enhances scalability, reliability, and determinism. The possibility of integrating ROS2 and the 3DEXPERIENCE PLM platform ensures seamless exchange of data between the two systems, enabling the design teams to integrate ROS2's real-time communication capabilities and control of robotic systems within the 3DEXPERIENCE collaborative environment for design, simulation, and operation data management. Moreover, the integration of ROS2 and 3DExperience could enhance simulation capabilities by achieving a faithful correspondence between the digital twin models and real counterparts.

To ensure reliable and efficient data connection and transfer between the robot/mock-up area and the control room area, a robust Network Infrastructure is needed and is therefore preliminarily designed, as shown in Figure 4.10.

The DTT RH Facility Control System's Network Infrastructure is made of different subnets:

- Diagnostic Network: collects diagnostic information elaborated from each component, detects the causes of any malfunction and acts on it.
- Real-Time Network: transmits command signals and sensor data. Supports low-latency communication for real-time control tasks.
- Video Network: dedicated to video streams from the visualization server providing high-quality visual feedback to operators.
- Operative Network: manages non-critical information. Balances system load by offloading non-essential communications.
- Safety Network: an analog, hardwired network for transmitting emergency stop signals. Directly connected to Robot industrial PCs and the

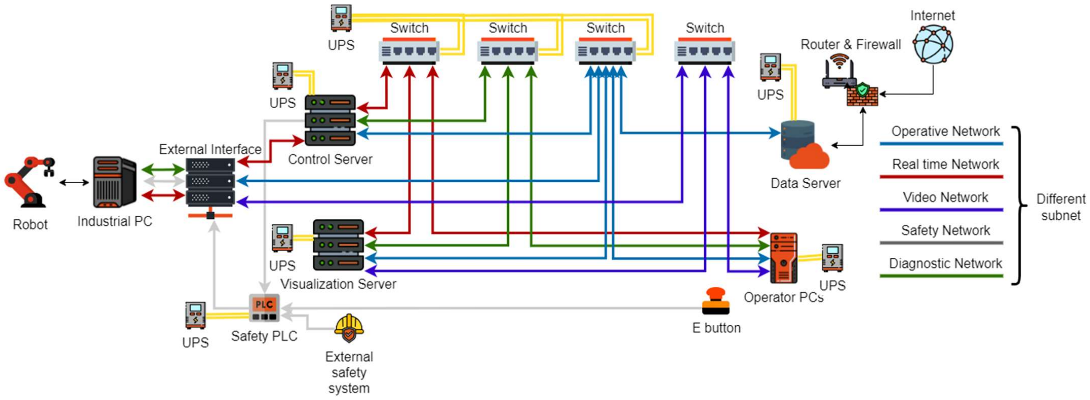


Figure 4.10: Network Infrastructure for the DTT RH Facility Control System [136, 137]

Safety PLC, ensures immediate response to critical failures and enhances overall safety.

The Control System is designed to operate in two possible States:

- *Off-line Planning State*: the digital twin is not connected to the physical equipment and is used alone for virtual testing of RH tasks and operators training. This allow the human operators to take confidence with the control devices by only affecting the digital twin models in VR environment with no impact on the real environment.
- *On-line Operation State*: connection to physical equipment is enabled and RH tasks are tested in the real physical environment. digital twin models are connected in real-time to physical counterparts, and proper calibration among them shall be ensured. Data extracted from on-site sensors are collected, stored in the digital twin models, and displayed to the human operators for analysis. Only experienced operators should be allowed to operate in this State, to avoid the risk of physical equipment damage.

For each State, three Operation Modes are available:

- *Supervision Mode*: used for main pre-planned movements, in which operators monitor task progress and system data.
- *Teleoperation Mode*: human operators directly control the robots for precise movements, using haptic-feedback and VR devices for enhanced interaction.
- *Shared Control Mode*: combines autonomous robot actions with operator inputs, aiding operators in precision tasks.

Each logical architecture shown is then further branched to include all the design components. The detailed description of each subsystem goes beyond the scope of this thesis work, in which therefore a general description of the subsystems design is provided.

The Logical architecture for the Buildings & Services subsystem is not reported as the site identified to host the DTT RH Facility is already built, featuring all the logical blocks already defined in the Logical architecture of the Facility and shown in Figure 4.2. The required developments mainly regard civil engineering works to adapt the site to the technological and plant requirements of the other subsystems. Therefore, even if a project for the civil engineering work shall be draft and verified by the DTT RH Facility design team as well, its discussion will be simplified to prioritize the other subsystems, more relevant to the scientific purposes of the work.

#### P-Step of RFLP at subsystem level

Once drafted, the subsystem's logical architectures are translated into physical architectures by developing digital twin models, first of all CAD models. With this step, the Concept Design of the facility and of its subsystems takes shape.

As already stated, according to the V-model way of application, each RFLP stage of the left-side *Specification Stream* shall be carried out in constant connection to the correspondent stage of the right-side *Testing Stream*, in order to verify and validate the system since the early design stages and avoid the risk of unexpected, time and money wasting, late modifications. Therefore, the architecture and Concept Design of each subsystem and, therefore, of the whole facility, have been iteratively optimized and refined several times, basing on the results of the Integration, Verification and Validation steps.

The Physical architectures of the main facility subsystems, as they are after several design iterations, represent the resulting Concept Design and are shown in next Section 4.2.2

### 4.2.2 Concept Design for facility subsystems

The present Section describes the Concept Design developed for the DTT RH Facility subsystems through the application of the RFLP paradigm. The version herein described are the result of an iterative process among the RFLP steps of the V-model's *Specification Stream* and the Integration, Verification and

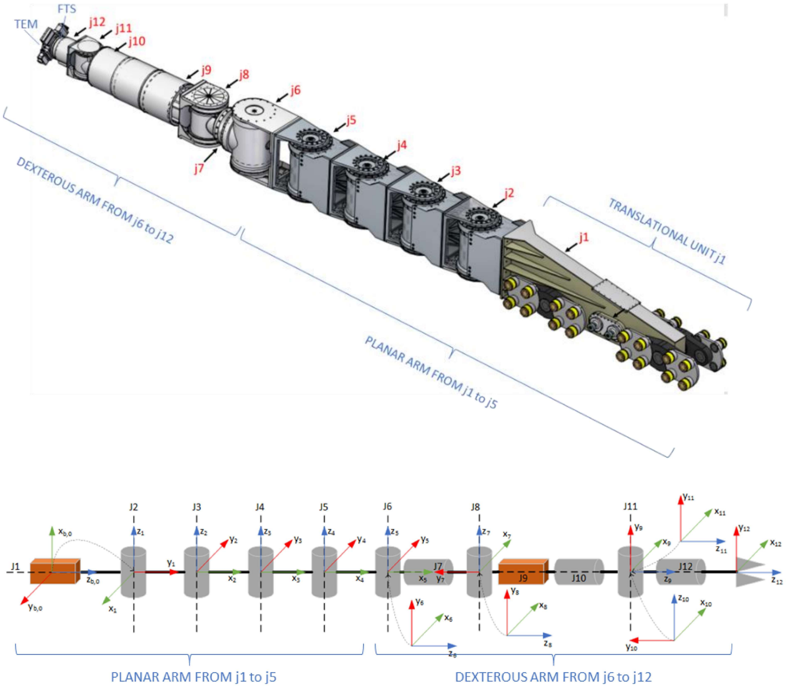


Figure 4.11: HYRMAN Concept Design and kinematic configuration [37, 68, 138, 133]

Validation steps of the V-models' *Testing Stream*, which are however described more in detail in the next sections.

### HYRMAN Concept Design.

The Concept Design and kinematic configuration developed for HYRMAN are the result of an iterative design and virtual verification process[37, 68, 138, 133], and are shown in Figure 4.11.

It is a 12 DoF full electric manipulator. The first DOF is a translational unit (carrier) allowing the manipulator to radially move on the rail placed on the Equatorial Port #3 internal walls, to enter the in-vessel environment. The remaining DOFs are rotational joints with exception of joint 9 which is a prismatic joint. Joints from J2 to J6 compose the planar arm for toroidal movement in the tokamak's equatorial plane to reach the sectors of the FW module to be handled, while joints from J7 to J12 compose the dexterous arm for reaching the sector's FW module to be handled. Joint angular and translational ranges are reported in Table 4.4.

HYRMAN has a modular design that allows its reconfiguration when needed.

Table 4.4: HYRMAN joint ranges [133]

| Joint No. | Joint Range |
|---|---|
| 1 | – |
| 2 | ±100° |
| 3 | ±100° |
| 4 | ±100° |
| 5 | ±100° |
| 6 | ±100° |
| 7 | ±180° |
| 8 | ±100° |
| 9 | 0 to 540 mm |
| 10 | ±180° |
| 11 | ±100° |
| 12 | ±180° |

Figure 4.12: HYRMAN Concept Design overall dimensions in its full-length configuration [133]

Depending on the operational requirements, this modularity allows to both remove the dexterous arm, obtaining a planar arm configuration attached to a translational joint, and remove one or more of the planar joints J3, J4 and J5, which are identical. The dexterous arm can be then attached to the reconfigured planar arm. These modules have been designed to be easily and quickly connected and/or disconnected using standard laboratory tools by means of electrical connectors and bolted joints with alignment pins.

Overall HYRMAN dimensions are shown in Figure 4.12, while estimated mass for each main subsystem is provided in Table 4.5. HYRMAN is designed to withstand a maximum payload of 350 Kg at the end of its entire kinematic chain. HYRMAN's planar arm is instead designed to withstand a maximum payload of 600 Kg at 1 meter from the last planar joint.

Table 4.5: Mass and material of HYRMAN subsystems [133]

| **Subsystem** | **Limbs Material** | **Mass [kg]** |
|---|---|---|
| Translational Unit | Steel S355 GL | 1330 |
| Planar Arm | Al 7075 | 670 |
| Dexterous Arm | Al 7075 | 440 |
| **Total** | | **2440** |

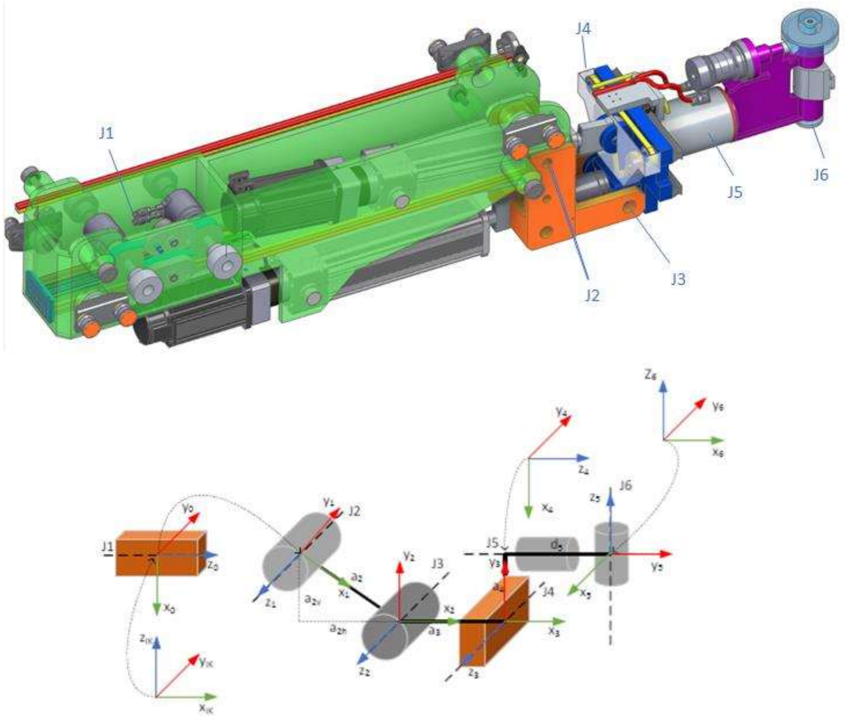


Figure 4.13: CMM Concept Design and kinematic configuration [68, 40, 35, 134]

### CMM Concept Design

The Concept Design and kinematic configuration developed for CMM are the result of an iterative design and virtual verification process [68, 40, 35, 134], and are shown in Figure 4.13, with particular reference to the case of CMM equipped with Second Cassette End Effector (SCEE), even called Left/Right Cassette End Effector (LC/RC EE).

It is a 6 DoF full electric actuated device. The first DoF is a translational unit (carrier) radially moving on the rails of the Lower Lateral Port #4 to allow the CMM to enter the in-vessel environment. The remaining DoF are rotational and translational joints. Joint ranges are reported in Table 4.6.

Table 4.6: CMM Concept Design joint ranges [134]

| Joint No. | Joint Range |
|---|---|
| 1 | – |
| 2 | −10° ; +42° |
| 3 | ±26°$^*$ |
| 4 | 275 mm |
| 5 | ±4° |
| 6 | ±100° |

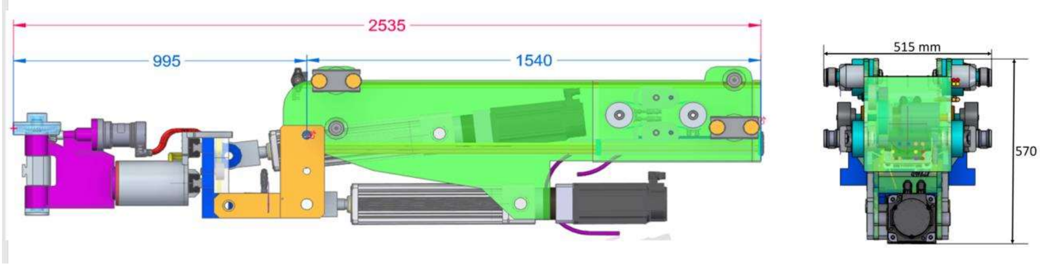


Figure 4.14: CMM Concept Design overall dimensions [134]

Overall dimensions of CMM are shown in Figure 4.14, while estimated mass for each main joint is provided in Table 4.7. CMM is designed to withstand a maximum payload of 400 Kg at 850 mm from the end of the kinematic chain.

The design and kinematic configurations for the CMM equipped with Central Cassette End Effector (CCEE) are the same of the CMM-SCEE up to joint J4. After that, they change due to the different requirements and operative procedure. For the development of the CMM's CCEE design, the study of the corresponding RH procedure has been fundamental to clarify all the systems requirements, functions, and logical components. The Central Cassette RH procedure is few

Table 4.7: CMM joints mass and material [134]

| Subsystem | Limbs Material | Mass [kg] |
|---|---|---|
| Joint 1 | Al 6061 | 100 |
| Joint 2 | Al 6061 | 40 |
| Joint 3 | Al 6061 | 35 |
| Joint 4 | Al 6061 | 25 |
| Joint 5 | Steel S355 Jr | 55 |
| Joint 6 | Steel S355 Jr | 10 |
| **Total** | | **265** |

more complex with respect to the case of the Second Cassette, because the Central Cassette is handled with the Dummy Rail, that is the demountable portion of the outboard toroidal rail in front of the lower lateral ports #4 to be removed to free the in-vessel access for divertor RH operations. Moreover, while in the case of the Second Cassette the divertor cassette is just placed by the CMM above the toroidal rails and then preloaded through an additional torque tool, in the case of the Central Cassette the CMM equipped with CCEE is in charge of both its handling and its preloading.

Figure 4.15 shows the key logical components of the CMM-CCEE, each one designed to perform a specific operation during the Central Cassette RH installation/removal procedure. Taking as reference, for instance, the CC removal procedure, the CMM-CCEE shall execute the following main operations:

1. Approach the Central Cassette + Dummy Rail system.
2. Grab the Dummy Rail through the Dummy Rail grab interfaces (additional DoF required to expand the grab interfaces).
3. Lock to the VV duct through the duct interface pins (additional DoF required to expand the duct interface pins).
4. Advance the linear actuator for preload holding (additional DoF required to actuate the linear actuator).
5. Retract the Dummy Rail's locking pins through an additional linear actuator (additional DoF required).
6. Retract the linear actuator for preload release and, parallelly, orientate the divertor cassette with the divertor orientation interface (additional DoF required to linearly move the divertor orientation interface).
7. Unlock from the VV duct.
8. Leave the vessel environment and extract the Central Cassette + Dummy Rail system.

In total, five additional DoF are therefore added on the CMM base structure when it is equipped with the CCEE.

### MOCK-UPS CONCEPT DESIGN.

The Physical architecture representing the Concept Design of the Mock-ups subsystem [135] directly derives from the logical architecture described in previous Section 4.2.1. Its exploded view is shown in Figure 4.16.

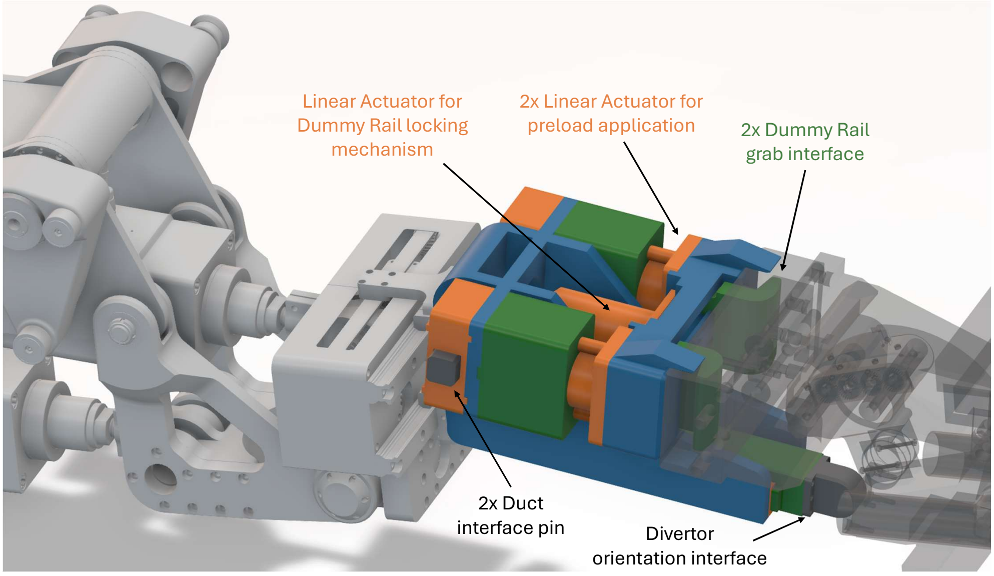


Figure 4.15: CMM equipped with Central Cassette End Effector (CCEE)

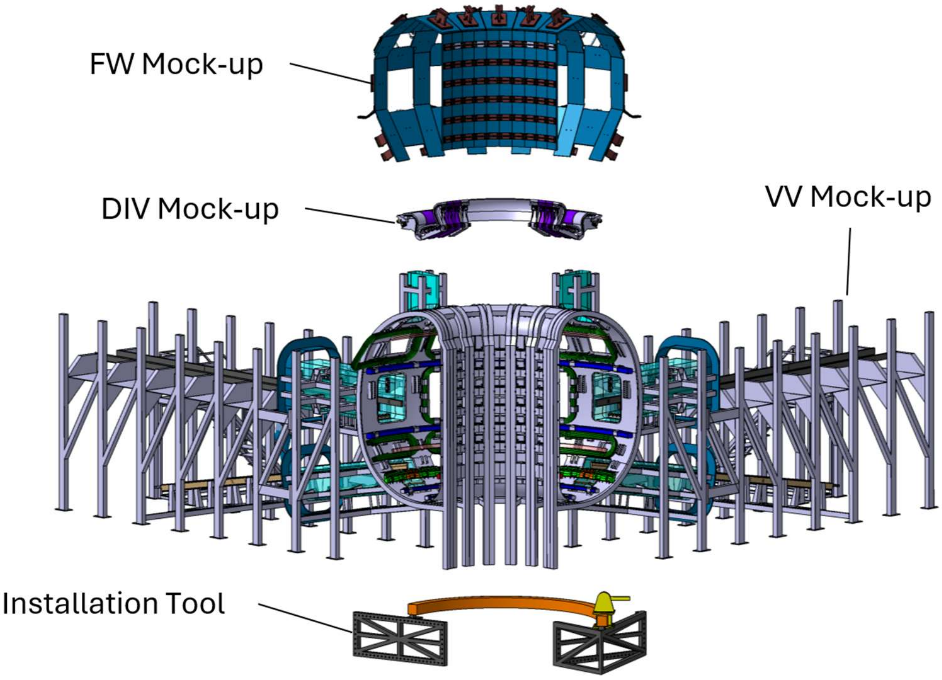


Figure 4.16: Exploded view of the Mock-ups Concept Design [135]

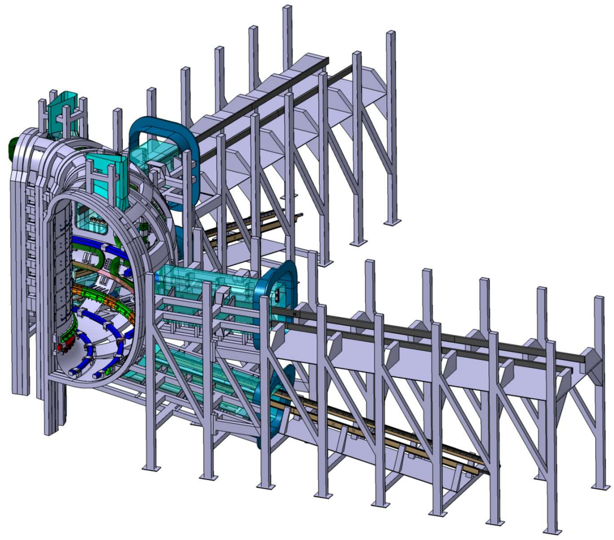


Figure 4.17: Vacuum Vessel (VV) Mock-up Concept Design

The Mock-ups concept design is a 110 degrees replica of the DTT Vacuum Vessel and in-vessel components, including 5 complete sectors. Sectors at the extremities are RH sectors, equipped with full mock-ups of Equatorial Port #3 and Lower Lateral Port #4, respectively allowing for HYRMAN and CMM access to the in-vessel mock-up area, and partial mock-up of Upper Port #1 for possible future test of the IFW Lifting System. As already explained while describing the Mock-up subsystem's logical architecture, the VV Mock-up is mainly made of a carbon steel support cage, that supports the in-vessel Mock-up modules Support Pads and Plates, which instead are made of austenitic stainless steel. At the RH sectors, it is made of a Port Mock-up, which in turn is composed by the Port Support Pads supporting the Radial Rails and by the Port Placeholders defining the boundaries of the robots workspace, and its Support Frame. Behind the Ports Mock-up there are the Cask Mock-ups, steel plates hosting Radial Rails extension which shall be handled by the crane to move the robot from the loading/unloading area of the Facility Hall to the operative location on their Support Frame, as well as to move the robot form a RH sector to the other one if necessary. Finally, internal and external Interfaces, such as Toroidal Rails, Radial Rails and the Regulation System for in-vessel Components (RESC), are also part of the VV Mock-up, as well as the Placeholders for in-vessel components (like In-vessel Coils, Stabilizing Plates and Inner Shall). The VV Mock-up Concept Design is shown in Figure 4.17.

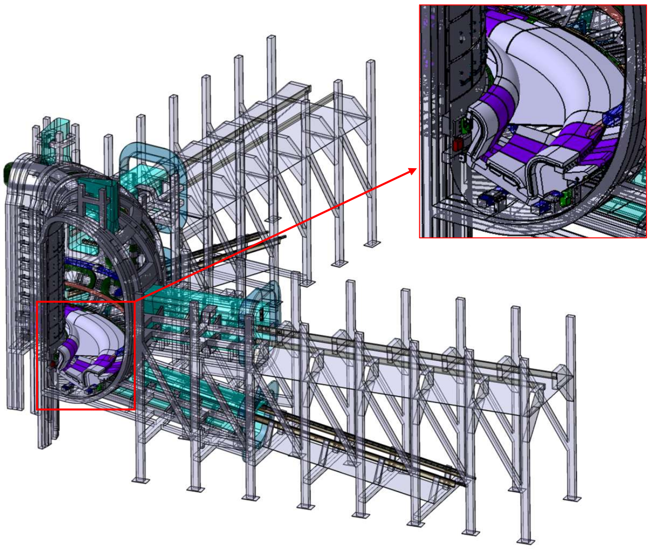


Figure 4.18: Divertor Mock-up Concept Design, with alternative operative positions represented in purple

The Divertor Mock-up Concept Design is shown in Figure 4.18. The operative positions for the Divertor Cassette Mock-up are represented in purple; as already mentioned, the Concept Design foresees a single unit of Divertor Cassette Mock-up, modular and reconfigurable to act as both Central Cassette and Second Cassette (Right and Left). The two Handable Divertor Cassette Placeholders and the Walkable Divertor Cassette Placeholder are instead represented in grey. The first shall be manually placed at the side of the Divertor Cassette Mock-up whose handling is under testing to provide the same surrounding working environment of the real future DTT RH operations; the second shall provide both the lower limit for the HYRMAN working space (it shall therefore reproduce the divertor upper surface) and a walkable access for personnel to the Mock-up in-vessel environment.

The FW Mock-ups Concept Design is made of one Mock-up for each FW module configuration and Handable FW Placeholders for the remaining positions. FW Mock-up modules can be exchanged with the Handable Placeholders to be placed in any of the available positions in the five sectors. Each FW Mock-up module is designed as a steel plate reproducing the external geometry and inertial properties of the corresponding DTT module. The FW Mock-up Concept Design is shown in Figure 4.19.

The whole Mock-ups system occupies a surface area of 144 $m^2$, with a height of 5.6 $m$.

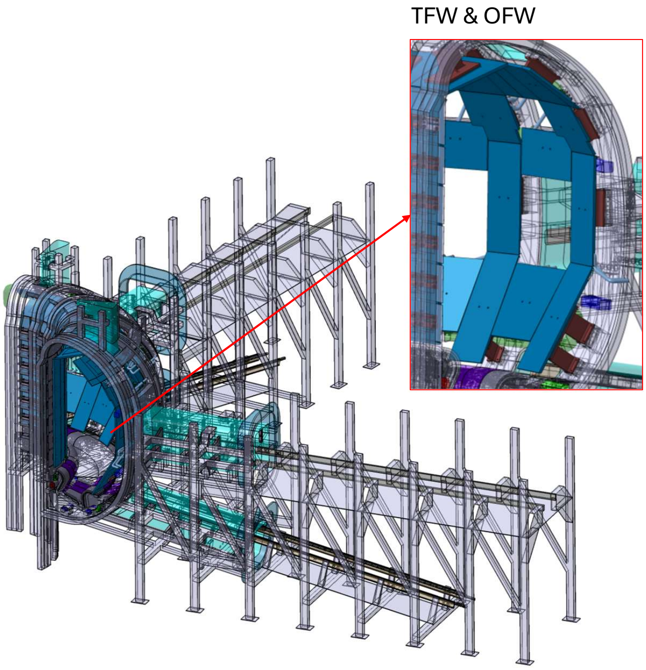


Figure 4.19: FW Mock-up Concept Design, with focus on TFW and OFW modules

### CONTROL SYSTEM CONCEPT DESIGN.

The Control System conceptual architecture has been widely described while showing its logical architecture in previous Section 4.2.1. Its translation into a physical architecture is made by defining the Control Room layout, hardware allocation and operators organization [137]. As already stated, the Control Room has a fundamental role to make the DTT RH Facility one of the most advanced robotics laboratory for fusion research.

The control room (CR), beside ensuring the high-level control of the machinery operating within the DTT RH Facility, is the primary workspace for the operators.

During RH operations, the RH work-cell team is composed by (Figure 4.20):

- One RH Operations Supervisor and team leader named Responsible Officer (RO) that coordinates the different robotic machines operations and the actions taken by the operators of the lower levels.
- Two RH Operators (RHO) that teleoperate and control the robotic systems and utilize the remote handling equipment under the supervision of the RO.
- One Manipulator Operator (MO) that oversees the manipulator master station task.

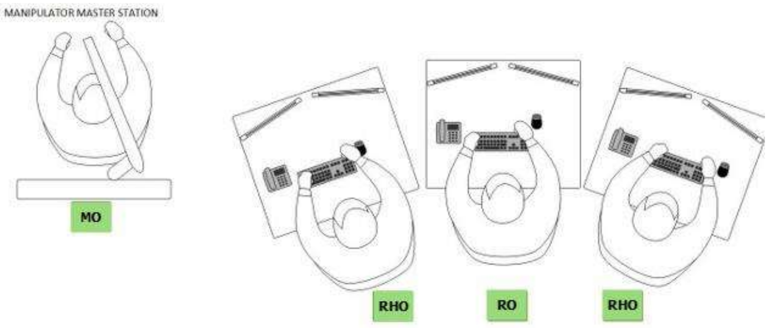


Figure 4.20: RH work-cell team composition in the Control Room [137]

The dedicated workstation equipped with a force-feedback device is planned to be used for performing precision tasks during teleoperation. The MO should ensure precise control of operations; therefore, it requires at least one precision force-feedback devices that provide force feedback to the operator. This feedback can be used not only to relay the force measured by force/torque sensors but also to create virtual walls and, more generally, to implement shared control algorithms to assist the operator. The minimum suggested number of hardware components for the workcell are listed in Table 4.8.

The CR is hosted by the ground floor of a two-floors prefabricated already present in the building hosting the DTT RH Facility. As shown in Figure 4.21, the Control Room is divided in three main areas: Area A, Area B and Area WC.

In the Concept Design, the Area A is designated to host the work-cell and is intended to be the main area of operation. This area is already provided with windows facing the mock-up area. The work-cell includes four operator workstations: one manipulator master station and three work-desks. The manipulator master station should be composed by: at least one force-feedback device, one master station monitor, one ergonomic seat with arm support, one operator's PC. Each operator work-desk is composed of: two or more work-desk monitors, one ergonomic seat, one operator's PC. The work-cell will also feature: a large wall-mounted monitor to facilitate clearer task status supervision, two VR headsets with controllers, two or more joysticks. Operators should be able to use the remote handling equipment and the operator's PC but shouldn't be able to connect to the machines inside the mock-up area in the absence of a supervisor.

Area B is designated as storage area. Dimensions for this area are 450 mm

Table 4.8: Minimum number of hardware components for the RH work-cell in the Control Room [137]

| **Component** | **Q.ty** |
|---|---|
| Wall-Monitor | 2 |
| Docking station | 1 |
| Manipulator master station monitor | 2 |
| Workdesk Monitors | 8 |
| Operators PC | 2 |
| Supervisors PC | 1 |
| Manipulator Master Station PC | 1 |
| Joystick | 2 |
| Force-feedback Device | 1 |
| VR Headset | 2 |
| Joystick | 2 |
| Monitor for Server Management | 1 |
| Control Server | 1 |
| Data Server | 1 |
| Visualization Server | 1 |
| UPS | 6 |
| Switch Video | 1 |
| Switch | 3 |
| Router | 1 |

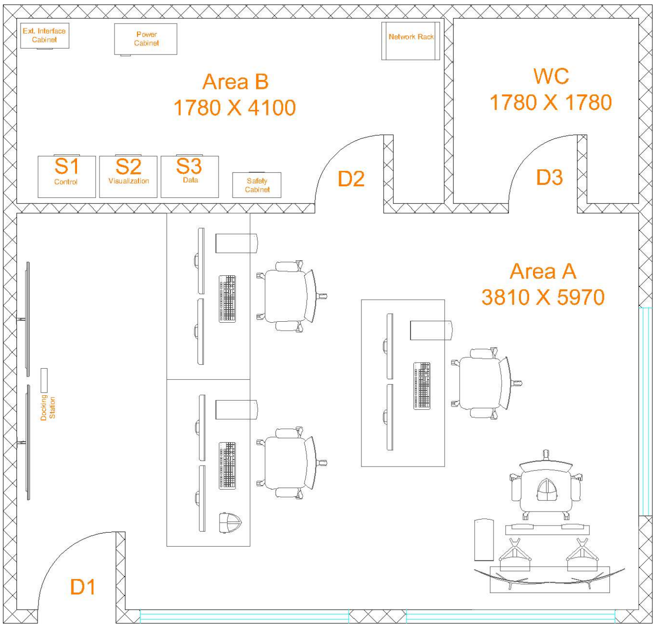


Figure 4.21: Control Room layout [137]

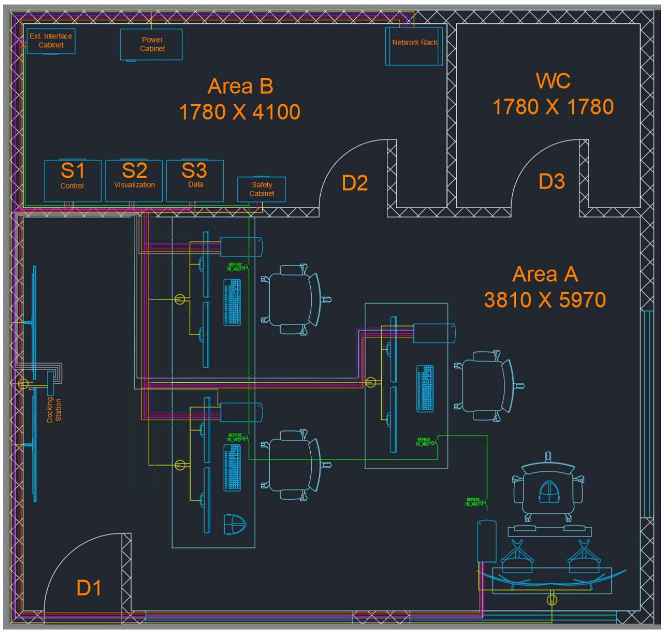


Figure 4.22: Control Room cables layout [137]

x 780 mm. This area is intended to store: Control Server, Visualization Server, Data Server, Safety cabinet, Network rack containing switches and router, Power cabinet, External Interface, Task Report, Task Log, other documents containing information on the completed procedures and performed tasks, additional hardware backup supply (e.g. batteries, I/O devices, external storage). The access to this area should be restricted to personnel authorized by the RO.

The arrangement of networks and components within the Control Room Concept Design is shown in Figure 4.22. The cables considered are those within the Control Room only, cables originating from external interfaces are not included.

### Civil and Plant Works for the Building & Services subsystem.

The main Civil and Plant works identified as necessary to adapt the existing building to the requirements and functions of the DTT RH Facility and its main subsystems are: improvement of the Electrical System to satisfy DTT Robots and Cabinets requirements; new Pressurized Air System for Robots operations, new Heating, Ventilation and Air Conditioning (HVAC) System for all the areas, improved Surveillance System, ex-novo safety plans and devices for the operators.

These Concept Designs act as feasibility projects for the next phase of Engineering Design and Manufacturing contract award to industrial companies, demonstrating the feasibility of the project within allocated contract budget.

### 4.2.3 INTEGRATION, INTERFACE MANAGEMENT AND IMPLEMENTATION IN THE DIGITAL TWIN OF THE SUBSYSTEMS CONCEPT DESIGN

Integration, Verification & Validation steps are relevant since the first phase of development of the subsystems Concept Design. As already mentioned, according to MBSE principles and the V-model proper way of application, the steps of the *Testing Stream* (Integration, Verification and Validation) shall constantly support the steps of the *Specification Stream*, with one-to-one matching between same-level steps: Requirements analysis coupled with Validation, Functional analysis coupled with Verification, Logical Architecture design coupled with Integration (see Figure 2.13).

A digital-twin based development process allows to store the digital twin models over the PLM platform database throughout the development cycle, and connect them with other models from different design stages. This is enabled by the several applications provided by the PLM platform, that allow to cover the entire cycle of system development internally to the PLM on-cloud database where all digital twin models are stored. For instance, 3DEXPERIENCE platform provides both cloud-based and client-based applications to cover the entire product development lifecycle (as shown in previous Figure 3.3). In this way, it is possible to trace requirements, functions and design parameters up to Integration, Verification & Validation stages, in which they are connected to test-case simulation models for automatic verification. Requirements traceability is then guaranteed, as well as instantaneous and autonomous update of simulations' results is enabled.

Proper interface and integration management during Concept Design development is of primary importance to avoid unexpected integration issues in later stages of the project. The Integration step is carried out by performing the analyses and simulations to ensure that the Concept Design of each subsystem properly interface with the other subsystems, also guaranteeing reliability to the Concept Design of the entire Facility. The digital twin models can be used for these interface analyses and integration simulations employing the PLM platform applications. Therefore, this phase is mainly characterized by simulations at system level (that is the entire facility), rather then focused on the specific subsystem only.

In the Case Study of the DTT RH Facility, a *distributed* approach has been adopted for developing both the Concept Design and the Engineering Design. Therefore, the Concept Designs for the DTT RH Facility subsystems have also been developed by separate design teams. In similar cases, one of the design teams or a dedicated group shall be responsible of the integration of the Concept Designs and implementation and management of their digital twin models in the main digital twin of the entire facility, with constant version update throughout their development. This team will hereafter be referred to as digital twin Management Team. If digital twin models can be automatically created, modified and managed by the design teams provided with access to the PLM platform's cloud-space and applications, the role of the digital twin Management Team is to grant proper accesses and authorization to design teams' members to avoid unintended actions on models beyond their design area. Instead, if the design teams are not provided with access to the PLM platform's cloud-space and applications, the digital twin Management Team must collect, manage and implement in the digital twin over the PLM platform on-cloud database the several models developed by each design team. This Integration phase requires constant interaction among design teams, to ensure all information regarding each model at each design version is transferred and implemented in the digital twin.

The digital twin 3D CAD model of the DTT RH Facility Concept Design, with all subsystems integrated and implemented over the 3DEXPERIENCE platform, is shown in Figure 4.23.

This phase also includes challenging *Interface Management* tasks, aimed at clearly identifying the boundaries of each subsystem and ensuring that each subsystem properly interfaces with the surrounding ones. This step is also fundamental to ensure proper transfer to the companies of all information necessary to complete the Engineering Design and Manufacturing: the different companies involved in the project shall have completely clear which are the boundaries and interface requirements of their Scope of Supply.

RH ports Radial Rails represent an example of challenging-to-manage interface system, as they are part of the Mock-up subsystem but their design strongly depend on the Robots' requirements, functions and design. The chosen approach for the management of this interface at the Concept Design stage

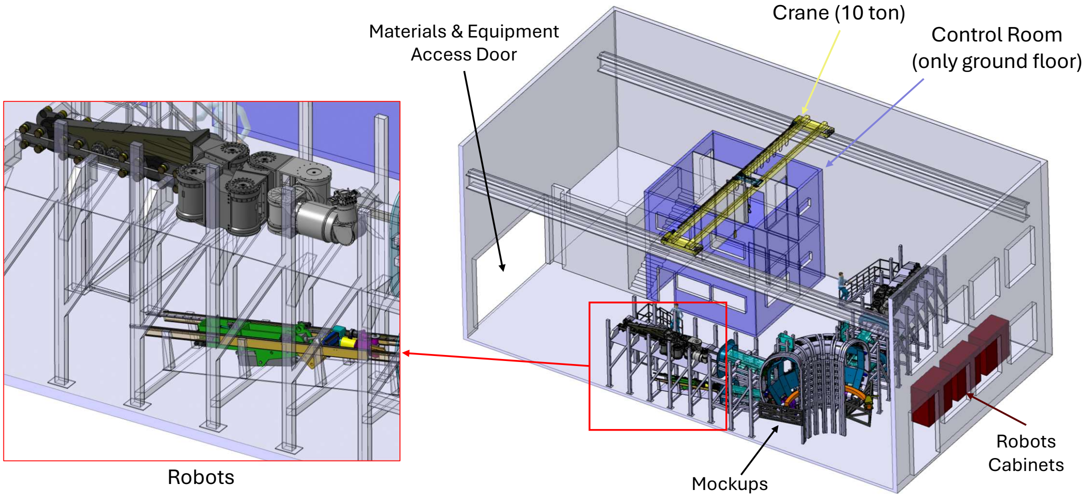


Figure 4.23: Physical Architecture (Concept Design) of the DTT RH Facility

foresees the development of the Radial Rails Concept Design by the design team in charge of the Robots subsystem Concept Design development, while the implementation in and adaptation to the Mock-up subsystem Concept Design by the design team in charge of its development. The same interface management issue will be faced in the Engineering Design phase and will be even more complex as it will represent an interface between two different manufacturing companies instead of two different design teams of the same project, at a more detailed design stage closer to manufacturing (see Section 4.3.2).

To enable manufacturing companies to proper understand the boundaries and interfaces of their Scope of Supply, interfaces shall be properly documented in the tender Technical Specification, through dedicated sections or Interface Sheet documents, as also described in Section 4.2.5.

Interface and Integration analyses and simulations can be generally divided in two types:

- Static Integration analyses: the digital twin 3D CAD models are first integrated in a unique 3D CAD assembly and proper interference and collision analyses are performed through the tools offered by the PLM platform's CAD modeling application (that is Assembly Design on-client app for 3DEXPERIENCE). Internal and external interfaces among subsystems are also analyzed to ensure that every component is in its nominal design location (position and orientation) with respect to the interfacing systems. This activity also helps to better clarify and organize internal and external interfaces for each subsystem. Components' localization is also verified against the Global Coordinate System (GCS) of the subsystem's 3D CAD assembly, to ensure they respect their nominal design location (position and orientation) with respect to the global reference frame. Once subsystems assemblies are integrated in the main digital twin of the entire facility, their localization is verified against the GCS of the 3D CAD assembly of the entire facility.

- Kinematic/Dynamic integration analyses through robotics simulations: once static integration analyses have been successfully performed, kinematic and dynamic simulations shall be performed to ensure that the subsystems properly integrate during operations too, that means ensuring that the robots are properly designed to perform the assigned RH Tasks without colliding with the surrounding environment.

Robotics simulations are particularly important for the digital-twin based development of RH facilities, and, more in general, of RH systems, during both design and operations phases. In fact, during the design phase they allow for:

- Virtual integration analyses between RH equipment and work environment during operation, that means virtual integration among the RH facility's subsystem.
- Virtual verification of compliance of both RH equipment and surrounding tokamak/mock-up components design with allocated space requirements and constraints.
- Off-line trajectory planning and virtual verification for each RH Procedure.
- Virtual test of possible off-normal rescue RH Procedures.

Instead, during the operational phase, robotics simulation environments allow for:

- Off-line training of human operators, providing the virtual environment to execute teleoperation affecting digital twin virtual models only, without connection to real physical equipment.
- Assistance to human operators during on-line teleoperation procedures, extending the visual information coming from the limited number of onsite cameras and, therefore, increasing their perception of the operative environment.
- Connection to robots' Programmable Logic Controllers (PLC) for both transferring trajectories programmed off-line within the robotics simulation environment and, vice-versa, receiving trajectories programmed on-line from robots PLC.
- Workflow validation through simulation of RH Tasks sequences, Procedures and processes at facility-oriented level, instead of robot or task-oriented level, enabling estimation of mission performance metrics, such as the cycle time.

- Real-time connection during operation between digital twin models and physical counterparts, for visualization, monitoring and optimization of RH Procedures at facility-oriented level. This in turn allows to obtain an "alive" digital twin of the whole facility, similar to the industrial plants ones.

The use of robotics simulations during the operational phase of the facility is further discussed in Section 5.

3DEXPERIENCE platform's *DELMIA* area offers a wide set of tools for robotics simulations, such as the Equipment Design and Robot Simulation on-client applications. The first allows to implement in the digital twin 3D CAD models the kinematic configuration of the robots, allowing to create their digital twin kinematic models. The second allows to set-up and run robotics simulation, such as simulation of RH Tasks.

3DEXPERIENCE applications for robotics are designed for operation simulation of industrial factory work-cells but can efficiently be applied to the similar case of RH operations in RH facilities for fusion. Robotics simulations in employing the 3DEXPERIENCE platform can be carried out following the steps below.

1. **Creation of the digital twin simulation model.** The Concept Design digital twin models already present in the simulation environment are used to create a Study-Model dedicated to the simulation, to avoid to impact to the master digital twin models in case of simulation's re-iteration tests varying design parameters.

2. **Organization of the simulation model's hierarchical tree and assignment of resources.** In *Equipment Design* on-client application, the hierarchical tree structure of the CAD general assembly is properly re-organized for the simulation's scopes and each CAD system is assigned of the specific 3DEXPERIENCE resource. The available resources are designed for industrial application, but can easily be adopted in the context of the RH facility. The most relevant are: Robot, Tool Equipment, Control Equipment, Manufacturing Product, Manufacturing Cell. For instance, the Manufacturing Cell indicates the overall CAD assembly of the environment in which the operations are simulated, represented by the specific work-cell in industrial application and by the entire RH facility in the case herein discussed. Or, to provide another example, the Manufacturing Product, which in industrial work-cell applications is the tool that the manufacturing robot picks to perform machining, handling or any other type of operation, is the tokamak's component to be handled by the robot in the RH facility application. The resources determine the capabilities of each digital twin model in the simulation environment. For instance, only Robot and Tool Equipment resources can be equipped with kinematics, run robotics simulations and pick other resources, while only Manufacturing Product resources can be picked by other resources.

3. **Kinematics implementation.** In *Equipment Design* on-client application, the kinematics is implemented in the robot digital twin models. This step allows the user to create the robot kinematics chain by defining the joint positions and orientation, set joint ranges, set joint speed and acceleration ranges, set the Home position, set the Tool Center Point (TC), implement Inverse Kinematics (IK) solver algorithms (which can either be automatically defined by the platform basing on the kinematics created or defined by the user), define simulation controllers allowing for robot manipulation in simulation environment.

4. **Simulation set-up.** In *Robot Simulation* on-client application, the robotics simulation is created, set-up, run and analyzed. During the simulation's set-up, the user defines the initial Simulation State and the simulation Task. The organization of robots' operation implemented in the 3DEXPERIENCE Robot Simulation application matches the usual organization of the RH Maintenance Manual. In fact, procedures involving multiple tasks executed by different robots can be organized, sequenced in parallel or in series, managed, run and reviewed together. These are called *Master Tasks* in the platform and can be used to implement RH Missions, with reference to the structures of Operations Sequence Description (OSD) within Maintenance Manuals depicted in previous Figure 4.1, like Divertor RH Mission. Then, 3DEXPERIENCE *Service Tasks* are the tasks assigned to the specific robots, and match the RH Tasks of the Maintenance Manual OSD's structure, like, for instance, Divertor Central Cassette installation. *Service Tasks* are set-up to plan the trajectory traveled by the robot, by adding each movement, grab, release or handling operation. This can be done either in Forward Kinematic (FK) approach, by moving the robot step-by-step in the consecutive positions and recording the joint values as *Motion Activity* within the created *Task*, then obtaining the final completed trajectory; or in Inverse Kinematics (IK) approach, by defining a number of target frames (positions and orientations) along the trajectory and letting the IK solver determine the number and joint values of the consecutive *Motion Activities* making up the *Task* and allowing the robot to pass through the defined target frames with its Tool Center Point (TCP). Hybrid approaches, in which part of the *Motion Activities* are planned in FK and others in IK, are also valuable options. Each grab/release *Activity*, or set of *Motion Activities* inside a robot 3DEXPERIENCE *Service Task* corresponds to a specific RH Action of the Maintenance Manual's OSD. This one-to-one matching between 3DEXPERIENCE Robot Simulation hierarchical organization in *Service Tasks*, *Tasks* and *Activities*, and, respectively, the Maintenance Manual OSD's organization in RH Missions, RH Tasks and RH Actions, makes the 3DEXPERIENCE Robot Simulation application perfect as Digital Maintenance Manual core tool.

5. **Simulation run and analysis of results.** In *Robot Simulation* on-client application, the simulation is run. A wide amount of analyses can be executed, for instance: collisions and limit distances analysis; data monitoring, visualization and export (joints position, velocity and acceleration values, and TCP coordinates); joints value/speed/acceleration limits analysis; reachability analysis; 3D representation of the volume occupied by

the robots during the execution of the simulations. Animations can also be saved.

At the end of the process, the robot's digital twin models are equipped with robotics simulation models that can be managed and reorganized as desired at facility level, even in combination with simulation models of other robots. During facility's operational lifecycle, trajectories planned in 3DEXPERIENCE Robot Simulation environment can also be transferred to the real robot through the *Robot Programming* on-client application, that uses specific robot translators to convert robot *Service Tasks* into controller-specific languages, and vice-versa. This topic is deepened in Section 5.

As part of the robotics simulation activities contributing to the present thesis, an obstacle avoidance path planning algorithm to simulate and verify hyper redundant manipulators for tokamaks maintenance has also been developed and successfully applied to the test case of the DTT HYRMAN [139]. It is an IK algorithm able to find at least one optimal collision-free path for the manipulator, with the possibility of easily changing the optimization criteria. It also allows for easy data exchange with 3D CAD environments and to store joints sequence of optimal trajectory for future analyses.

These robotics simulations, as well as those executed within 3DEXPERIENCE Robot Simulation application, are kinematic simulations, which consider rigid body kinematics and neglect the dynamic effects cause by the weight, acceleration and velocity of the system. Dynamic simulations are instead augmented with dynamic engines that consider components weight, accelerations, and velocities to calculate forces and torques acting on the robotic system. Multi-body flexible dynamics simulations also allows to represent flexible dynamic behavior of mechanical multi-body structures such as robots. Even if RH equipment usually moves at velocities and accelerations so low that vibrations can be neglected, dynamic simulations are still essential to consider in the integration analyses and trajectory planning the exact configuration assumed by the robotic system due to its flexible behavior. In fact, accuracy requirements to have reliable simulations are so strict that the deviation between the rigid kinematic CAD models generally used for virtual simulations and the real flexible ones are not acceptable. Ensuring proper calibration between digital twin simulations models and real ones during real-time simulations of procedures is one of the most challenging scientific open points of the proposed approach. This topic will be discussed in more detail in Section 5.

### 4.2.4 VERIFICATION & VALIDATION OF SUBSYSTEMS CONCEPT DESIGN

During Verification & Validation, subsystems functions and requirements are verified for each subsystem independently from the other ones, unlike the previous phase of Integration among the different subsystems. In particular, as represented in the V-model, the Verification step is linked to the Functional analysis step and aims at demonstrating that each subsystem design is able to perform its design functions, while the Validation step is linked to the Requirements analysis step and aims at demonstrating that each subsystem design satisfies the design requirements.

In a digital-twin based system development approach, Verification & Validation are performed by creating simulation models linkable to the other digital twin models, such as 3D CAD models, requirements models, and test management models, all stored on the on-cloud database of the PLM platform. In particular, test management models allow to organize the virtual test-cases and link the simulation outputs to the requirements, automatizing the verification process. Moreover, dedicated simulation models can be linked to the 3D CAD models of the main project, so as to automatically update the design parameters after the test execution in case modifications are needed. This is done by creating 3D CAD Study-Models only including the CAD assemblies relevant for the simulation and to be used as CAD base models for performing the simulation. The link between the Study-Models and the master digital twin models is kept, but can be deactivated to reiterate the simulation with several design parameters. When the simulation tests have completed and the design requirement is met, the design parameters are frozen and the link with the master digital twin models can be reactivated to transfer the modification and update it.

Robotics simulations can be seen as a transitional test practice between the Integration and Verification & Validation steps of the V-model. In fact, even if they primarily allow to perform integration tests among the different subsystems, as described in the previous section, they are also valuable to verify & validate specific robots' design functions and requirements. For instance, a design requirements for the DTT RH Robots is to execute the RH Tasks guaranteeing a minimum clearance of 20 $mm$ between the moving components and the surrounding environment. Robotic simulations allow to verify this requirement for each robot. The simulation (or verification) output parameter, in this case the minimum clearance between the system robot with handling component and surrounding environment, is automatically read from the simulation and used in the test management model to be linked to the requirement parameter stored in the requirements model. The comparison between the two values provides the result of the test-case. Since all the models are stored on-cloud, every time there is a modification either in the design parameters, or in the requirement parameter value, or even in the verification output parameter value, the test-case result is automatically recalculated by the test management model.

Other Virtual test simulations needed to achieve Verification & Validation of the subsystems Concept Design of RH facilities for fusion reactors, also performed in the Case Study of the DTT RH Facility, are the structural Finite Element Analyses (FEA) to be executed on both Robots and Mock-ups. For the Robots, they allow to: verify robotic components compliance with stress, strain and displacement under nominal and extreme operational loads; perform fatigue and durability assessment by predicting the component lifetime under cyclic conditions; perform buckling and stability verifications; analyze vibrational behavior by identifying natural frequencies and potential resonance risks; perform thermo-mechanical simulations; verify contact and joint stiffness; simulate failure mode scenarios. For the Mock-ups, structural analyses allow to verify the structural integrity of the system in each static and dynamic load case for each RH Task. Moreover, they are especially important for the Mock-up system to ensure that the inertial properties and structural behavior (flexibility) of the designed mock-up components match with the ones of the corresponding DTT components, with the ultimate goal of making the robots handle the same loads within the same surrounding environment of the future DTT during installation, removal and handling operations. In this case, an iterative process is carried out until the proper matching is achieved between the structural behavior of the mock-ups and the corresponding DTT components, as shown in Figure 4.24.

### 4.2.5 COST ESTIMATE AND DOCUMENTATION OF SUBSYSTEMS CONCEPT DESIGN

The Concept Designs developed for the DTT RH Facility's subsystems, integrated with each other, verified and validated, shall act as feasibility projects supporting the tenders Technical Specifications for the award of the Engineering Design and Manufacturing contracts to manufacturing companies, one for each subsystem in alignment with the *distributed approach* for subsystem projects

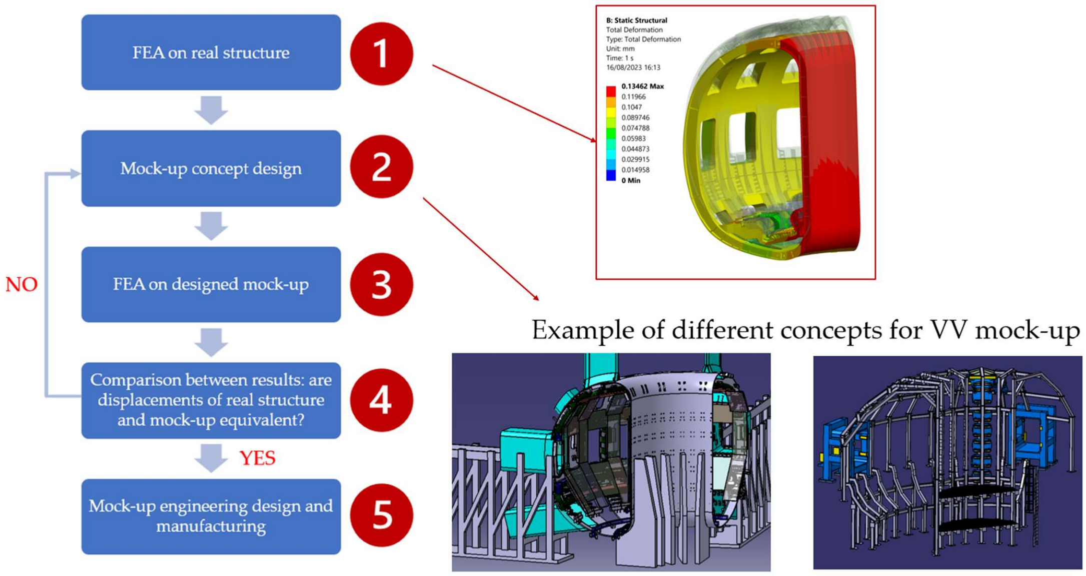


Figure 4.24: Iterative structural Finite Element Analyses (FEA) to ensure proper match between structural behavior of mock-ups and corresponding DTT components

development chosen for the DTT RH Facility. A cost estimation shall be carried out on the developed Concept Designs to set the amount of the contracts and demonstrate the feasibility of the projects within the contract budget. The following cost factors shall be taken into account:

- Project Management & Engineering costs.
- Manufacturing Engineering costs.
- Raw Materials costs.
- Manufacturing costs (personnel and machinery).
- Component costs (sensors, actuators, brakes, gears and transmissions, controllers, power electronics, cables and connectors, gripper and tools, etc.).
- Additional equipment costs.
- Software Development costs.
- Packing and Transportation costs.
- Assembly and Integration costs.
- Costs for Factory Acceptance Tests (FAT) and Site Acceptance Tests (SAT).
- Costs for assistance on-site.

- Security costs.
- Certifications costs (if necessary).
- Overhead.
- Profit.

For each subsystem, the tender Technical Documentation shall include all the material necessary to make the manufacturing companies fully understand the project and its requirements, both during tender award phase and during contract execution. The developed Concept Design shall serve only as one of the possible solutions, to demonstrate the feasibility of the project within the contract budget. The company remains free to modify the design, even substantially, provided that the project requirements are verified.

The Technical Documentation can be organized in different ways. In the Case Study of the DTT RH Facility project, different approaches are adopted by the design teams of the different subsystems, each achieving successful award of the contracts. The Robots tender Technical Documentation package have been organized in the following way [134, 133]:

- Main Technical Specification document, introducing the project, summarizing the Scope of Work, and describing the general requirements and the Work Breakdown Structure (WBS). The WBS represents the list of activities to be achieved by the company, each of them opportunely documented after completion. In the case of the DTT RH Facility's Robots these are: Project Management, Engineering, Procurement and Manufacturing, Assembly and Factory Acceptance Tests (FAT), Packing, Transport and Delivery to facility site, Site Acceptance Tests (SAT), and Assistance on Site. The procedures, objectives, and requirements of the FAT and SAT must be appropriately specified by the design teams and subsequently verified during their execution by the company.
- Requirement document, with detailed tables of requirements for the Engineering Design.
- Interface Control Document with annexed Interface Sheets, describing the interfaces between the project and the external systems (the other subsystems of the RH facility).
- Concept Design 3D CAD Model, showing the Concept Design developed as feasibility project.
- Concept Design Description document, describing the Concept Design developed as feasibility project, and supporting the Concept Design 3D CAD model.

The Control System Technical Specifications have been organized as the Robots' ones, except for the Concept Design 3D CAD Model and Description document, not present and replaced by a description of the Control System Architecture and Control Room layout combined within the Requirements document [137].

Instead, for the Mock-ups subsystem, a slightly different approach is chosen by the dedicated design team, with more information condensed in the Technical Specification document [135]. The Mock-ups tender Technical Documentation includes:

- Technical Specification document, including the following information: Scope of Supply (Hardware, Test, Documentation, and Logistic Deliverables, and WBS); technical requirements (manufacturing requirements, surface treatment requirements, welding requirements, components description and specific requirements, interfaces description and requirements, materials requirements); assembly operations description; Factory Acceptance Tests (FAT) requirements and description; logistic Requirements; Site Acceptance Tests (SAT) requirements and description; list of prescribed directives, regulations, codes and standards; required Milestones, Deliverables and Schedule of Activities.
- Concept Design 3D CAD Model, showing the Concept Design developed as feasibility project.
- 2D Drawings for Mock-ups type module (VV, FW, Divertor) and Interfaces, supporting the Technical Specification document and the 3D CAD Model by providing the manufacturing requirements in terms of dimensions, manufacturing tolerances, and inertial properties.

The tight deadlines prescribed by the PNRR public funding have made the employment of MBSE approach and design efficiency tools, such as digital twins and PLM platforms, even more essential, during the development of both the Concept Design and the Engineering Design.

## 4.3 ENGINEERING DESIGN AND MANUFACTURING OF RH FACILITIES

After completion of subsystems' Concept Design by the RH facility design teams, that generally also contribute to the stakeholder fusion reactor project and come from private or public bodies (mainly research centers, public agencies and academies), the Engineering Design and Manufacturing is usually entrusted to private manufacturing companies. This is done in the Case Study of the DTT RH Facility as well, in which the contracts for Engineering Design and Manufacturing have been successfully awarded to four different manufacturing companies, one for each subsystem, under the management of ENEA agency as contracting authority, responsible of the DTT RH Facility project. Hereinafter, the manufacturing companies awarded of the tender will be referred as contractors companies, while the DTT RH design teams partner of ENEA contracting authority will be referred as customer design teams.

Even if this phase of the digital-twin based development of the RH facility is in charge of different manufacturing companies that are free to employ the preferred design approach, methods and tools, keeping following MBSE principles and applying the V-model framework in RFLP approach is of primary importance to ensure the proper development of the design and of its digital twin. During the Engineering Design phase, the V-model is clearly applied with an increased level of detail and of the weight of manufacturing and technological concerns on design choices.

At this stage, the RH facility design teams that have developed the Concept Design shall supervise the work carried out by the companies through periodical follow-up and progress meeting, ensuring that it is aligned with the requirements and scope of the supply.

The facility digital twin shall constantly be implemented with the new or updated models produced during the Engineering Design by the manufacturing companies. To achieve this goal, two options are available:

- Access to the PLM platform cloud database and applications is granted to the manufacturing companies, which can therefore directly design with and modify the digital twin models under their responsibility, already available over the PLM platform cloud database. This option simplifies the digital twin Management task but requires the availability of several licenses to be granted to the manufacturing companies and the need for their design members to learn and operate with tools they are not likely skilled on. Moreover, permissions for manufacturing companies' design teams to access, visualize, and edit digital twin models shall be carefully managed to avoid the risk of unintentional modifications of models not under the own responsibility. Finally, with this options privacy concerns are more relevant, and the digital twin Management Team shall carefully avoid that project's confidential information outside the manufacturing companies' scope of work are not shared with them.
- Manufacturing companies develop the design over the preferred software and produce models of different format that must be than implemented in the platform and integrated with the other subsystems by the digital twin Management Team. This option makes the digital twin Management

task more complex but does not require availability of a wide number of licenses for the PLM platform and allows manufacturing companies' design teams to employ the preferred software they are skilled on to develop the design models. Moreover, this option significantly reduces the risk of unintentional models' modification, as every edit and update is made by the digital twin Management Team, and of sharing project's confidential information with manufacturing companies.

### 4.3.1 Third iteration of RFLP application for subsystems Engineering Design

As already stated, at this stage design decisions, methods and employed tools are chosen by the manufacturing companies. However, ensuring proper prosecution of the design workflow started in previous design stages can benefit the outcome of the project and enable its digital twin for seamless employment in the next stage of operation of the RH facility.

In this perspective, the application of the V-model should be reiterated at the Engineering Design level for each subsystem representing the scope of each supply (Robots, Mock-up, and Control System), starting from the RFLP paradigm. Therefore, the steps of Requirements analysis, Functional analysis, Logical architecture, and Physical architecture development are repeated once again at a deeper level of detail.

**Requirements** for Engineering Design are directly extracted, re-elaborated and further branched and expanded, if needed, from the supply requirements. To properly achieve this step, supply requirements must be fully understood and reviewed by the design teams of manufacturing companies. The contracts Kick of Meeting (KoM) and the first follow-up and progress meetings between DTT RH Facility design teams that have developed the Concept Design and manufacturing companies' design teams are therefore fundamental to make them proper understand requirements and scope of the supply.

**Functions** diagrams of Concept Design are reviewed and further expanded at Engineering Design level for each subsystem by each company. This represents the last functional analysis allowing to define all the functions and functional parameters the final subsystem must perform.

The definitive **Logical architecture** for the subsystem is directly derived from its functions. The Logical architecture developed for the Concept Design is reviewed and further branched to define all subsystem's components and parts. At the end of this step, it is possible to obtain and update in the PLM platform the complete PBS of the RH facility.

Finally, the complete **Physical architecture** is obtained by developing the design of each component. As already done during the Concept Design stage, a definitive physical architecture for the subsystem is only achievable after several iteration of virtual simulation tests able to completely integrate it with other subsystem, as well as verify and validate it. The obtained physical architecture represent the final Engineering Design, ready for preparation of manufacturing documentation to be approved by the customer design teams. The Engineering Design is the result of a Concept Design's revision based on a Design For Manufacturing and Design For Assembly principles [140], in light of the long-term manufacturing experience of the contractor companies. However, any design modification implemented during the Engineering Design development, to adapt it to the manufacturing needs, must be agreed with the DTT RH Facility customer design teams, to ensure proper integration with requirements and other subsystems.

The following main activities are included in the Engineering Design development by the contractor companies:

- Design development of electromechanical parts with iterative verification analyses and simulations,
- Development of hardware layout, low-level (for the Robots) and high-level (for the Control Room) control system architecture, logic diagrams, wiring and instrumentation diagrams.
- Preparation of manufacturing, assembly and metrology drawings.
- Design of low-level control system and power supply parts (for the Robots).
- Design of Control System software and firmware.
- Design of any necessary tool and fixture for construction, machining, handling, assembly and testing.
- Design of a detailed test plan on the Control System software module and on the whole architecture.

The final physical architecture of the DTT RH Facility at engineering design stage is shown in Figure 4.25

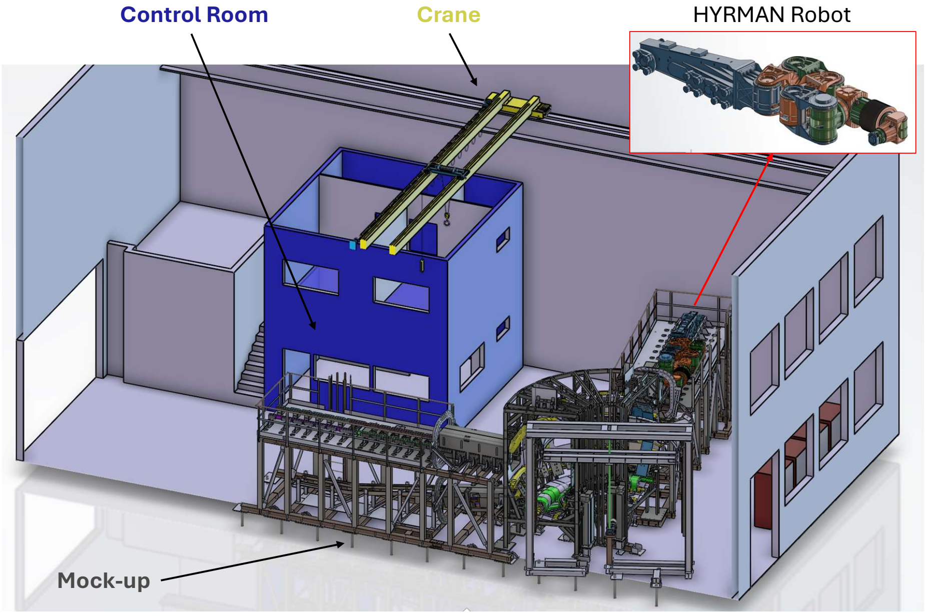


Figure 4.25: Physical architecture of the DTT RH Facility at Engineering Design stage

### 4.3.2 INTEGRATION OF ENGINEERING DESIGN DEVELOPMENTS WITH OTHER SUBSYSTEMS AND IN THE DIGITAL TWIN

In a *distributed approach* for the subsystems' development, as the one employed in the Case Study of the DTT RH Facility, the digital twin Management Team is responsible for the integration, implementation and update of the digital twin models in the PLM platform on-cloud database throughout the Engineering Design process. This is a task that requires constant supervision and integration checks among each contract, to ensure that no design model is lost and the digital twin is always updated along the design development. At the same time, the digital twin itself helps again to check correct subsystems' integration and manage their interface.

An example of challenging interface management task during the procurement of the DTT RH Facility's subsystem is the same provided at the Concept Design stage, that is the interface between the Radial Rails and the Robot Wheels. The Radial Rails are part of the Mock-ups contract, while their design depends on the Robots' design. This interface issue has been solved by assigning the design of the Radial Rails to the Robots' contractor company, that has then to be transferred with all the related documentation (3D CAD models, 2D drawings, description documents, etc.) to the Mock-ups' contractor company for manufacturing.

The same interface represents a challenge not only for the correct robots operation while sliding on the rails, but also for the correct robots installation after arrival at the RH facility. In fact, once arrived at the RH Facility, the robots shall be installed on the Cask Mock-ups' Radial Rails. These installation operations involve multiple subsystems (Robots, Mock-ups and even Buildings & Services), and therefore shall be planned and managed by all the involved customer and contractor design teams, with the support of the comprehensive high-level knowledge of the digital twin Management Team. For the DTT RH Facility, this interface issues has been solved by transporting the Cask Mock-ups already assembled with the Robots: after manufacturing at the Mock-ups contractor factory, the Cask Mock-ups will be delivered to the Robots contractor factory for installation of the manufactured Robots; then, these components will be delivered together to the DTT RH Facility, already assembled and ready to be placed on the Cask Mock-ups Support through the crane available in the building. The packaging must be properly designed by the Robots manufacturing company to safely protect the assembly composed by both the Cask Mock-up and the correspondent Robot during the transport.

Finally, another mentionable example of interface management issue is the interface between the Mock-ups and the Buildings. In the Case Study of the DTT RH Facility, the DTT RH Facility customer design teams had to coordinate the interface between the Mock-ups contractor design team and the Buildings' responsible personnel to provide to the Mock-ups design team all the required information needed to define the proper location of the installation holes of the Vacuum Vessel Mock-up on the building's floor.

### 4.3.3 VERIFICATION & VALIDATION OF SUBSYSTEMS ENGINEERING DESIGN

Virtual Verification & Validation of Engineering Design is performed through the same simulations and analyses as the Concept Design, mainly thermo-structural analyses and kinematics and dynamics simulations. Each contractor company employs the preferred software to carry out verification simulations, whose results must be carefully reviewed by the customer. Additional independent verification simulations carried out by the customer design teams are essential to both double-check the results and create Engineering Design virtual test simulations models to be stored in the PLM platform on-cloud database and linked with the other digital twin models, primarily requirements models.

In addition, further more detailed risk analyses shall also be carried out, such as FMECA (Failure Modes, Effects and Criticality Analysis), HAZID (Hazard Identification), HAZOP (Hazard and Operatbility Study) and RAMI (Reliability, Availability, Maintainability and Inspectability). FMECA enables a systematic evaluation of potential component-level failure modes, their effects, and their criticality, thereby supporting the prioritization of mitigation measures. HAZID facilitates a broad identification of hazards across technical, human, and environmental domains, while HAZOP offers a more detailed and structured exploration of deviations from intended operational parameters. RAMI analysis, in turn, quantifies system resilience and maintainability over the full lifecycle, highlighting design strategies for availability and fault tolerance in safety-critical environments. Applying RAMI methodologies to FOAK remote handling systems for fusion reactors is hindered by the lack of operational data, evolving system architectures, poorly characterized environmental loads, and stringent constraints on maintainability and recovery. These factors, combined with organizational and methodological gaps, currently limit RAMI from playing its full role as a quantitative design driver for RH robots. This also motivates the adoption of model-based and digital-twin approaches, capable of generating synthetic evidence on reliability and maintainability already in early design phases and of maintaining a live link between system models, RAMI analyses and operational feedback. Traditionally, such studies were carried out in conjunction with physical prototypes and testing campaigns; however, in the context of MBSE supported by digital twin technologies and PLM platforms, these analyses can increasingly be performed on virtual models. Digital twins of the robotic system, embedded within the PLM platform, allow hazard and reliability assessments to be integrated with functional architectures, simulation data, and real-time feedback, thereby enabling early detection of design weaknesses and continuous refinement of safety and reliability strategies throughout the lifecycle of fusion remote handling systems (see [141, 142, 143]).

Finally, realization of physical prototypes may be required in case critical parts of the subsystems are not fully verifiable through virtual simulations. This has been required, for the case study of the DTT RH systems, for the HYRMAN's Joint #6, whose components operation resulted to be close to the performance limits from the design analysis and simulation.

### 4.3.4 From Engineering Design to Manufacturing of subsystems

The manufacturing phase involves a first stage of manufacturing preparation and, then, the actual manufacturing stage. The manufacturing preparation marks the transition from Engineering Design to Manufacturing and includes: preparation of specifications for the purchase of materials and off-the-shelf products; definition and execution of all the activities necessary to qualify manufacturing procedures and processes, as well as the activities necessary to conduct software development; preparation of specific plans for mechanical structures, such as Welding Inspection Plan and Distortion Management Plan.

The activities carried out by the contractor companies for Engineering Design and Manufacturing preparation must be opportunely documented, so that, once completed, the resulting documentation proving the developed Engineering Design compliance with the contract requirements is sent to the customer for review. The phase of review of the Engineering Design and Manufacturing documentation is called Manufacturing Readiness Review (MRR) and involves multi-day meetings and document revision by the customer design teams. The required document deliverables and their contents are defined by the customer within the tender Technical Specification and may include: final 3D CAD models; mechanical and structural design reports; thermo-structural analyses, and kinematics and dynamics simulations reports; wiring and electrical schematics; software architecture and control scheme design report; electronics design report; risk analyses and FMECA/HAZID/HAZOP/RAMI reports; Design and Functional Requirements Compliance Matrix; Interface sheets; Manufacturing 2D drawings; Bill of Materials, drawing list and part list; software environment and tools description; assembly drawings and procedures; metrology drawings, procedures and calibration methods; material specifications and certificates; Welding Book; Manufacturing and Inspection Control Plans (MIPs). The successful completion of the MRR marks the beginning of the manufacturing operations.

To benefit the digital-twin based development process and in line with the MBSE approach, the contractor companies shall be encouraged to perform the previously described activities through dedicated software and digital tools, so as to produce resulting models alongside technical reports. This allows the digital twin Management Team to store in the PLM platform and connect to the master digital twin all the digital models developed by the contractor companies during Engineering Design and Manufacturing preparation activities, for both the design development (3D CAD models, 2D drawing models, complete PBS models, etc.) and its integration, verification and validation (simulation and analysis models, FMECA / HAZID / HAZOP / RAMI analyses models, test management models, Functional Requirements Compliance models). This approach is fundamental to also integrate the Engineering Design and Manufacturing preparation process in the model-based design approach adopted so far instead of dealing with a less efficient document-based approach.

### 4.3.5 Manufacturing, physical Verification & Validation through Factory Acceptance Tests (FAT), and delivery of subsystems to the RH facility site

The Manufacturing phase of the RH facility's subsystems is divided in the following chronological steps:

1. Procurement of all required materials, Robots low-level software, subsystems and components (including radiation-hard components and spare parts).
2. Procurement of all required materials and components for the manufacturing and assembly of the jigs and fixtures required to perform and complete FAT and SAT.
3. Manufacturing of the mechanical components.
4. Manufacturing of the electronic and electrical components, with unit subtesting of the single boards.
5. Robots low-level software production and testing of the identified critical parts.
6. Assembly and integration of procured and manufactured items, subsystems testing and integrated system testing, prior to FAT and SAT.
7. Procurement of all equipment required to carry out FAT and SAT.

These are valid for both the Robots and the Mock-up subsystems. For the Control System contract, the Manufacturing phase is instead better identified as Implementation phase. It includes:

1. Procurement of all hardware components to develop the control architecture of the control room.

2. Detailed design of all software modules.
3. Implementation and coding of all the software modules.
4. Preliminary testing of all software modules. Unit tests can be performed in this phase to evaluate each software module.

Once manufactured, the RH facility's subsystem are then assembled and physically tested at the contractor factory through the Factory Acceptance Tests (FAT). The assessments performed in the FAT Test Cases can either be explicitly prescribed by the customer within the Technical Specification document, or be at the discretion of the contractor, with just some examples provided by the customer as guideline, provided that they are able to verify all the design requirements specified in the dedicated documents or sections of the tender Technical Specifications.

In the case of the DTT RH Facility's Robots, the following illustrative FAT Test Cases have been provided to the contractors by the dedicated customer design team as guideline:

- Performance assessment for each Robot joint in terms of position and speed control, motion repeatability and resolution, load capabilities, etc.
- Performance assessment in terms of position and speed control, motion resolution, load capabilities, etc., of the terminal part of the Robot.
- Accuracy and repeatability assessment of the Robot terminal part with respect to its base frame.
- Robot kinematic reachability assessment.
- Robot flexibility assessment at full load conditions, and verification of the improvement of the terminal part positioning accuracy by adopting flexibility compensation techniques.
- Verification of telemetries from the Robot controller, with various Robot configurations, and actions in front of the foreseen commands to the Robot controller.
- Joint limits assessment and verification of the encumbrances.
- Verification of the tool interfaces.
- Assessment of the teach pendant functionalities.
- Assessment of the diagnostic and monitoring functionalities.
- Verification of alarms trigger levels.
- Verification of recovery and rescue procedures and devices.

Instead, for the Mock-up subsystem the following FAT Test Cases have been mandatorily prescribed to the contractor:

- Visual inspection.
- Weld inspection.
- Surface roughness of RH interface surfaces.
- Dimensional inspection.
- Assembly test of Divertor Mock-up on VV Mock-up.
- Assembly test of the Handable Divertor Cassette Placeholders on the VV Mock-up.
- Assembly test of the FW Mock-up on the VV Mock-up.
- Assembly test of the Handable FW Placeholders on the VV Mock-up.
- Tests on instrumentation.
- Functional Test of the Installation Tool.

For the Control System a set of minimum required FAT Test Cases has been prescribed to the contractor by the dedicated customer design team, separately for hardware and software. For the Control System's hardware, it includes the following Test Cases:

- Visual inspection of hardware components to check the external state.
- Validation of the electrical and logical operation of all off-the-shelf components.
- Electrical testing of safety and interface electrical panels.
- Verification of the operation of operating systems and software updates.
- Verification of the correct logical operation of PCs through a memtest cycle on RAM and hard drive.
- Verification of the operation of general libraries for interfacing with devices (HID, VR, monitors, etc.) and verification of device operation as per the device user manual.
- Verification of the logical operation of the security system consisting of a safety panel and safety operator devices (Emergency Stop + Enable).
- Electrical isolation testing for safety panels and interfaces.

For the Control System's software, the minimum required FAT Test Cases are the following:

- Individual software module testing within a simulation context (simulated robots) to verify compliance with all project requirements.
- Usability testing.
- Software vulnerability testing verifying that potentially vulnerability-causing actions have not been taken during the development cycle.

For each subsystem, the contractor company shall prepare FAT documentation or models including:

- Test Plan, including test objectives, identification of Test Cases, roles and responsibilities, schedule, test facilities and location.
- Test Cases, including for each Test Case the test description, layout and additional mock-ups required, suspension and restart criteria, required resources and tools, expected results, anomaly reporting and solutions, dependencies with other Test Cases, identification of required runs, Compliance and Traceability Matrices linking Technical Requirements and Test Cases/Runs.
- Test Procedures, including for each Test Case/Run the Run description, preconditions and required setup, input data, run detailed steps, expected post conditions.
- Test Report, including for each Test Case/Run the Test name and Case/Run IDs, data/charts describing the system behavior during the Test, pass/-fail indications and reasons, test records, inspection and quality records, certifications, qualifications, certificates of conformity or reports of nonconformity for each part.

The Test Plan, Test Cases and Test Procedures documents/models must be provided to the customer design teams before starting the FAT for review and acceptance. The phase of manufacturing and FAT documentation review is similar to the previous phase of MRR and is called Test Readiness Review (TRR). The successful completion of the TRR marks the beginning of the FAT execution phase. After the FAT execution, the Test Report allows the customer design teams to review the FAT performed and ensure that each technical design requirement is verified.

If not done before by contractor design teams, the digital twin Management Team shall create and store over the PLM platform on-cloud database, with linkage to digital-twin models, all the models developed by the contractor design teams during the manufacturing and FAT phase. This set of models includes: the as-built 3D CAD models, obtained through techniques like Reverse Engineering and Laser Scanning; test management models for FAT, linking the Test Cases to

Technical Requirements models, as done in the previous stages of virtual V&V and allowing to automate and implement in the digital twin the requirements tracking and physical verification process.

After the customer design teams have proven and accepted the successful FAT results, the RH facility's subsystems can be packed, transported and delivered to the operative site, that is the RH facility itself, where they will be unloaded and assembled in the operative configuration. At this point the different subsystems will interface among each other, therefore this phase requires strong integration effort by both the RH facility customer design teams and the contractors design teams. The RH facility customer design teams shall coordinate the organization of the operations of packaging, transport, delivery and assembly at the site, managing the interfaces among the contractor manufacturing companies and among the subsystems from their higher-level knowledge of the entire RH facility project. In particular, the digital twin Management Team can leverage the presence of updated and integrated digital twin models to provide massive support in this integration phase. The contractors design teams shall instead provide assistance on-site, leveraging on their lower-level, more detailed, knowledge regarding the subsystem under their responsibility.

The last part of the contracts for the procurement of the RH facility's subsystems is the execution of the Site Acceptance Tests (SAT). The SAT allow the commissioning of all the RH hardware and software equipment, and marks the beginning of the RH facility's operational lifetime. The SAT are faced by both customers and contractors design teams very similarly to the FAT. The same Test Cases are executed and the same plan, description and report documents and models shall be drafted. The only, significant, difference is the workspace. The execution of the tests at the RH Facility site allows, for the first time, to test the operation of the subsystems together, while interfacing each other. This means verifying the proper integration among subsystems and therefore the correct operation of the entire facility.

Commissioning and acceptance of RH hardware and software equipment (i.e., Robots and Control System) is among the global missions of RH facilities. For this reason, they will be discussed in the dedicated Section 5. Since the service life of the DTT RH Facility is not yet started, as it is currently at the end of the Engineering Design phase and is approaching the Manufacturing Readiness Review for each subsystem's contract, the discussion about the operational lifetime of RH facilities, starting with the SAT and commissioning of its subsystems, will be faced leveraging on the experience of the DTP2 RH facility, operating for ITER project since 2008. The next section of this thesis work will be specifically focused on the relevant scientific challenge of calibrating the digital twin models to the physical counterparts, in particular Virtual Reality (VR) kinematic models, also considering the effect of dynamic factors during operation. This is fundamental to ensure the reliability of the digital twin, thereby enabling its robust support during the RH facility's operational lifetime.

# 5

# Towards the operational lifetime of RH facilities

*This section evaluates the potentialities and constraints of a Digital-Twin based approach to RH facility operational lifetime management. The section also presents the proposed method to address the digitalphysical calibration problem, applied to the test case of the ITER Remote Handling Control System (RHCS) kinematic and VR models.*

The operational lifetime of RH facilities begins as soon as their subsystems are delivered to the facility site after manufacturing. In fact, Site Acceptance Tests (SAT) and commissioning of RH equipment are already fundamental step of the facility's service life, representing one of its global missions, as discussed in Section 2. Due to their complexity and high customization level, the supplied RH robotic equipment and the RH procedures shall be thoroughly tested before closing the contracts and accepting the supplies. This is even more important for the case study of the DTT RH Facility, in which the robot are not prototypes but the same final versions that will be used in future in DTT, where mistakes and unrecoverable operational incidents will not be tolerable. Therefore their correct operation shall be completely verified during SAT and commissioning, and then optimized and completely understood for proper control during the test campaigns at the DTT RH Facility, before employment in DTT environment.

In Section 2, the activities performed and results achieved by the most important RH facilities operating during the last 20 years for the acceptance and commissioning of the stakeholder fusion project's RH systems have been discussed, proving their importance and successful employment for these purposes. The development of the DTT RH Facility's subsystems has not yet achieved the manufacturing phase, with their delivery to the facility site for assembly, SAT and commissioning foreseen within 2026. Therefore, in the present section the experience gained by other already operating RH facilities is deepened and analyzed, to provide a robust reference for future application to the DTT RH Facility. ITER experience with RH systems and facilities is specifically deepened, with particular focus on the Divertor Test Platform 2 (DTP2) facility of VTT Technical Research Center of Finland. Some of the main innovations of the DTT RH Facility lie in the massive use of digital twin technologies over collaborative cloud-based PLM platforms, especially during the Facility's service life when the Human-Machine interaction in the Control Room plays a central role. So far, the application of digital twin technologies in RH systems and facilities for fusion has been mainly consisting of Virtual Reality models. These, coupled with advanced controllers, such as haptic devices with force feedback, allow to support the human operators in the Control Room by providing them information and instructions that enhance the environment visual perception coming from the limited number of on-site cameras. In this way, human operators can make more informed, aware decision while teleoperating the RH equipment. For instance, Joint European Tokamak (JET) has been one of the first projects to test the usage of digital twin and VR technologies in support of its RH systems [144], continuing and improving their application until nowadays and making its site one of the most advanced hubs for robotics and telerobotics in harsh environment such as fusion reactors, even due to the realization of the dedicated RACE facility. Since that time, these technologies have emerged as essential instruments in the control system for remote maintenance operations of tokamaks [145]. The development of these technologies will be further discussed in the present section. The experience gained from ITER RH system's development, specifically in its DTP2 Facility, will be deepened, with particular focus on and proposing an innovative solution for the problem of calibrating the digital twin and VR models to the real physical environment. The outcomes of this analysis is intended to be replicated on the DTT RH systems during their commissioning in the DTT RH Facility.

## 5.1 THE IMPORTANCE OF RH FACILITIES IN DESIGN FINALIZATION, ACCEPTANCE AND COMMISSIONING OF RH SYSTEMS: THE EXPERIENCE GAINED FROM ITER

As widely discussed in Section 2.2.2, the development of ITER RH system has been strongly assisted by RH facilities. They have been massively using for almost 20 years both to support design development, driving design optimization and finalization process through experimental test on mock-ups and prototypes, and to test, accept, and commission final version of RH equipment, control hardware and software, and procedures, as well as for training personnel in performing the challenging teleoperation tasks. As seen, different facilities have been developed, each focusing on a specific subsystem and procedure of the ITER RH system.

Digital twin and VR software module are also relevant within ITER Remote Handling Control System (RHCS). VR technologies have been already experimented over past years as part of ITER projects activities, to support both RH design teams for robotics trajectory planning and human operators in RH facilities. To provide reliable support in both these two activities, digital twin models, first of all VR models, shall faithfully reproduce the physical configuration of the physical counterparts. To achieve this scope, they must undergo a process of calibration to the real-world scenario. This process can only be completed once the real world scenario, i.e. the real stakeholder fusion device's in-vessel environment, is available. However, RH facilities allow to perform preliminary calibration activities that significantly reduce the gap between digital twin models and physical counterparts. Moreover, they allow to define the method, strategy and workflow for efficient, fast and seamless re-application of calibration activities on the real RH robots in the real stakeholder fusion device in as-built configuration. ITER experience has also allowed to recognize the importance of calibrating the configuration of digital twin models, such as the VR models, to the physical configuration of the real corresponding equipment. This is fundamental in robotics project where the complexity of procedures and the tight operational environment determine strict requirements in terms of matching accuracy between models and reality, such as fusion projects. Several solutions have been studied over last years as part of ITER project to calibrate RH systems' digital twin models to real physical behavior, in particular at DTP2.

However, a comprehensive solution has not yet been achieved and specific issues are still present. First of all, for instance, rigid body kinematics models, neglecting the effect of dynamic factors such as robot links flexibility or vibrations, are still used as part of the control system and of the digital twin models. The calibration between digital twin models and real-world scenario is one of the key steps to be achieved during the commissioning process.

Leveraging on the experience of ITER project, the problem of calibration between digital twin models and real-world scenario is more specifically addressed later in this chapter, after the description of the digital twin main roles during the operational lifetime of the RH facility. An approach for implementing flexible dynamic behavior of robotic mechanical structures in the digital twin and control system kinematic and Virtual Reality models is presented, with application to the ITER CMM-SCEE (Cassette Multifunctional Mover, equipped with Second Cassette End Effector) robot prototype present at DTP2 facility for the ITER Divertor RH procedures testing.

## 5.2 THE MAIN ROLES OF A DIGITAL-TWIN BASED RH FACILITY DURING ITS OPERATIONAL LIFETIME

After assisting the whole development process of the RH facility, digital twin models stored and managed over cloud-based collaborative PLM platforms provide significant support during the facility's lifetime, starting from the SAT and commissioning phase. If the facility development process has been correctly and constantly centered around the digital twin, as proposed in the present thesis, at the moment of its completion and start of operation the facility design and management team should have at disposal a comprehensive digital twin, storing all models, data, information elaborated during the design and progressively implemented, updated and managed in the PLM platform by the digital twin Management Team, for both systems and processes.

The functions of the digital twin in the facility's operational lifetime can be summarized in the following points:

- Provide an on-cloud repository, accessible from every project contributor from every place equipped with network access, for all design data, information and models of RH equipment and processes.
- Virtually simulate, test, evaluate parameters, review, and optimize RH Procedures through PLM platform's robotics simulation environment before

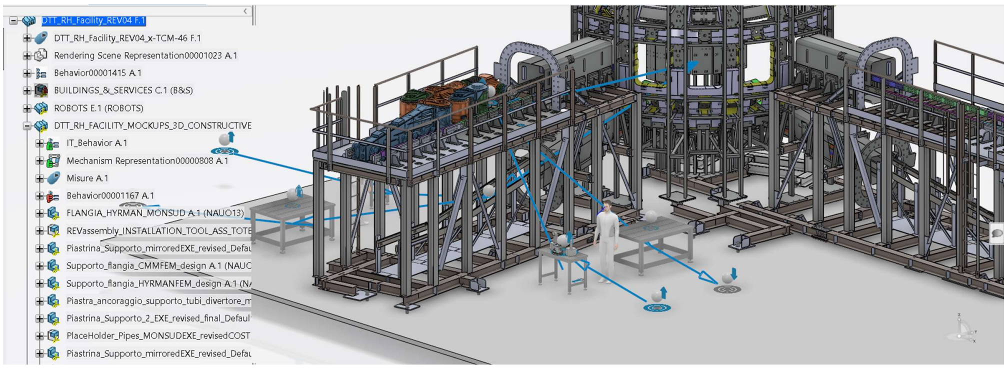


Figure 5.1: Virtual map of processes and material flow in DTT RH Facility, created through the *Factory Flow Simulation* on-client app of 3DEXPERIENCE

actual execution. 3DEXPERIENCE platform offers tools for sequencing different robotics simulations and create map of tasks, thereby allowing for modeling entire RH Procedures made of multiple RH Tasks executed by different robots.

- Implement facility process flows models connected to digital twin robotics simulation models to both test and verify their feasibility before actual execution and display in visual environment. This is applicable to both proper RH Missions, that are the ones to be repeated in DTT and whose testing is primary goal for the facility, and for any other process to be executed in the facility for storing materials, modifying environment configuration, and setting-up the RH Task test procedures by moving RH equipment from one position to another. To achieve this function, service handling equipment additional to RH systems, such as the building's crane, shall also be modeled, provided with kinematics and dynamics, and simulated. PLM platforms, such as 3DEXPERIENCE, offer dedicated tools for planning, simulating, analyzing, and reviewing processes and materials' factory flow, that can be efficiently employed for the same purposes in RH facility projects, making use of its digital twin models. This is done on the case study of the DTT RH Facility, employing the 3DEXPERIENCE applications *Factory Flow Simulation* and *Process Flow Simulation*. An example of the map of processes and materials flow in the DTT RH Facility, also including ergonomic simulations of handling operations by facility's personnel, is shown in Figure 5.1.

  This allows to completely simulate and test RH Procedures including all the related pre-processes and post-processes, thereby evaluating, reviewing and possibly optimizing efficiency parameters of the entire RH Procedure.

- Store the digital Maintenance Management Plan including all the workflows, schemes, processes, materials, equipment, and human operators instructions for each RH procedure to be tested in the facility, accessible through user-friendly tools supported by 3D CAD, VR and Augmented Reality (AR) technologies, and even from portable devices. Robotics simulations coupled with factory and process flow simulations are especially important for this purpose, offering an "alive", real-time updated, modeling and visualization base for the Maintenance Manual and Maintenance Management Plan implementation in the digital twin.

- Virtually test possible upgrades and optimizations for both RH procedures and equipment, employing process and robotics simulations models.
- Virtually test new RH procedures, tasks, operations, and equipment or tooling.
- Virtually test new environment configurations and resource allocations.
- Connect digital twin robotics simulation models to real robots for transferring trajectory paths and data in both directions: trajectories planned in virtual environment through the digital twin robotics simulation tool, offline without connection to the real equipment, can be extracted and transferred to the robots; vice-versa, trajectories planned on-line by controlling the real robots through the teach pendant and recording the traveled path can be uploaded on the PLM platform, run in robotics simulation environment, and stored within the robot's digital twin. This is done by importing specific robot translators in the PLM platform's on-cloud database, that allow for translation of robot tasks into controller-specific languages, and vice-versa. For instance, in 3DEXPERIENCE the *NRL Teach*, integrated into *Robot Programming* on-client application, enhances *Teach* function by presenting the Native Robot Language (NRL) program text within the interface, enabling direct editing and insertion of NRL instructions. The *NRL Teach* panel displays the task's instructions in the native robot language. In this way, 3DEXPERIENCE allows for both off-line programming, with no connection to real robots, and on-line programming, with connection to real robots.
- Real-time connection to real equipment. If the control system is built over the PLM platform, employing the dedicated tools, then the robot-embedded control hardware is already connected to the digital twin models. Otherwise, if the control system is separately developed by deploying dedicated custom-software integrated over robotics control frameworks such as ROS2, usual approach in RH Control System for fusion facilities also adopted for the case study of the DTT RH Control System, the digital twin models can be connected to the control system framework and Command & Control (C&C) unit through Low Level Communications Interface Protocols (LLC); the enabled connection between the control system framework and the digital twin PLM platform environments allows easy exchange trajectory files among each other, as well as to employ the same C&C unit for commanding both the hardware equipment and the digital twin simulation models. This enables both off-line test of the control system, unit and devices, only affecting the digital twin CAD/AR/VR models in PLM platform's robotics simulation environment instead of the real ones and allowing for human teleoperators training, and on-line representation of robot's physical behavior in the work environment, through

the digital twin CAD/AR/VR models in PLM platform's robotics simulation environment. Connection to actuation equipment and C&C unit allows to control the robot both in real and in simulated environment, while connection to sensor equipment allows to extract and link to digital twin models real-time data and information. These are then used to improve the accuracy of the digital twin model and close the gap with the real behavior, providing accurate and reliable real-time visual information to human operators to take more aware decisions during teleoperation in the control room.

To provide reliable information for planning, monitoring, controlling, and optimizing RH and facility procedures, digital twin models shall accurately match their physical counterpart. This is of even more fundamental importance during the challenging tasks of teleoperation of massive robots handling heavy-weight components in tight spaces with required accuracy on the order of a few millimeters. However, digital twin and control system models, such as kinematic models or VR models, are generally built with rigid body kinematics assumption, therefore neglect the dynamic behavior of the robot due to links flexibility, joints compliance, and vibrations. Robots for RH in fusion reactors are generally huge, heavy-weight cantilevered mechanical structures that handle components weighing tons and move at very low speeds and acceleration. In such cases, while vibrations can be neglected due to low speed and acceleration, link flexibility and joint compliance instead determine significant deviations from the nominal rigid body configuration. For such cantilevered structures, the deviation increases moving from the beginning to the end of the kinematic chain, causing a significant offset in the pose (position and orientation) of both the robot's end-effector and the handled component. This millimeter-scale offset is comparable to the expected level of accuracy required by the control system for teleoperation. Therefore, digital twin and control system models shall undergo a complex calibration process to achieve the required accuracy.

This concern is especially relevant for the digital twin VR kinematic models, that are generally built in rigid kinematics assumption while for RH objectives shall instead accurately reproduce the dynamic flexible robot configuration. In RH systems' design and control, digital twin VR models are generally used for three main purposes:

- Trajectory planning for RH operation sequences with digital twin robotics simulation models either in PLM robotics simulation environment, with assistance of VR tools, or even in dedicated VR environments for robotics simulations, to be then linked to the digital twin models on the PLM platform on-cloud database. Trajectory planning allows for finding the optimal trajectory for the execution of RH tasks, avoiding collisions and guaranteeing that limit distances between RH equipment and tokamaks surrounding environment are guaranteed. Trajectory planning activities are fundamental since the early design stages, to verify that the robot design can be integrated with the tokamak environment and to find at least one feasible trajectory to perform each required RH Task.

- Training human teleoperators by manipulating virtual equipment off-line, with no connection to the real-world environment and therefore without the risk of equipment damage.
- Supporting human teleoperators during on-line manipulation of real equipment, by providing them with 3D virtual renderings both on screens and in VR immersive environment, expanding the visual information of the limited number of on-site cameras and providing additional instructions even through AR techniques.

Calibration of digital twin VR models to the real-world scenario is of primary importance for all these purposes, to ensure that the virtual images at disposal of the human operators match the real equipment configuration in real-time during the execution of the RH procedures.

In next section, the problem of calibration between physical equipment and digital models in robotics and in the ITER RHCS is deepened.

## 5.3 THE PROBLEM OF DIGITAL TWIN CALIBRATION TO REAL-WORLD SCENARIO

As mentioned, digital twin models, especially VR models, must accurately reflect the real positions of the RH equipment to serve their purposes. In fusion RH applications the large handled loads can cause deviations of the RH equipment configuration from the rigid body kinematics typically assumed in VR models [146]. In fact, VR software generally works with CAD models in nominal rigid configuration. However, during operation, the actual pose of the RH equipment might deviate by a certain $\Delta$ from the nominal one, due to dynamic influences, such as deformation caused by the weight of the equipment itself and the weight of the component being handled, as schematically represented in Figure 5.2. Additionally, deviations in the actual configuration of the equipment from its nominal design occur because of manufacturing impacts, such as variations within tolerance and non-conformities. The discrepancies between the actual and nominal pose during operation can be categorized into two types: geometric errors and non-geometric errors.

Geometric errors are directly associated with the robot's physical design and movement mechanics, encompassing inaccuracies in link lengths, misalignment of joint axes, and offsets in encoders. These errors arise primarily due to the real manufacturing processes, which are identified and selected depending on contingent workshop availability and procurement time and cost, and may result in differences between the actual and nominal configurations. Generally independent of the payload, these systematic errors can be mathematically modeled by modifying the robot's kinematic equations on the basis of the as-built system's actual dimensions measured with metrology systems.

Non-geometric errors are not directly related to the robot's physical geometry. They encompass factors such as thermal expansion, elastic link deformation depending on structural characteristics, joint compliance, backlash, hysteresis, gear transmission inaccuracies, accumulation of tolerances, gearbox flexibilities, looseness in joints and bearings, non-linearities in sensors, temperature variations, etc. These factors primarily stem from dynamic influences, notably the weight of the robot and the payload it carries, assuming that the robot moves slowly enough that dynamic effects such as vibrations can be disregarded. These errors are frequently non-systematic, more challenging to predict, and typically vary with operating conditions, being proportional to the payload and influenced by the robot's position and orientation [147]. They can be characterized by specific parameters also depending on probability distributions consistent with the available information.

These errors create a mismatch between the actual configuration that the robotic equipment adopts in operation and the nominal configuration outlined in the digital twin and control system models. Given that RH robots generally have cantilevered designs, this mismatch grows along the kinematic chain, peaking at the end-effector region. As a result, inaccuracies arise in the end-effector's positioning, which can undermine safety, efficiency, and precision during RH activities. Consequently, the handled component's spatial pose may also face significant alterations. Considering the critical accuracy and reliability required to RH equipment during operations, it is essential to accurately quantify, assess, or predict the deviation between the real and expected end-effector poses and integrate these findings into the digital twin and control system models. Therefore, these models must be appropriately calibrated, with parameters adjusted to match the real-world configuration of the equipment, instead of the nominal design, within the accuracy requirement (that generally is one order of magni-

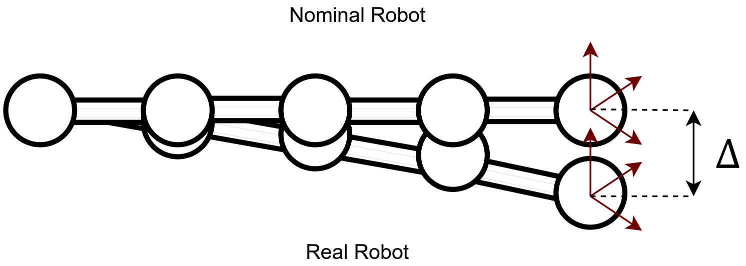


Figure 5.2: Offset between real and nominal robot's configuration at the end of the kinematic chain

tude lower of the minimum required clearance between moving systems and surrounding environment).

Three kinds of calibration are generally performed on robotic manipulators to implement the deviations caused by geometric and non-geometric errors in the digital models: joint-level calibration, kinematic calibration and non-kinematic calibration.

Joint-level calibration, or level-1 calibration, involves the initial step of sensor calibration, which aligns the joint sensor readings (such as encoders and force/-torque sensors) with the true measurements from the physical equipment. This process guarantees that the joint zero position in the digital twin and control system models accurately corresponds to the actual zero position in the real joint system.

Kinematic calibration, often referred to as level-2 calibration, focuses on correcting geometric errors by incorporating kinematic error models into the digital twin and control system models. This process begins with the calibration of the robot base frame with respect to the environment base frame, and then proceeds by modifying geometric parameters such as the lengths of links, offsets at joints, and the orientations of axes to match the real as-built correspondents, relying on measurement data collected through metrology technologies.

Non-kinematic calibration, or level-3 calibration, is focused on adjusting non-geometric errors by integrating non-kinematic error models into the digital twin and control system models. This approach considers dynamic factors influenced by the payload, like link deflection and joint compliance. [148, 149, 150].

Various strategies have been established to incorporate both geometric and non-geometric errors into robotic control systems via kinematic and non-kinematic calibration methods. Typically, kinematic calibration involves developing error models by adjusting kinematic parameters, such as the Denavit-Hartenberg parameters, based on real-world robot measurements collected using metrology tools like laser trackers and motion capture systems. In contrast, non-kinematic calibration is more intricate because it has to address non-linear dynamic behaviors. Consequently, Artificial Intelligence and Machine Learning techniques, leveraging convergence optimization algorithms, are frequently utilized to adjust and compensate for deviations caused by non-linear non-geometric factors from the standard configuration [151, 152, 149].

The execution of calibration procedures is growing rapidly in the industrial sector as well, employing the afore-mentioned methods to ensure accurate and reliable operation of manufacturing robots. However, calibration activities in the industrial sector are mainly focused on the real robot systems, as there is less need for accurate matching between real word equipment and control telemetry data and models, that instead is fundamental in fusion RH tasks to enable reliable teleoperation.

VR models are among the collection of RH digital twin and control system models for which calibration is necessary. Nowadays, methods to enable VR models, renderings and simulations with real-time structural flexibility simulation capabilities are under study, in the research field commonly known as Flexible Multibody Dynamics [153]. However, real-time dynamic, structural Finite Element simulations of flexible multibody structures are still limited by the high computational capacity required compared to the one provided by the current technology.

The last part of this thesis work proposes a simpler, highly computationally efficient method for calibration of the digital twin VR models of RH systems for fusion. Even if this process is discussed regarding calibration of RH robots' models, it is important to underline that calibration of the operative environment's models to real as-built geometry must also be carried out to ensure reliable simulation of robots' operation and integration with surrounding components.

The method herein proposed is developed as part of the calibration activities for ITER RH system, in collaboration with the Fusion For Energy (F4E) agency (European Joint Undertaking for ITER and the Development of Fusion Energy, based in Barcelona, Spain). In fact, calibration activities are currently on-going on ITER RH hardware and software systems, massively benefiting from the support of mock-up and prototypes in RH facilities. The method for digital twin to real-world calibration employs as test-case the ITER Cassette Multifunctional

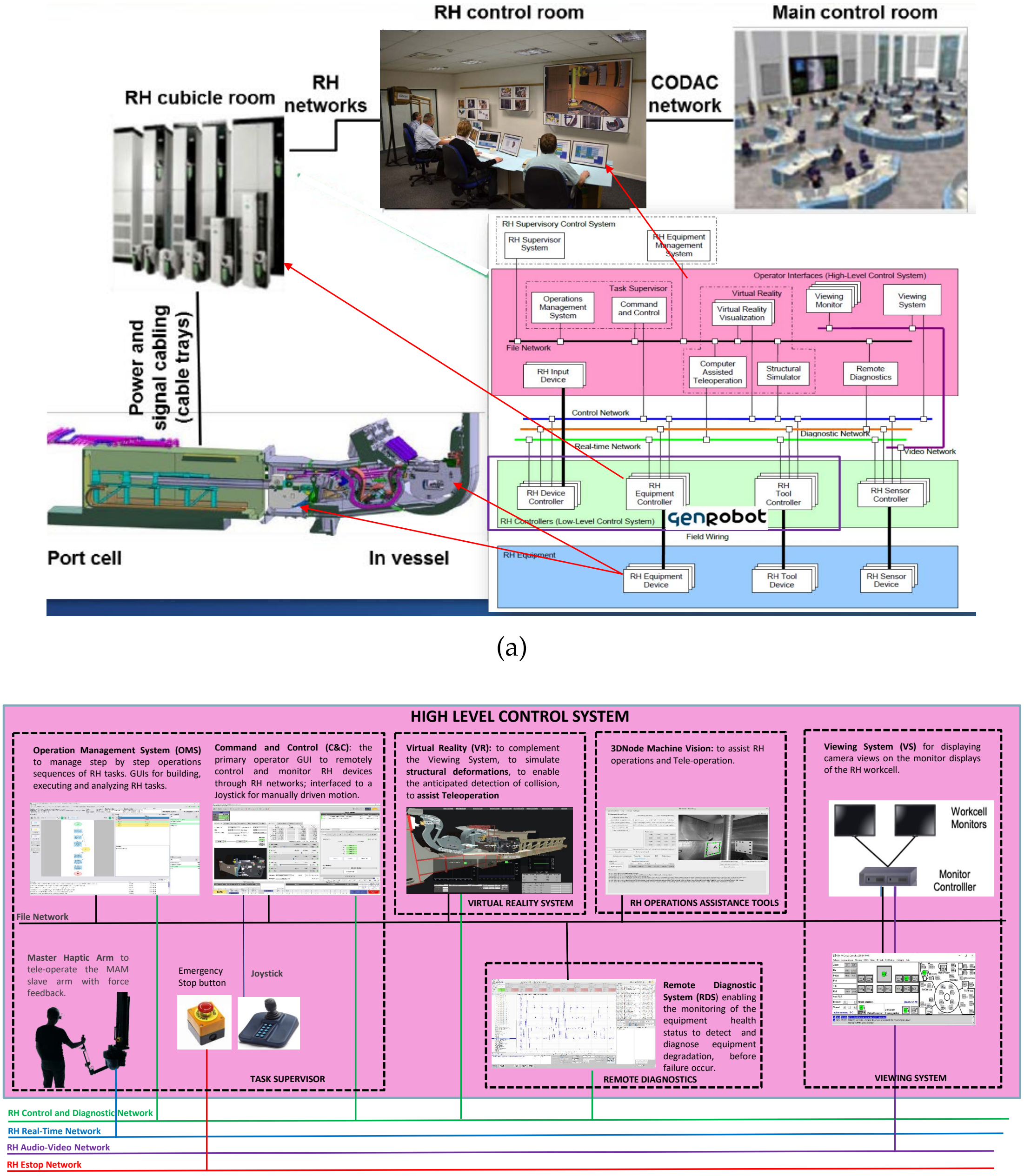
Mover equipped with Second Cassette End Effector (CMM-SCEE) prototype available at Divertor Tokamak Test 2 (DTP2) facility of VTT Technical Research Center of Finland in Tampere. Its VR model is calibrated by developing a Structural Simulator tool to be embedded in the VR module of the ITER RHCS.

As ultimate goal, the outcome of this activity shall then be re-applied on the DTT RH equipment in the DTT RH Facility, during the first phase of the facility's service life dedicated to RH equipment's commissioning.

## 5.4 Calibration of Digital Twin models to real-world scenario: the Structural Simulator tool for the VR module of the ITER RH Control System

The problem of calibration and compensation of geometric and non-geometric errors, deflections and compliancies in RH systems has been widely investigated for several years as part of ITER RHCS design activities [57]. Specific focus has been paid on the calibration of the VR models available to the operators, to enhance their closeness to reality and overall reliability during trajectory planning and both on-line and off-line teleoperation. In the ITER RHCS architecture, a specific module is dedicated to the VR as part of the High Level Control System. The ITER Remote Handling Control System (RHCS) is engineered with an intricate, layered structure to oversee sophisticated maintenance operations within a nuclear fusion setting. It amalgamates the High-Level Control System (HLCS) and the Low-Level Control System (LLCS) to allow accurate, real-time control of RH devices, as depicted in Figure 5.3a. The HLCS is in charge of supervisory control, human-machine interfaces (HMIs), and coordination throughout RH activities. It comprises five principal components: Operation Management System (OMS), Command and Control (C&C), Virtual Reality (VR), 3DNode Machine Vision, and Viewing System (VS). These elements enable the use of sophisticated visualization aids like virtual reality settings and real-time video feedback, enhancing teleoperation and situational awareness. Detailed functionalities of these modules are elaborated in [154] and illustrated in Figure 5.3b. Conversely, the LLCS, focused around the GENROBOT controller, is tasked with the direct manipulation of actuators and sensors in the RH equipment, ensuring precise and rapid reactions to commands via real-time networks and crucial safety protocols [155]. Communication across these layers is handled by dedicated industrial networks ensuring high reliability and minimal delay, featuring real-time EtherCAT protocols for motion and safety interlocks alongside high-bandwidth video and telemetry data channels. Safety-critical features, such as emergency stop controls and collision avoidance algorithms, are incorporated in light of the tight and intricate design of the ITER vacuum chamber and port structures [156]. All software components are produced following strict safety and quality criteria (SIL-1/SIL-2, MISRA C/C++), with RH facilities like DTP2 being integral for their testing and validation. This cohesive control infrastructure is vital for sustaining ITER Remote Handling (RH) competency, necessitating human-in-the-loop processes due to the reactor's complexity, variance, and safety requirements. The systems layered, modular design enhances operational flexibility and fault tolerance while supporting the long-term upgradability and maintainability of the RH system, which is crucial for ITER's extensive operational duration.

The VR models implemented within the ITER RHCS's VR module must accurately reflect the real positions of the RH equipment in the remote environment, which can have significant deviation from the nominal configuration with rigid body kinematics assumption [146]. To this end, a Structural Simulator (SS) tool is integrated into the VR module of the ITER RHCS to synchronize in real-time the models' configuration with the actual equipment. This ensures precise replication of both geometric and non-geometric errors resulting from link deflection and internal joint clearance or compliance. R&D efforts have been dedicated to the divertor RH equipment to establish a consistent methodology for real-time structural deformation modeling under load [57]. Leveraging the extensive calibration and compensation expertise of the ITER RHCS design teams and utilizing a wealth of empirical structure measurements from past test campaigns, an innovative strategy for developing the SS tool aimed at calibrating the VR models of the ITER RHCS is under development and is shown in this section. The primary focus of the SS development process is to ensure high accuracy and frequent updates, with the objective that the VR models closely reflect their real counterparts in real-time. The resulting accuracy shall be of one order of magnitude lower than the maximum clearance tolerated between the moving systems (robot plus handling component) and the surrounding environment, that in the case study of the CMM-SCEE translates into a required accuracy of $\pm 3\ mm$ or less, measured at the extremity of the kinematic chain where the



(a)

**Operation Management System (OMS)** to manage step by step operations sequences of RH tasks. GUIs for building, executing and analyzing RH tasks.

**Command and Control (C&C)**: the primary operator GUI to remotely control and monitor RH devices through RH networks; interfaced to a Joystick for manually driven motion.

**Virtual Reality (VR):** to complement the Viewing System, to simulate **structural deformations**, to enable the anticipated detection of collision, to **assist Teleoperation**

**3DNode Machine Vision:** to assist RH operations and Tele-operation.

**Viewing System (VS)** for displaying camera views on the monitor displays of the RH workcell.

**Master Haptic Arm** to tele-operate the MAM slave arm with force feedback.

**Remote Diagnostic System (RDS)** enabling the monitoring of the equipment health status to detect and diagnose equipment degradation, before failure occur.

(b)

Figure 5.3: (a) Architecture of ITER Remote Handling Control System (RHCS); (b) ITER RHCS High Level Control System [157]

maximum deviation occurs; then, the tool must update at a frequency of 2 $Hz$ or more to be compliant with real-time output requirements.

### 5.4.1 Discussion about current calibration approaches at ITER and introduction to the test-case of the CMM-SCEE at DTP2 facility

Design teams for the ITER Remote Handling Control System have made expertise in kinematic calibration and compensation through the use of the Divertor Test Platform 2 (DTP2) at the VTT Research Centre of Finland (refer to Section 2.2.2). The RH robot for the ITER divertor is quite similar to the one used for the Divertor Tokamak Test (DTT) and comprises three main subsystems: (1) the Cassette Multifunctional Mover (CMM), (2) an end-effector (among the Second Cassette End Effector - SCEE, Standard Cassette End Effector - StCEE, and Central Cassette End Effector - CCEE), and (3) the payload (among the Second Cassette, Standard Cassette, and Central Cassette). Experimental calibration and compensation campaigns have been conducted with a prototype setup of the CMM-SCEE, which handles the Divertor Second Cassette [115]. The CMM-SCEE configuration is a robotic mover equipped with five joints: the first Radial Drive joint enables radial movement along the port's rails, the second Lift joint and the third Tilt joint allow for vertical movement, and the fourth Cantilevered Rotational (CRO) joint and the fifth Hook Rotational (HRO) joint facilitate toroidal movement (see Figure 5.4).

VTT have utilized the DTP2 facility, incorporating CMM-SCEE and Divertor Second Cassette mock-ups, in collaboration with Fusion For Energy (F4E) and ITER Organization (IO) teams to explore the impact of dynamic factors on the robotic structure. Promising solutions have been suggested for model-based calibration and compensation [115], including adding virtual joints to the kinematic model [62] and using deflection representation [61]. Kinematic and Non-kinematic error models were designed for integration into the control system's kinematic models. However, implementation of these error models in the VR models has started but still remains incomplete. Currently, nominal VR models based on rigid body kinematics assumption are still used in ITER RHCS. Therefore, there is a pressing need to develop a Structural Simulator tool that integrates error models into VR models to accurately reflect the real equipment.

Throughout the experimental campaigns at the DTP2 facility, a substantial

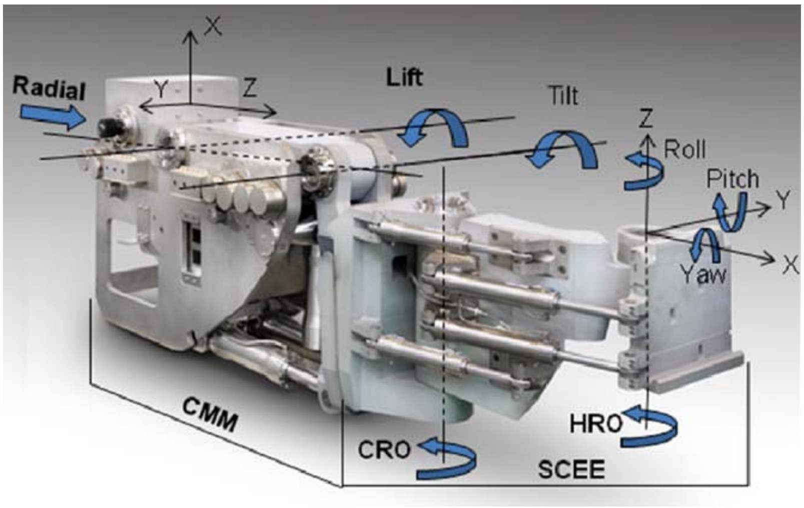


Figure 5.4: CMM-SCEE kinematics [115]

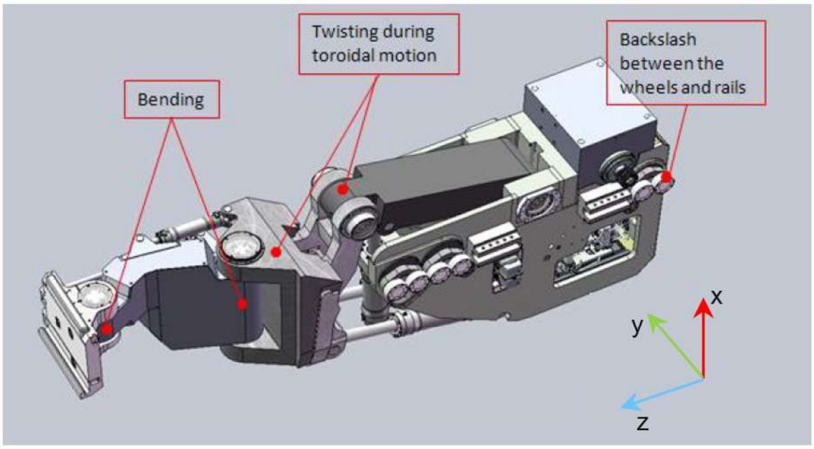


Figure 5.5: CMM-SCEE main non-geometric errors [158]

volume of measurement data was gathered from actual structures using metrology methods. These data were instrumental in identifying and measuring three primary non-geometric errors affecting the kinematics of the CMM-SCEE [158]. As depicted in Figure 5.5, these errors include: (1) backlash occurring between the wheels of the Radial Drive and the rails, resulting in rotation around the y-axis; (2) twisting at the Lift joint location during toroidal movements, due to link flexibility and joint compliance, leading to rotation around the z-axis; (3) bending at the CRO and HRO locations, attributed to link flexibility, resulting in rotation around the y-axis.

## 5.5 A new method based on the Virtual Joints concept for the calibration of Digital Twin VR models

Leveraging the extensive expertise of ITER RHCS design teams in calibrating and compensating RH equipment, alongside a wealth of real structural measurements from previous testing campaigns, a novel method for designing the Structural Simulator (SS) tool intended for calibrating the VR models of the ITER RHCS is introduced and explained in this section. This technique is developed using as test case the models of the existing DTP2 CMM-SCEE prototype previously utilized in calibration and compensation tasks. The new methodology revolves around the concept of virtual joints, which are supplementary joints incorporated into the kinematic chain of the VR model, designed to simulate the three primary errors detected in the CMM-SCEE structure during past calibration activities. Contrary to earlier methods, these virtual joints are integrated solely into the VR model without embedding them in the kinematic models within the controller. To implement this approach, the CMM-SCEE kinematic VR model is equipped with three additional Virtual Joints located at the critical points where the main non-geometric errors arise. For the CMM-SCEE case study, the shortness of the links and the compactness of the system do not require the splitting of CAD parts, hence the Virtual Joints have been placed in-between different CAD parts of the assembly by reorganizing its product tree. In case of longer robotic arms equipped with longer links (for instance, DTT HYRMAN), the links CAD part may need to be split in one or more sub-parts, in-between which the rotational Virtual Joints shall be inserted. The CMM-SCEE VR CAD model equipped with three virtual joints at the locations of non-geometric errors, is depicted in Figure 5.6.

Besides the three virtual joints that improve the CMM-SCEE kinematic chain, an additional rotational Virtual Joint is incorporated into the divertor cassette body to simulate its deflection under its own weight when lifted at the outboard edge by the CMM-SCEE. The position along the divertor cassette body of this Virtual Joint and its angular value are determined based on prior structural analyses and experimental activities conducted at DTP2 [159]. Specifically, the divertor cassette's deflection due to its own weight has been modeled as a 0.112-degrees rotation around axis A, depicted in Figure 5.7.

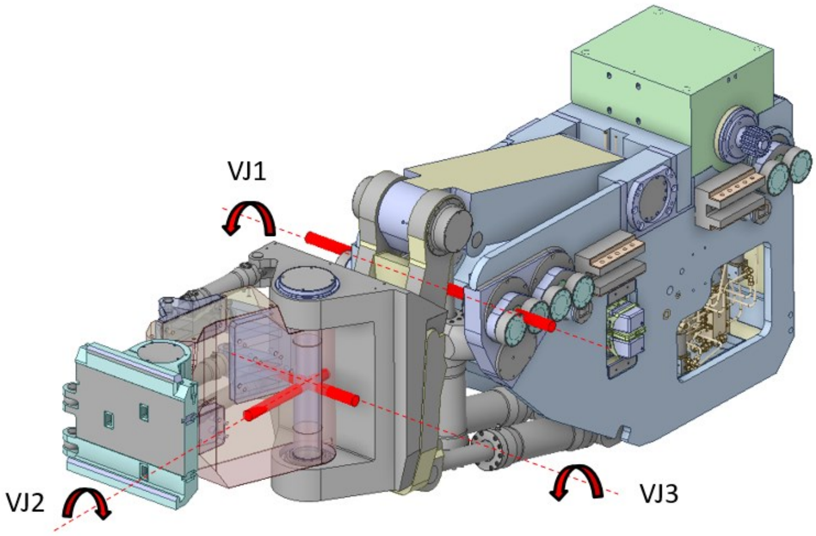


Figure 5.6: Location of Virtual Joints simulating the CMM-SCEE structural behavior

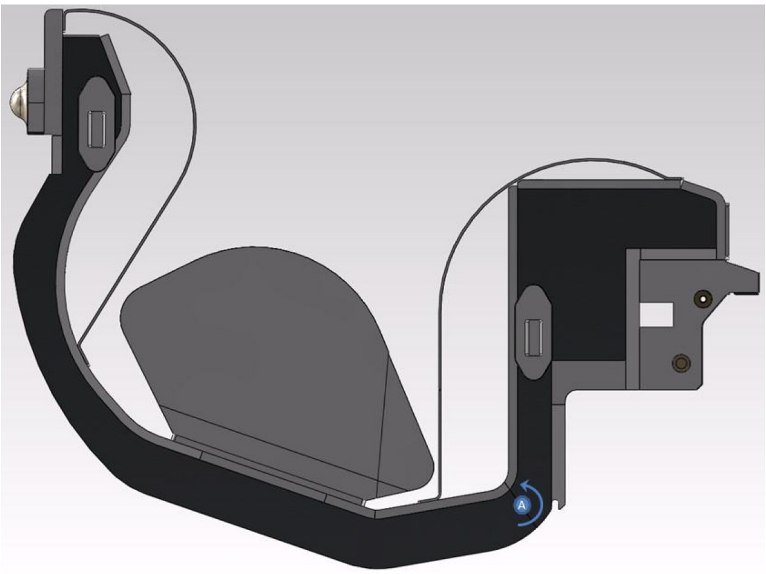


Figure 5.7: Location of Virtual Joint simulating divertor cassette's deflection due to its own weight

Table 5.1: Look-up table connecting the Virtual Joint values to the HRO joint values in No Load and (divertor cassette) Load configurations

| | RADIAL DRIVE BACKLASH (VJ1) | | | | | TWISTING (VJ2) | | | | | | BENDING (VJ3) | DIV BENDING |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| HRO Value [deg] | -61 | -39 | -21 | -6 | 0 | -61 | -48.8 | -36.6 | -24.4 | -12.2 | 0 | Any | Any |
| No Load VJ value [deg] | 0 | 0 | 0 | 0 | 0.001 | -0.01 | 0.002 | 0.014 | 0.026 | 0.038 | 0.05 | 0.27 | 0 |
| Load VJ value [deg] | 0.14 | 0.125 | 0.12 | 0.11 | 0.115 | -0.75 | -0.56 | -0.39 | -0.21 | -0.08 | 0.04 | 1.79 | 0.112 |

After importing CAD models into the VR software, virtual joints are integrated into the kinematic chain similarly to how nominal joints are added. To correlate these virtual joints with the nominal controlled joints, look-up tables are employed. Data were collected by adjusting both the payload, considering a zero payload for "No Load" and a 9000 N payload for "Load" configurations, and the toroidal position of the CMM-SCEE by altering the fourth CRO and fifth HRO joints. Consequently, a look-up table maps the values of each Virtual Joint, derived from on-site measurements of the corresponding non-geometric error, to the HRO joint value under both Load and No Load conditions, as detailed in Table 5.1. For HRO joint values not referenced during experimental studies and therefore missing from the table, the corresponding Virtual Joint values are calculated using linear interpolation. This ensures a realistic VR reproduction of the CMM-SCEE flexible structure in any operational configuration, driven by actual measurement data.

The lookup tables are encoded within a Low Level Communications Interface Protocol (LLC) bridge using C++, facilitating the connection between the GENROBOT controller and the VR software. This setup permits the transmission of RAPI command messages by using the five nominal joint values from the C&C module of the control system, thereby avoiding the necessity for changes in the kinematic model of the controller. The controller retains information solely about the nominal joints, lacking awareness of the virtual joints, which are exclusively integrated into the VR model and in the LLC bridge. These virtual joints are triggered based on the values of the nominal joints, thanks to the look-up table's implementation within the LLC bridge. The design of the Structure Simulator tool ensures a high update rate, as the virtual joints are manipulated identically to the nominal joints, using straightforward interpolation of available measurement data without extensive computational background processing, leading to a computationally efficient calibration process for the VR models.

### 5.5.1 Preliminary results from the implementation of the Virtual Joints to the ITER CMM-SCEE's VR models test-case

The effectiveness of the Structural Simulator (SS) tool based on the virtual joints concept, has been evaluated by uploading and comparing a nominal CMM-SCEE model (lacking virtual joints) with an SS model (featuring virtual joints) in VR environment. The comparison consisted in measuring the distance between two reference frames located at the extremity of each model's kinematic chain, specifically on the tip of the divertor cassette at its outermost point. Figure 5.8 illustrates the deviation between the nominal model (depicted in green) and the SS model with virtual joints (depicted in grey with a gold divertor cassette's nose) in the worst-case scenario. This worst-case scenario arises when the CMM-SCEE is moved toroidally with the CRO and HRO joints at their limits, consistent with the measurement data. In this pose, the reference frames are separated by a total distance of 131 mm, consisting of 110 mm vertical gap (X-axis) and 50 mm gaps in the toroidal and radial directions (Y-axis and Z-axis, respectively). These findings align with those gathered at DTP2 during previous experimental campaigns, yet they require further validation through additional, specific measurement data in subsequent testing phases. Moreover, they highlight the need to compensate such deviations through a reliable and well-designed compensation strategy. The compensation methods under evaluation as part of the ITER RHCS activities are shown in next Section 6. In order to confirm fulfillment of the update frequency requirement, timing logic is integrated around the command message transmission function within the LLC bridge. The command message is sent exclusively to the nominal robot without executing the SS, and the time needed to send the message is collected as output to calculate the update frequency. This value is then compared to the same result when the SS is in operation. The findings from the test are as follows:

$$\tau_n \approx 1\,ms \tag{5.1}$$

$$f_n \approx 1000\,Hz \tag{5.2}$$

$$\tau_s \approx 75\,ms \tag{5.3}$$

$$f_s \approx 13\,Hz \tag{5.4}$$

Where $\tau_n$ and $f_n$ denote the message latency and update frequency when the SS is deactivated and only the nominal VR model is operated, while $\tau_s$ and

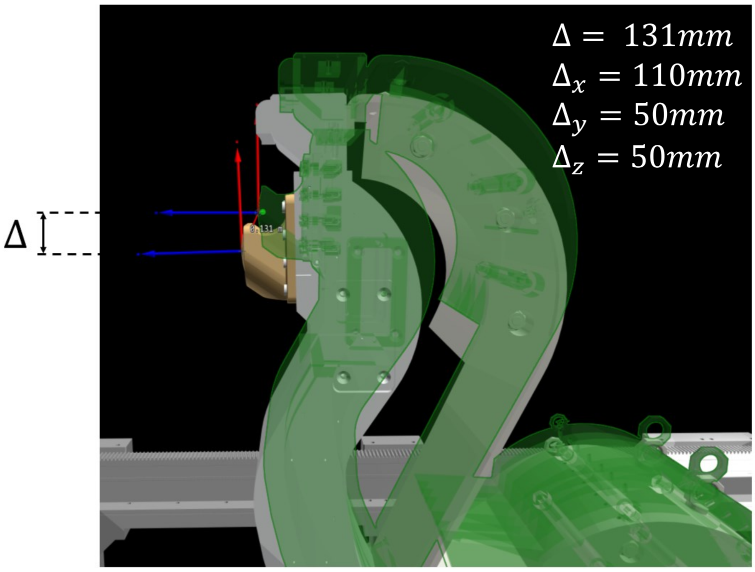


Figure 5.8: Resulting deviation between CMM-SCEE nominal model without Virtual Joints (depicted in green) and SS model with Virtual Joints (depicted in grey with gold Nose)

$f_s$ respectively indicate the message latency and update frequency when the SS is activated, allowing the real SS VR model to be commanded with lookup table readings and virtual joints updates. The update frequency requirement of at least 2 Hz is verified, despite showing a reduction in performance by approximately two orders of magnitude when the SS with virtual joints is active. These results are further discussed in next Section 6, by also analyzing possible future developments of the SS tool arising from its limits.

## 5.6 CALIBRATION ISSUES IN VIEW OF THE DTT RH FACILITY OPERATION

Calibration between digital models and real-world scenario, as well as compensation of geometric and non-geometric errors, shall also be performed during commissioning of DTT RH equipment in the DTT RH Facility. DTT RH robots are also huge and heavy-weight structure that handle massive components in a cantilevered manner. HYRMAN, the largest among the DTT RH robots, is a cantilevered structure almost 9 meters long, weighing 2.5 tons and handling a maximum payload of 350$kg$. Therefore, geometric and non-geometric errors, such as link deflections, will likely be significant and will need accurate calibration within digital control models and compensation. Calibration strategies for DTT RH equipment have not yet been established.

The approach proposed, applied and preliminary tested for ITER RH, such as the kinematic model's calibration methods developed at VTT Research Center and the VR models' calibration approach employing virtual joints concept developed as part of this thesis, are suitable for replication to DTT project during commissioning of its RH equipment in the DTT RH Facility. In this regard, the calibration process could follow the following steps:

1. Reconstruction of as-built 3D CAD models for both robots and environment (mock-up and buildings) through metrology techniques, such as Reverse Engineering and Laser Scanning, to be implemented in VR and robotics simulation environment of the PLM platform (3DEXPERIENCE). This could allow for the calibration of the operative environment and for the first significant reduction of the effect of geometric errors on the pose of robots.

2. Execution of an intense phase of on-site test campaigns aimed at studying the structural behavior assumed by the robots in the different load scenarios, employing metrology instruments and technologies. The measurement data shall be divided in two set, one to build the look-up tables of the Structural Simulator tool in virtual joints concept, and the other one to verify the correct behavior of the calibrated digital twin VR models against real physical equipment.

3. Data collection, data cleansing, filtering, reconstruction and analysis.

4. Definition of the proper number and position for virtual joints.

5. Drafting of the look-up tables by determining the interdependence between virtual joints and nominal joints, and the proper virtual joints values in function of the nominal joints.

6. Preparation of a LLC bridge connecting the PLM platform's robotics simulation in VR environment to the control system for proper communication among VR model, control system software and hardware, and physical RH equipment. Look-up tables shall be embedded in the LLC bridge as part of this step.

7. Execution of an intense phase of on-site test campaigns to verify the correct implementation of the Structural Simulator in virtual joints concept and connection to the control system, as well as the closeness between the calibrated digital twin VR models and the real physical counterparts, leveraging on the huge amount of data previously collected specifically for this purpose.

8. Optimization of the calibration process on the basis of the achieved results.

9. Improvement of the calibration process with additional new methods, employing, for instance, Artifical Intelligence, Machine Learning, closed-loop feedback techniques constantly enhancing the Structural Simulator tool accuracy with real-time measured data, and more.
10. Development and application of a compensation strategy.

These activities could benefit of the cooperation with the F4E and IO RH teams, currently working on the same topics.

The activities of commissioning of RH hardware and software equipment, such the calibration and compensation, represent the beginning of the facility's operational lifetime, and their successful completion marks the end of the RH Facility subsystems' procurement contracts.

Since then, the actual test of RH equipment, procedures, control framework, processes and operations will start, with the goal of achieving their complete testing and optimization before transfer and application to the real DTT site in Frascati, including every normal and off-normal procedure scheduled in the Maintenance Management Plan. Training courses for teleoperators will also start, for which assistance on-site from the contractors design teams of both the robots and the control system will be provided. The facility's digital twin, embedding all its data over the PLM platform on-cloud database, will keep supporting the management, monitoring, optimization, and update of the facility, as well as providing additional 3D/VR/AR visual information and data to the operators in the Control Room.

# 6

# Discussion

*This section summarises the outcomes of applying the proposed Digital-Twin based development method to the DTT RH Facility case study and discusses the results of the virtual-joints based digitalphysical calibration method tested on the ITER RHCS models. It also analyses potential enhancements to both the overall workflow and the calibration approach in light of remaining limitations.*

The work proposes a digital-twin based approach to the design, development, and operation of RH facilities for fusion projects. Even if Model-Based Systems Engineering (MBSE) methods and tools are nowadays widely adopted in industrial sectors, document-based design methods are still prevalent in fusion projects, due to several factors. MBSE principles depict cloud-based models instead of documents as better instruments to manage the product design process, from the early stages of conception and user needs identification, up to the phase of operation management and optimization. Indeed, cloud-based models allow for easy and constant design update implementation, as well as for design parameters interconnection and tracking, while featuring easy accessibility and information exchange. The models are centered around the digital twin concept, that allows to collect, centralize, easily access, manage and edit design data. The framework for storing the huge amount of data embedded by the digital twin is provided by Product Lifecycle Management (PLM) platforms, that are multi-user, multi-disciplinary, cloud-based platforms allowing to cover the entire product lifecycle. Cloud-based PLM platforms are structured around MBSE's design frameworks, such as the V-model embedding the RFLP paradigm. Such frameworks enable easy accessibility, transition and interconnection among data from different models, that in turn allow for systematic and efficient requirements traceability and iterative design application throughout the development process, guaranteeing constant design Verification & Validation. This is fundamental to ensure design efficiency and compliance within time and budget constraints, especially in complex projects. Cloud-Based Design and Manufacturing approaches also base the manufacturing planning and management process, in addition to the product design one, on the digital twin data stored on the cloud repository. This enables one-to-one interaction and data exchange between digital models and physical counterparts during operation for monitoring, control, and optimization. The concepts discussed so far converge and materialize in the Industry 4.0 paradigm, that, based on digital twin models stored over cloud-based PLM platforms and supported by IoT technologies, enables complete digitization of all products and processes within the industrial factory. This marks the transition from the digital twin concept, generally referred to products, to the Digital Factory concept, referred to entire industrial plants or facilities.

So far, these principles, concepts, frameworks, and tools have been mainly applied in the industrial sector. This doctoral thesis shifts their field of application to publicly funded and managed complex projects, like fusion projects. RH facilities provide the proper context for a digital-twin based design development approach, supported by frameworks and tools typical of Industry 4.0. In fact, application of these technologies to RH facilities is facilitated by their similarity in terms of set-up and dimensions with industrial work-cells. Indeed, modern industrial work-cells supported by Digital Factories are characterized by robotic machines executing components' handling and machining operations, just like RH facilities. It must be underlined, however, that significant differences between RH facilities and industrial robotics workcells are anyway present, especially regarding the control technologies, more advanced in RH facilities as enable remote operations with high precision and safety, the customization and specialization level of robotics equipment and procedures, higher in RH facilities, and the operations standardization, frequency and speed, much higher in industrial robotics workcells due to mass production volume needs. Nevertheless, these differences do not limit the suitability of RH facilities for application of specific frameworks and tools typical of MBSE and Industry 4.0, centered around digital twin/factory models managed over a PLM platform. Actually, digital twin models can be connected to the RH facility's control system to provide additional information, telemetry data, and visual input to teleoperators.

This doctoral thesis demonstrates the applicability of the mentioned concepts, approaches, frameworks and tools to RH facilities for fusion, providing a workflow even extendable to further facilities supporting fusion projects. This workflow centers the RH facility's design, development and operation process on its digital twin, managed over a PLM platform. This enables the application of an MBSE approach and of its most common tools, like the V-model embedding the RFLP paradigm. In complex projects such as fusion reactors and fusion facilities, managed and developed by geographically spread and multi-disciplinary design teams, the use of these frameworks facilitates project accessibility and data exchange, ensures its constant update, guarantees requirements traceability and verifiability, and allows for easy iteration between design and verification stages. Moreover, digital twin models such as 3D CAD, VR/AR and robotics simulation models provide virtual and graphical instruments that:

- Facilitate the RH facility's design and management team in integrating systems, managing interfaces, executing virtual verification tests before physical ones, as well as virtual test for modification, optimization, and upgrades to equipment or processes before their application to the physical counterparts, monitoring operations, and building digital Maintenance Management Plan augmented by visual real-time information and instructions. Real-time communication between physical equipment and corresponding digital twin, passing through the control system if necessary, can be enabled for visualization and monitoring of operations, and for transferring of information and telemetry data both ways.
- Provide a repository for all project data, easy to be accessed and update.
- Provide additional instruments, visual information, and data to teleoperators in the Control Room.

To prove its consistency, the proposed workflow is applied to the Case Study of the DTT RH Facility. The DTT RH Facility provides the proper context to show the efficiency of the digital-twin based method in driving the development and managing the entire lifecycle of such facilities, from the first stages of requirements engineering to the operational phase.

The application to the DTT RH Facility shows how to center the entire design development process around its digital twin, developed and managed through the tools of a PLM platform such as 3DEXPERIENCE by Dassault Systèmes, that also serves as on-cloud data repository. The use of a comprehensive platform embedding tools to cover the entire lifecycle development of products and facilities enables the application of iterative design methods prescribed by the V-model and its RFLP paradigm. The V-model is iteratively applied three times in RFLP approach: first at system level, that is the entire RH Facility, allowing to develop its Architectural Design and to define its main subsystems that make up its Logical Architecture; the second time it is applied at subsystem level, allowing to develop the Concept Design of each subsystem and, therefore, of the entire facility. Finally, the third time it is again applied at subsystem level but to develop the Engineering Design, enabling each subsystem for manufacturing. The Case Study also allows to define a workflow to manage the responsibility among design teams and manufacturing companies, in which the first are responsible of the subsystems' Concept Design, while the second of their Engineering Design after tender award.

The Case Study proves the fundamental support provided by the digital twin, especially for subsystems' integration, interface management, subsystem's iterative design and verification through virtual tests and simulations. The DTT RH Facility is now under realization, with many of its subsystems under manufacturing. It is expected to be completed within 2026, only three years after the start of design operations and within the tight deadline set by the PNRR public funding. This demonstrates how the application of the proposed practices successfully streamlines the process of design, integration, and management of RH facilities for fusion projects and allows to meet time and budget constraints.

Limitations to the application of these technologies to RH facilities are not missing and lead to further possible developments of the research. Indeed, for proper operation the facility's digital twin shall strongly be based on an extensive IoT network, just like Digital Factories for industrial plants. This may be a less relevant issue for an RH facility, as the hardware and software infrastructure enabling the extensive IoT network required is already provided by the presence of the RH control system. However, this still means guaranteeing a stable communication between hardware, control system software, and digital twin models through dedicated industrial networks, ensuring high reliability and low latency. These include real-time EtherCAT-based protocols for motion control and safety interlocks, as well as high-bandwidth channels for video and telemetry data. Another drawback is represented by the need for both large storage space for the PLM platform's on-cloud database and wide number of available licenses to provide the RH Facility's design teams with access to the platform environments, whose cost can be relevant. Moreover, storing the huge amount of data embedded in the digital twin over the PLM platform on-cloud database requires careful risk management in terms of privacy protection, data loss avoidance, management of data access and edit authorizations, and hacker infiltration avoidance during operation. Even if already faced and often overcome in private companies, this issue needs to be further addressed to enable safe adoption of cloud-based PLM platforms in big science projects such as fusion ones, where several design teams from different bodies are involved (research institutions, private companies, consortia, start-ups, etc.). At ITER, for instance, the whole control system is secured in an internal Plant Operating Zone (POZ) with a very restricted firewall for pushing data into the POZ. Implementation of cloud-based PLM platforms within an isolated POZ is feasible but not straightforward. A cloud-based PLM platform such as 3DEXPERIENCE cannot normally be operated in the Plant Operating Zone as an internet-hosted Software as a Service (SaaS), given that the POZ is subject to stringent segmentation and firewall rules that typically prohibit bidirectional connectivity with external networks. Compliance with cybersecurity and regulatory constraints requires to implement PLM platforms with a slight different method compared to their classic way-of-use, with two main alternative options available:

- Deploying a hardened, on-premise instance of the PLM platform on a local private network inside the POZ. For instance, 3DEXPERIENCE platform offers three alternative ways for its utilization: over the Dassault Systemès Public Cloud (less safe option for the cybersecurity and isolation needs of nuclear facilities), over a Private Cloud maintained by either a third-party company or an own Information Technology (IT) department, On-Premise within an own network [160].
- Establishing a controlled, often one-way, replication mechanism through which validated PLM datasets (e.g. configuration baselines, work packages, procedures, CAD views, DT snapshots, etc.) are transferred from the PLM platform external cloud into a local, predominantly read-only environment within the POZ.

However, this aspect requires further in-depth analysis as part of the future work.

Further investigations are also needed to build a proper interface between the facility's digital twin and the control system. As discussed, the digital twin models managed through the PLM platform tools offer wide potential applications to the need of the RH control system. For instance, they can both act as storage repository for control system data, and provide tools for implementation of a digital Maintenance Management Plan to be used during operation as Operation Management System and as digital Maintenance Manual, sending VR simulations enhanced with AR instructions to human teleoperators in the control room to increase their perception of the operational environment. However, the methods to interface digital twin models and the tools provided by the PLM platform with the RH control system framework need further in-depth studies, also to completely define the software to be custom-developed as part of the control system and the ones employable from the PLM platform. Reliable interface between the PLM platform environment and the control system is also required to enable real-time connection between physical equipment and corresponding digital twin models, as data shall likely pass through the control system during transition from the on-site sensor equipment to the digital twin models, or, vice-versa, from digital twin models to on-site actuators.

An accurate design of the interface between the PLM platform and the control system software architecture is even more required if one considers that Commercial Off-The-Shelf (COTS) PLM platform, such as 3DEXPERIENCE, are tailored to industrial applications and companies' needs. This means that the RH System design team shall carefully integrate with the control system software architecture those PLM platform's tools that could actually help the RH systems' development and operation. Nevertheless, modern PLM platform's tools are generally widely customizable by users, enabling the possibility to align them to the needs of RH systems' designers and operators. The ultimate solution to completely satisfy the requirements of the highly customized and specialized RH systems, procedures and teleoperation activities would be the in-house development of a comprehensive PLM-like software platform for design, development, management, control and operation of RH systems. However, this promising activity lies outside the scope of the present work, nevertheless it can be deepened as part of its future work. Anyway, a similar platform, customized, tailored and dedicated to the needs of the RH systems, would less be interfaceable with the rest of the stakeholder fusion project, removing the possibility of data and model sharing on a common PLM database.

Anyway, one of the most important open points to be overcome to ensure reliability and trustworthiness of digital-twin based approach, widely discussed in this doctoral thesis work, regards how to guarantee accurate calibration between physical equipment and corresponding digital twin models, even during real-time operations. This is especially important in context where accuracy and reliability are primary requirements, such as robotics in fusion reactors. Digital twin models shall reproduce in real-time the physical behavior of meters-long, tons-weighing cantilevered robotic structures with millimeter accuracy, during both trajectory planning and teleoperation procedures. The complexity of this mission is easily understandable. The main issues related to the methods currently adopted to overcome this scientific challenge lie in the too high computational efficiency required to perform real-time structural dynamics simulations of flexible multi-body systems.

This thesis proposes an approach for real-time calibration of digital twin models, like VR models, to real equipment configuration. It consists of a Structural Simulator tool, first developed to support the VR module of the ITER Remote Handling Control System (RHCS) test case, and based on the concept of virtual joints. The structural simulator, tested on the VR models of the CMM-SCEE prototype at DTP2 facility, demonstrates successful achievement of real-time calibration at an update rate of approximately 13 Hz, higher than the required 2 Hz. This efficiency is achieved as the structural simulator relies on virtual joints implemented in the VR model's kinematic chain, and refreshed through straightforward linear interpolation of measured data. When a move command carrying the nominal joint values is issued from the Command & Control (C&C) unit, the Virtual Joint values are also updated through rapid interpolation of the look-up table's values implemented in a Low Level Communications Interface Protocol (LLC) bridge. The results in terms of update rate are certainly important even if less impactful than the ones regarding accuracy, as the structural offsets change slowly.

Nevertheless, the accuracy results also seem satisfying as the structural simulator tool employing the virtual joints concept looks able to reproduce faithfully the structural behavior of the CMM-SCEE handling the Divertor Second Cassette. It effectively replicates the non-geometric errors identified in experimental on-site studies. Measurements carried out within the VR software reveal a significant deviation between the nominal model and the structural simulator model with virtual joints, resulting in a maximum total error of 131 mm at the kinematic chain's end (i.e., tip of the divertor cassette) in the worst-case scenario, a factor that must be considered both in trajectory planning and during off-line/on-line teleoperation. This issue is magnified by the fact that the clearances available between the RH systems and the tokamak's surrounding environment frequently measure around or below 20 mm. However, completed validation of the structural simulator tool's accuracy can only be completed after comparison with dedicated metrology data to be collected from scratch at DTP2 facility, activity that will be carried out as part of the future work to this research.

A robust strategy to compensate the resulting deviation shall therefore be developed during trajectory planning. The compensation approach impacts both the physical robots and their digital models, as it aims to ensure that robots can correct both geometric and non-geometric errors encountered during the execution of RH Tasks within the constraints of the compact tokamak environment. Two potential strategies are being explored:

1. The calibrated structural simulator VR model, using the Structural Simulator tool with virtual joints to incorporate errors, serves as a benchmark for trajectory planning in VR simulation environment. This ensures it neither collides with nor approaches the minimum distance threshold from the tokamak's surroundings. Concurrently, the nominal model's joint values are recorded in a trajectory file, which can be stored and transmitted from the C&C to rerun the trajectory whenever needed.
2. A compensation algorithm is crafted to consistently adjust the calibrated structural simulator VR model, aligning it with the nominal configuration based on the offset at the end of the kinematic chain. This offset is calculated from measurement collected either during previous metrology activities or in real-time through on-board and environment sensors and cameras (by using, for instance, Machine Vision / Motion Capture systems). This approach, however, could reduce computational efficiency due to the increased calculation demands each time the robot's configuration alters.

Both options are viable during teleoperation. The first approach implies that human teleoperators should use the real structural simulator VR model with virtual joints, even if they command the nominal VR model. The second approach suggests that teleoperators can use a single reference model because the background compensation algorithm continually aligns the structural simulator VR model (and the real robot) with the nominal configuration. Current activities involving the calibration and compensation loop focus on the first approach. Specifically, they are examining the ability of the VR structural simulator model using virtual joints to follow a linear path along each segment of the planned trajectory, without altering the performance of the controller internal kinematics.

The structural simulator tool for ITER RHCS's VR module does not miss drawbacks that determine possible further developments and improvements. Primarily, the splitting of CAD parts to add intermediate virtual joints effectively reproduces the robotic system's position at the endpoints of each link and of the kinematic chain. However, it fails in accurately simulating the elastic deformations that individual link structures undergo. This shortcoming could pose challenges when precise details are necessary not only for the end-effector's position but also for the robot's configuration along its kinematic chain. One possible solution to this issue involves editing the mesh by adjusting node positions using methods like 3D morphing [61].

The reliance of the suggested calibration method on measurement data obtained from on-site experimental tests in actual RH facilities represents another downside. Although this method underscores the necessity of RH facilities for the finalization, acceptance, and commissioning of RH hardware and software equipment, relying on these facilities' availability is not always feasible, potentially restricting the proposed method's applicability. Enhancements are essential for this approach to be widely applicable to various robotic systems without the need for physical test facilities. Such improvements might include estimating link flexibility and joint compliance through initial analyses (such as structural FEA, tolerance assessments, etc.) that could replace the on-site measurement data utilized in this study. The effectiveness of these methods in refining the tool could be assessed using the divertor RH equipment prototypes at DTP2, by employing available on-site test measurement data to validate the preliminary outcomes from simulations and analyses. Models populated with simulation data should anyway undergo a process of validation and calibration with actual on-site measurement data before final operation. However, this approach would allow to have preliminary calibrated models as long as on-site tests in RH facilities or in the real fusion device environment are not feasible. A possible calibration procedure involving a first preliminary population of calibration models with simulation and analysis data, and their later iterative correction with measurement data from on-site metrology test campaigns, is shown in Figure 6.1.

The accuracy of the structural simulator tool may be further improved by increasing the amount of on-site measurement data collected, and then using them to train Artificial Intelligence or Machine Learning models. An extensive test campaign for acquisition of measurement data could allow to map the structural behavior of the robot in several points of its workspace and under several load cases. Then, these data could be used to train a neural network able to predict the structural behavior of the robot in any point of its workspace and under any load configuration, even those not included in the measurement dataset. The predicted structural performance would be obtained and repre-

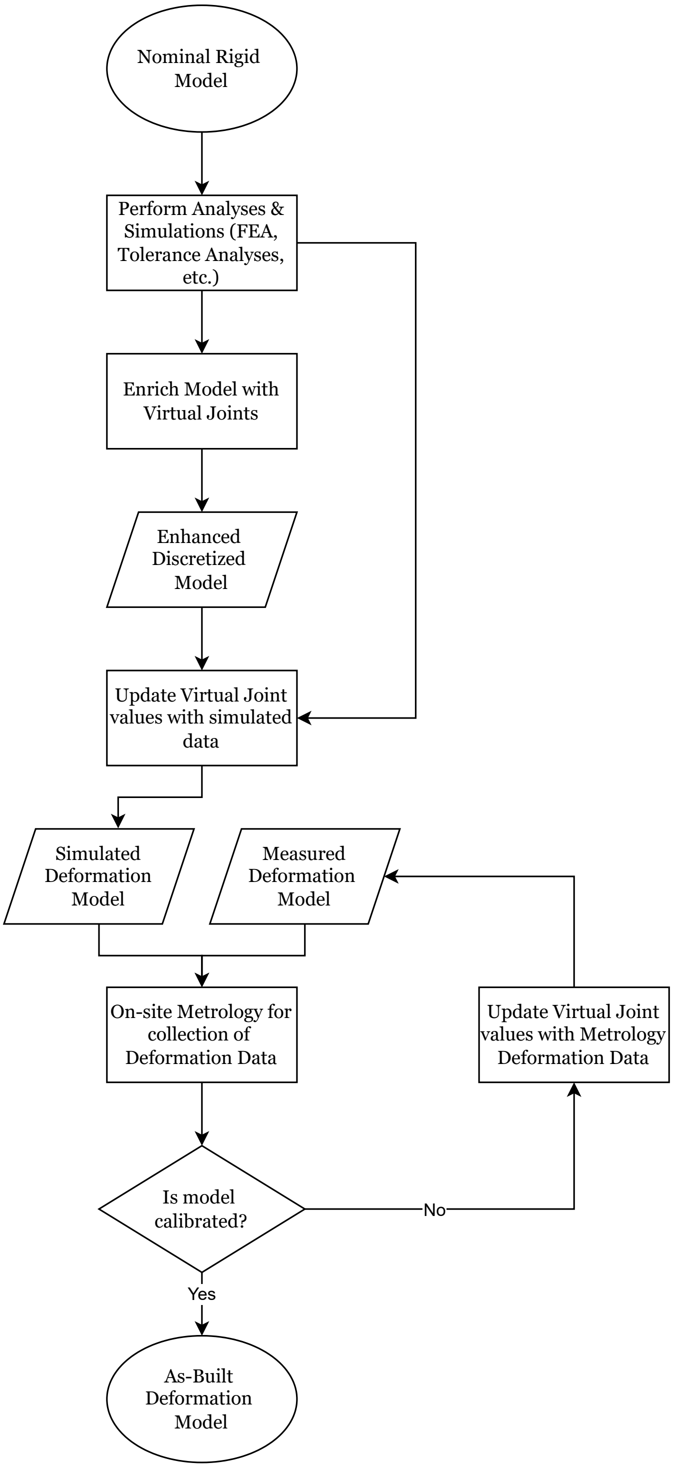


Figure 6.1: Calibration procedure featuring a preliminary calibration fed by simulation data and a next correction fed by metrology data

sented through constant calculation and update of virtual joint values, based on readings from joint position and applied load sensors. The same technologies could also be used for real-time update of robot's pose leveraging on real-time collected measurements, if the necessary instruments are available (on-board and environment measurement sensors and cameras, Machine Vision / Motion Capture systems, etc.).

Finally, additional enhancement of the structural simulator tool's performance may obtained by acquiring distance measurements via specific sensors or on-board and environment cameras (Machine Vision and Motion Capture systems) while executing RH Tasks. Using these real-time data for feedback would permit fine-tuning of the virtual joints reference values in the look-up table. This approach involves supplying the virtual joints with reference values that are continuously refreshed based on real-time measurements rather than relying on data from earlier test campaigns, creating cyclic update loops able to boost the tool's accuracy. The same process could even employ other types of data, such as joint and link accelerations measured through accelerometers and IMUs mounted in strategic location of the robotics equipment. Of course, the process of data acquisition, look-up table values update and VR model adjustment could lead to reduce the tool's computational efficiency.

The information coming from these sensor data could also be implemented in algorithms dedicated to compensate or recovery from different virtual-real mismatch scenarios. Specific control actions may be automatically executed based on the operational context, reconstructed through real-time data coming from sensors mounted on the equipment. For instance, motion could be slowed down in case RH equipment approaches the surrounding environment beyond the defined threshold, or recovery joint move commands could be sent in case of envisaged recovery scenario event, or the RH Task could even be automatically stopped for specific scenarios.

In the end, a standardized, validated, calibration and compensation strategy able to be generalized and re-applied to any other RH system of any other fusion device will also need to be delivered to the fusion and robotics research communities. As part of this process, for instance, a standard method could be developed to robustly identify the minimum number and position of the virtual joints, based, for instance, on the information coming from collected metrology data.

# 7

# Conclusions

## 7.1 Achieved results

In conclusion, the present doctoral research provides a digital-twin based, model-driven, structured workflow for development of RH facilities, generalizable to any similar facility that supports any fusion project, in view of a future pilot fusion power plant such as DEMO. The proposed workflow goes beyond the classical document-based design frameworks and methods currently adopted in most of big science research projects, such as fusion ones. The key achievement of this thesis, with respect to the current State Of The Art in the related scientific field, can be summarized in the following points:

- Deepening of strategies and technology issues to Remote Handling (RH) systems and procedures safety, reliable and efficient development.
- Demonstration of the necessary role of RH facilities for development of a safety, reliable and efficient RH system, through analyses of achieved results of already developed facilities.
- Transfer of industry-related concepts, frameworks, and tools to the fusion research field to structure a digital-twin based workflow for the development and lifecycle management of RH facilities, applicable from the early design to operation stages. This approach, massively employing instruments such as digital twin models, PLM platforms, MBSE's frameworks like V-model embedding the RFLP paradigm, enables the application of a cloud-based, model-driven design development process that overcomes the time and cost wastes of typical document-based approaches, and boosts project efficiency and smoothness.

- Application of the digital-twin based workflow to the DTT RH Facility case study, an innovative project that aims at representing a hub in the current global scenario of similar facilities. The method is applied to develop the Facility's design from the early requirement analyses to the current manufacturing phase, guaranteeing efficiency and compliance with short time and cost budgets in completing all the steps of: architectural design; subsystems concept design with preliminary Verification & Validation (V&V); subsystem integration and interface management; identification of requirements for manufacturing and physical V&V tests (FAT and SAT) and transfer to manufacturing companies; follow-up, management and integration of subsystems engineering design and procurement from manufacturing companies. The path for next activities of digital-twin based management of the Facility's operational lifecycle is also set, for proper integration, monitoring, evaluation, and optimization of operations since the first commissioning to decommissioning phases.

- Deploying a high-potential solution for the challenge of digital-physical calibration in digital-twin based systems: the virtual-joints based Structural Simulator. As demonstrated by the application to the test-case of the ITER CMM-SCEE VR model, this solution successfully reproduces the errors deviating the robot pose from the nominal one, and deriving from static and dynamic mechanical factors, by representing the expected structural behavior with a real-time update frequency higher than the required one.

## 7.2 FUTURE DEVELOPMENTS

The thesis work leaves broad scope for future research developments, arising from limitations anyway present both in the proposed approach for development of RH facilities and in the proposed solution to address the specific digital-physical calibration problem. Possible future developments for the large-scale adoption of the proposed digital-twin based workflow in the development of RH facilities are:

- In-depth study of privacy safeguards proposed by PLM platforms, such as 3DEXPERIENCE, to protect: (1) the confidentiality of on-cloud stored data in large projects involving multiple entities from both public and private sectors, and from several countries; (2) the security of operations avoiding hacker infiltration, deepening the possibility of integrating cloud-based PLM platforms within isolated Plant Operating Zone (POZ).

- Increasing the reliability of the permissions management process to ensure that project data are properly accessed, edited, shared and transferred by and among all design actors involved in the project, and the risk of unintended design modification and data loss is minimized.

- Further development of an interface solution between the digital twin operative environment over the PLM platform and the control system, to ensure correct data transition and sharing between digital models and physical counterparts, even in real-time during operation. As part of this process, the control system hardware architecture capability to sustain the smooth transition and sharing of all digital twin data shall also be verified, in order to enable the IoT infrastructure that typically sustains modern high automation industrial factories integrated in the Industry 4.0 context.

Instead, possible future developments to the proposed virtual-joints based structural simulator as solution for the specific digital-physical calibration problem are the following:

- Validation of the proposed method's accuracy through dedicated measurement data collected in additional test campaigns to be performed.
- Development of a reliable compensation strategy, able to guarantee safe and efficient processes of trajectory planning and virtual-assisted teleoperation.
- Increase of the structural simulator tool's accuracy in representing the geometry of the deflected links, either increasing the number of virtual joints or through, for instance, mesh-editing techniques.
- Definition of robust and experimentally validated method, strategy, and workflow for RH systems calibration and compensation to deliver to the fusion and robotics research communities. This standardized workflow shall also include a method to define the minimum number and position of the virtual joints, based, for instance, on the insights of the collected measurement data.
- Feasibility validation of using predictive analyses (FEM, tolerance analyses) instead of on-site collected measurements to build the look-up tables and, hence, determine the virtual joint values. This would make the proposed method more independent from the collection of large amount of measurement data on-site in physical RH facilities.
- Collection of a huge amount of measurement data in several poses and load conditions to train a neural network able to predict the robot structural behavior, and therefore the virtual joint values, in any pose and load case.
- Implementation of a feedback loop that updates virtual joint values based on real-time measurements of the robot tip pose with respect to the environment (acquired through on-board and environment cameras as part of Machine Vision and Motion Capture systems) and on sensor readings (such as accelerators and IMU), instead of pre-collected measurement data.
- Development of algorithms to manage and propose solutions to different scenarios depending on the virtual-real mismatch.

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