# Technical specification for the procurement of the DTT RH Facility Control Room

| Access: | ☐ contractual | ☐ open | ☐ restricted |
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AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE,
L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE

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**Abstract**

*This document is the technical specification for the procurement of the DTT RH Facility Control Room.*

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# Terms, Definitions and Acronyms

| Term | Definition | Acronym |
|---|---|---|
| Acceptance Data Package | Collection of documents delivered by the Contractor before any payment milestone that declares and demonstrates the conformance of the deliverable in all respect with the applicable specification(s), drawing(s) and all requirements. | ADP |
| Contractor | Economic operator which has concluded with DTT S.c.a r.l. the contract for the supply of the DTT Vacuum Vessel and Ports. | -- |
| Subcontractor | Economic operator which is not Party of this Contract and who enters into a legal commitment with the Contractor in order to perform a part of the Contract. | -- |
| Customer | The entity that shall award the tender for the subject of the present Technical Specification and that shall be in charge of verifying the adherence to the required prescriptions. In this definition Customer should be understood as ENEA. | -- |
| Deliverable | Tangible or intangible good or service produced as a result of the contract signed with DTT. A deliverable could be hardware, tests, documentation, logistic, assistance, software products. | - |
| Kick-of Meeting | First meeting where DTT S.c.a r.l and Contractor project teams define the baseline and rules for the execution of the contract. | KoM |

| Term | Definition | Acronym |
|---|---|---|
| | Mandatory starting points before any othercontractual activities are initiated | |
| Management and Quality Specification | Specification of requirements regarding project management and quality management to be before and during the execution of a Contract. | MQS |
| Project and Quality Management Plan | Document describing the management system developed, implemented and maintained by the Contractor throughout the life-cycle of the Contract to ensure that the Contract Requirements are met and that evidence of such compliance is maintained. | PQMP |
| Work Breakdown Structure | Activity-oriented breakdown of a project into smaller components. | WBS |
| Product Breakdown Structure | Product-oriented breakdown of a project into smaller components. | PBS |
| Site | The location where the DTT RH training facility will be installed (Napoli, Italy). | -- |
| Component | Part of a system delimited according to structural or functional aspects, which can still implement independent sub-functions. | |
| Tokamak global coordinate system | The main frame of reference used for the DTT facility, a three-dimensional Cartesian frame of reference. | TGCS |
| Applicable Document | Document that can be applied to | AD |
| Factory Assembly & Acceptance Tests | Factory Assembly & Acceptance Tests (at Contractor's factory or subcontractors') | FAT |
| Guide to the expression of the Uncertainty of Measurement | Guide to the expression of the Uncertainty of Measurement | GUM |
| Identification Code | Identification Code | ID |
| Lifting Frame | Lifting Frame | LF |
| Manufacturing Design Report | Manufacturing Design Report | MDR |
| Non-Destructive Testing | Non-Destructive Testing | NDT |
| Site Acceptance Tests | Acceptance Tests on site | SAT |
| Signature of Contract | Signature of Contract | SoC |
| To be confirmed | To be confirmed | TBC |
| Visual Testing | Visual Testing | VT |
| Work Package | Work Package | WP |

# Reference Documents

RHCR-REF-000: [CR_0] Control Room Technical Specification
RHCR-REF-001: [CR_1] Control Room Architecture and Technical Requirements
RHCR-REF-002: [CR_2] Control Room Technical and Economical relation
RHCR-REF-003: [CR_3] Interface Control Document
RHCR-REF-004: [CR_4] ControlRoom-IS-001-Power
RHCR-REF-005: [CR_5] ControlRoom-IS-002-Internet
RHCR-REF-006: [CR_6] ControlRoom-IS-003-HYRMAN

RHCR-REF-007: [CR_7] ControlRoom-IS-004-CMM
RHCR-REF-008: [CR_8] Management and Quality Specification

# 1 Introduction

## 1.1 Introduction to the DTT RH and to the RH facility

DTT is one of the largest superconducting tokamaks under construction with the mission to get scientific and technological proofs of power exhaust in prospect of the first nuclear fusion power plant. The 5.5MA maximum plasma current, 6T toroidal magnetic field at the plasma center, and 2.19m plasma radius make DTT a flexible and compact facility for testing D-shaped plasmas with different configurations of heat load spreading. The facility is under construction in Frascati.

Since after plasma operations radiation levels of components and environment will preclude human access in the in-vessel environment, Remote Handling operations are required in DTT for maintenance procedures.

The following RH Classification has been defined for the proper design of the RH systems:

- RH Class 1: Frequent maintenance: will need RH replacement / maintenance. Mockups are required as part of design process.
- RH Class 2: Infrequent maintenance: only unscheduled maintenance. May involve mockups for design process.
- RH Class 3: Maintenance in the event of failure: failure probability < 1 in 200 years. Design for RH repair. RH equipment procured after assembly. Non-RH Classified: do not require remote maintenance.

Since DTT First Wall (FW) and Divertor modules are classified as RH Class 1 and RH Class 2, the construction and the successful operation on the DTT facility require the construction and early operation of a RH facility. The purpose of this project is to install and operate a test stand for full-sized DTT RH systems.

The RH facility is located at *Università degli Studi di Napoli Federico II – Complesso Napoli* Est, in Napoli, Italy, at the laboratories managed by "Centro Servizi Metrologici e Tecnologici Avanzati" (CeSMA).

The main goals of the DTT RH Facility are:

- Testing RH procedures, verifying their feasibility in the scheduled time.
- Verification and Validation of Remote Handling Equipment (RHE), i.e. the robotic machines designed to execute the RH procedures.
- Implementation of a RH control system and a RH control room to be replied in real DTT facility.
- Training of human operators working in the control room about robot teleoperation and supervision of automatic procedures, so as to maximize safety during execution of procedures and prepare personnel to be then in charge of the RHE control of real DTT facility too.

The DTT RH Facility has been divided in 4 main sub-systems, as shown in next figure: *Buildings and Services, Mockups, Robots, Control Room.*

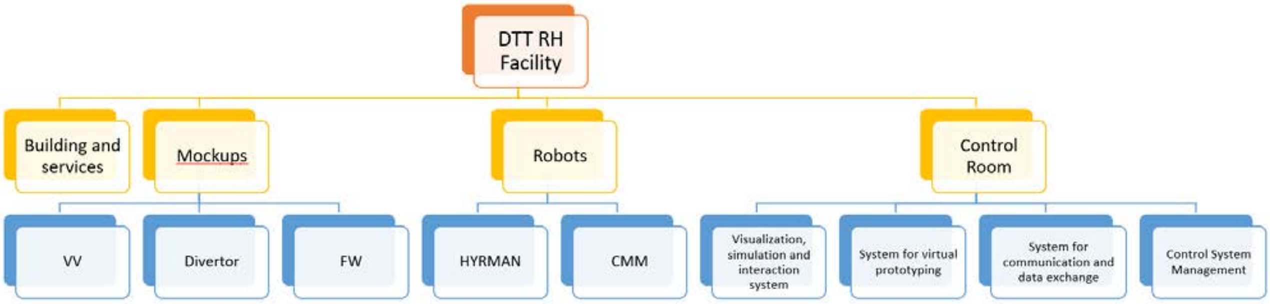


Figure 1 – Logical architecture of the DTT RH Facility

Considering the current baseline, the RH procedures to be tested in the facility are the handling of FW and Divertor modules.

The DTT machine is divided in 18 sectors, 20° degrees each, among which four are dedicated to RH: sectors #1, #5, #10, #15. Each sector is equipped with 5 ports connecting the in-vessel environment with the out-vessel one (see Figure 2).

The DTT FW system is made of Outboard, Inboard and Top FW.
The Outboard First Wall is composed of 5 modules for each sector (module #1, #2, #3, #5 and #6). The Inboard First Wall is composed of 2 modules for each sector (Standard and Limiter module). The Top First Wall is composed of 2 modules for each sector (module #1 and #2).

The FW modules handling procedures are carried out by a HYper-Redundant MANipulator (HYRMAN) approaching the in-vessel environment through the horizontal port #3 of RH sectors.

The DTT Divertor system is divided into 54 cassettes, 3 for each sector: the cassette in front of the port #4, called Central Cassette (CC), and the ones at the side of the port #4, called Second Cassette-left (SC-l) and Second Cassette-right (SC-r).

The Divertor modules handling procedures are carried out by a robotic carrier, the Cassette Multifunctional Mover (CMM), approaching the in-vessel environment through the lower lateral port #4 of each sector.

Note about the handling procedures of the Divertor modules: the strategy described above is included in the RH baseline at the start of DTT activities but could change in future.

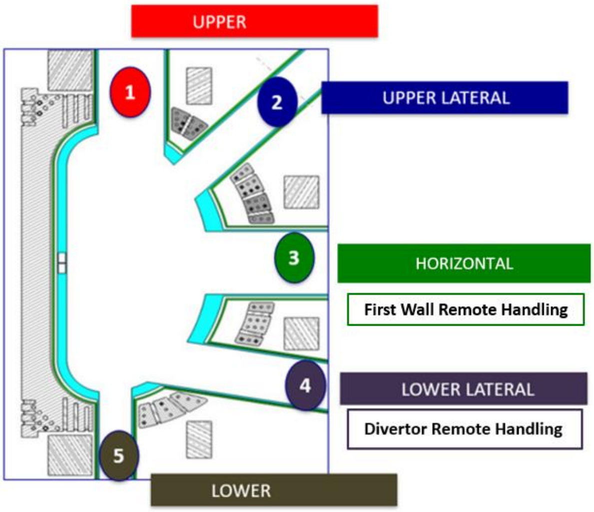


Figure 2 – DTT Ports configuration.

The building hosting the DTT RH Facility is located at *Università degli Studi di Napoli Federico II – Complesso Napoli* Est, in Napoli, Italy, at the laboratories managed by "Centro Servizi Metrologici e Tecnologici Avanzati" (CeSMA).

Figure 3 shows a preliminary layout of the DTT RH Facility including the mockups.

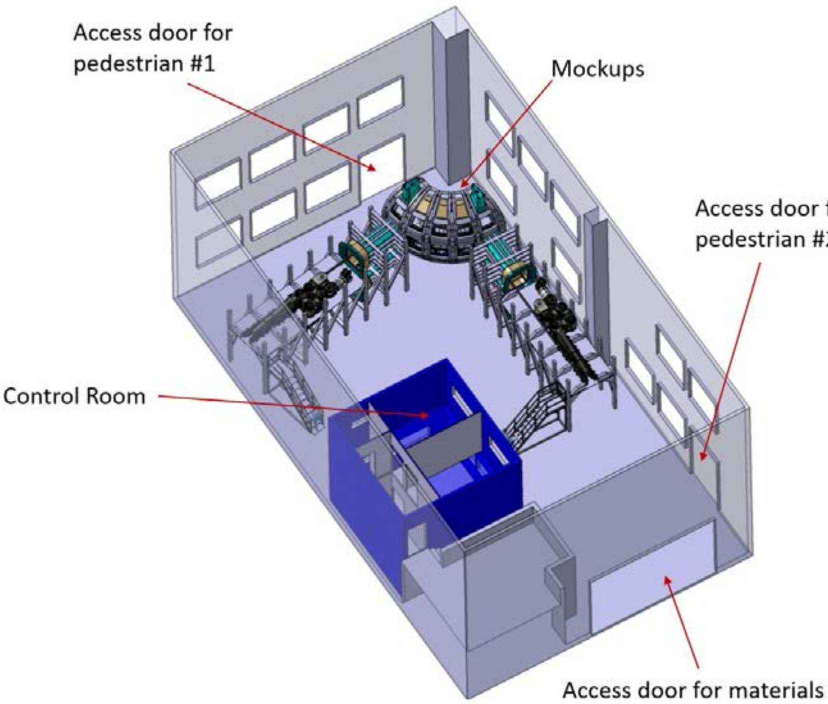


Figure 3 – DTT RH Facility layout with mockups

The mockups shall be positioned as roughly specified in Figure 4 and Figure 5, wrt the Facility Global Coordinate System centred in the central point of the volume enclosed by the building.

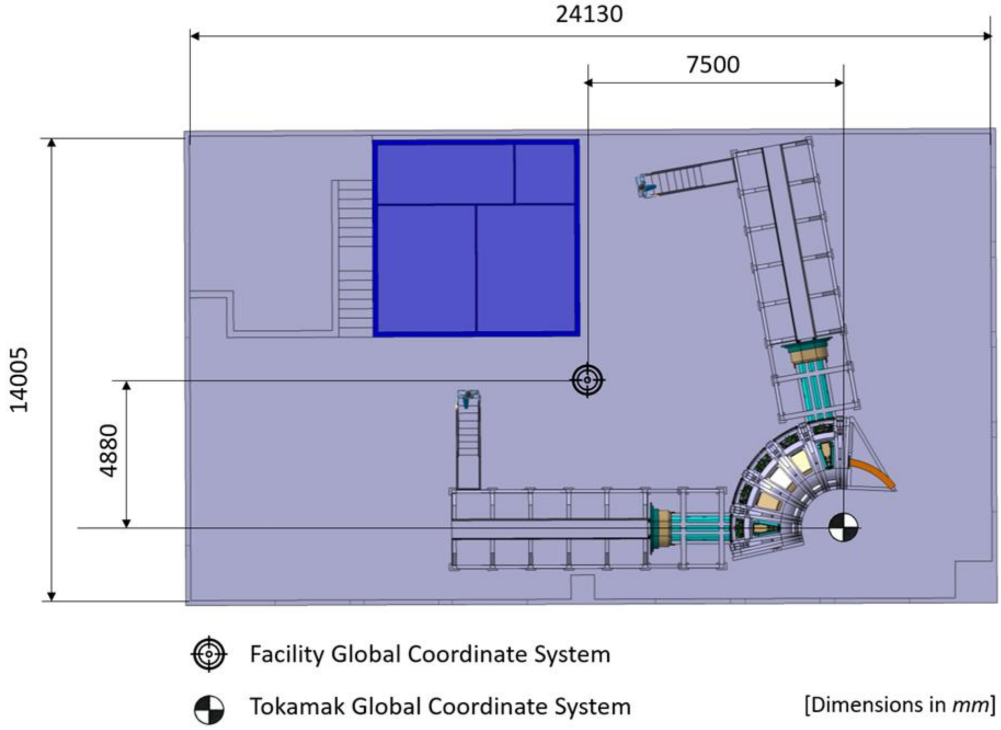


Figure 4 – Mockups position in the DTT RH Facility building, top view.

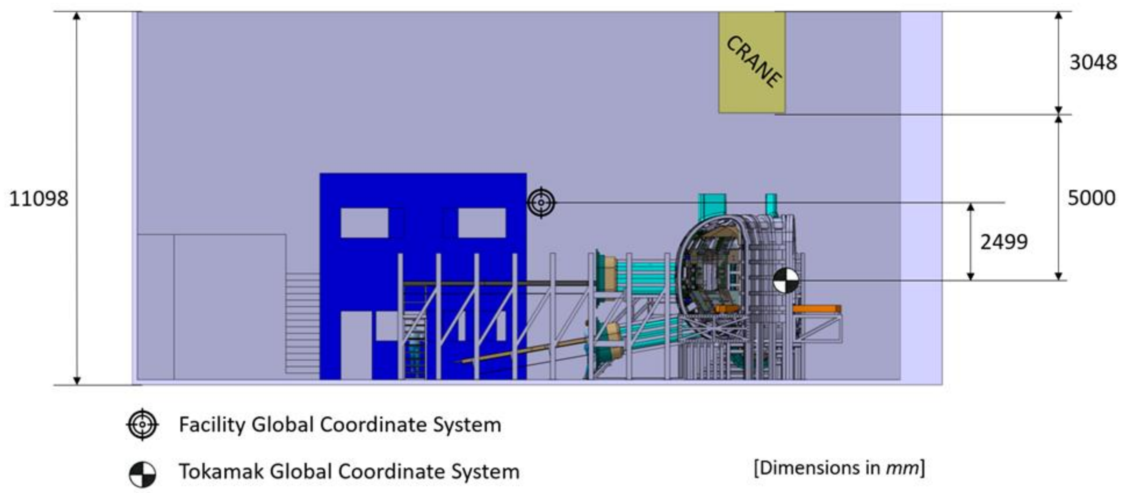


Figure 5 - Mockups position in the DTT RH Facility building, lateral view.

A crane with 10 tons of capacity is available inside the building for materials and components handling. Apart from assembly operations, the crane shall be also used:

- to transport and position each Cask mocKup with the specific robot mounted on it;

- to transport and position the Installation Tool on the Vacuum Vessel mockup, prior to the manual mounting by an operator.

The vertical encumbrance of the crane is roughly specified in Figure 5, while the working width in Figure 6.

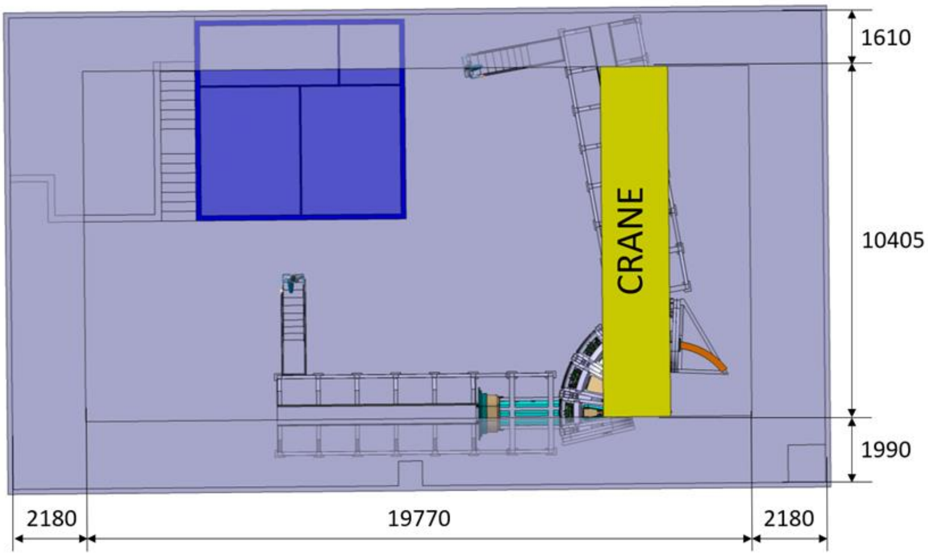


Figure 6 – Workspace of the crane available in the DTT RH Facility building.

Materials and delivered hardware shall access the building through a dedicated door with roughly dimensions specified in Figure 7.

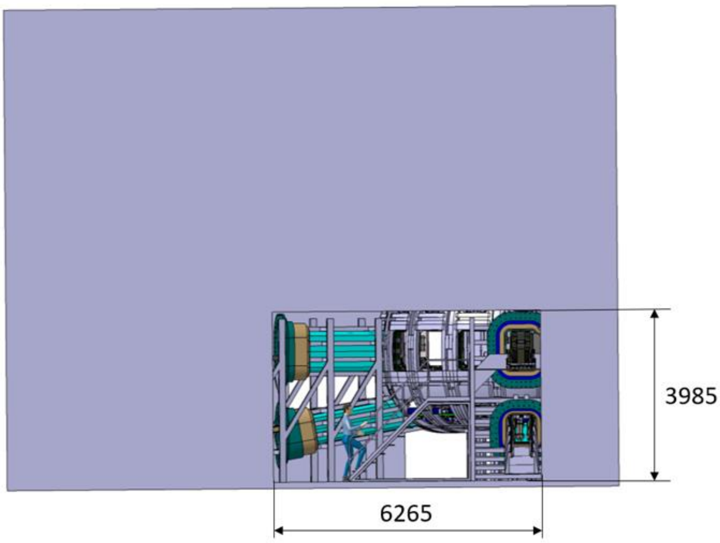


Figure 7 – Dimensions of the access door for materials, equipment and delivered hardware, already available in the building

## 1.2 Purpose of this document

The purpose of this document is to provide the technical specifications for the design and procurement of the control room of the DTT RH Facility.

The annexes, the applicable documents, and the reference information documents are integral part of this technical specification.

# 2 Scope of the Supply

In this section we include the scope of the supply. In particular, the supplier must deliver:

- Detailed design of the system, from the hardware and software point of view
- Demonstration of the system in simulation
- Deliverable reports summarizing the methods used, the executive design, the results of the demonstration, the user manual.
- Hardware, including the delivery of all the components defined in this TS
- Software, including all the functionalities and tools for the management and control of the control room, as defined in this TS

The control room is based on a Multi-Server/Multi-Clients communication system which includes five communication channels:

- Local Data Network
- Real-Time Network
- Video Network
- Operative Network
- Safety Network

The software comprises a series of modules:

- Human Machine Interface
- Diagnostic Software
- Dynamic Simulation Interface
- Motion Planner
- Teleoperation Control
- Collision Management
- Operation Management Software
- Authentication & Authorization Software
- Visualization Software

The hardware components include:

- Displays, comprising: n.8 workstations monitors, n.2 manipulator master station's monitor, n.2 wall monitors.
- Workstations, comprising: n.2 Operators PC, n.1 supervisor PC, n.1 manipulator master station PC.
- Human Interaction Devices, comprising: Joystick (>=2), Force-Feedback Devices (>=1), VR Headset and Controller (=2).
- Network Equipment, comprising: switch for video network, switch for operative network, switch for real-time and local data networks, router, UPS Type 1, UPS Type 2, UPS Type 3.
- Servers, comprising: control server, visualization server, data server.

Based on this Technical Specification, the Contractor shall:

I. Carry out a review of the provided documentation to determine if the network and hardware necessities have been correctly identified, and the organization has adequately planned for the implementation phase.
II. Prepare all executive design, plans, procedures, and work instructions for implementation and testing, then prepare any other technical documents as specified in detail in this document and in the Management and Quality Specification [RHCR-AD-003];
III. Assemble, test, and disassemble after test at the factory for the transportation to the site of all Blocks included in the RHCR Supply.
IV. Transport, deliver, and attend the tests on Site as required in this document.
V. Prepare and release the design and operation documentation.

The following activities, further detailed in this Technical Specification, are part of the Supply:

a) the development of the management documentation included in the Project and Quality Management Plan (PQMP), technical documentation and document deliverables;
b) the definition and execution of all the activities necessary to the implementation and testing procedures and processes according to the applicable codes and standards and laws or requirements of this specification and its annexes.
c) the procurement of all the materials, both raw materials and standard or off-the-shelf products.
d) the procurement, design, development, and implementation of all the necessary hardware, software, and testing at the Contractor’s workshop and at Site.
e) the assembly at the Contractor’s factory.
f) the tests at the Contractor’s factory (intermediate tests and FAT).
g) the final packing, delivery, and unloading of the components to the Site.
h) attendance to the execution of the Acceptance Tests on Site (SAT).

# 3 Work Breakdown structure (WBS)

The Contractor shall organise the Supply according to the following Work Breakdown Structure (WBS) that identifies groups of activities called Work Packages (WPs) with correspondent milestones and deliverables. In case of any update and further development of this WBS, the final WBS shall be submitted by the Supplier and accepted by the Client as part of the PQMP.

The following structure shall be adopted for description, plan, and organization of the work to be carried out:
- WP.0 - Project Management and Project Management and Project and Quality Management Plan (PQMP).
- WP.1 - Hardware design and development.
- WP.2 - Software design and development.
- WP.3 - Assembly, testing at Contractor's factory (FAT)
- WP.4 - Packing, transport and delivery
- WP.5 – Assistance on Site and SAT

## 3.1 WP.0 - Project Management and Project and Quality Management Plan (PQMP)

This Work Package comprises all the efforts related to the timely and appropriate management of the project activities. Work Package WP.0 shall include at least the activities listed in Table 1.

**Table 1. WP.0 - Project Management and Project and Quality Management Plan (PQMP)**

| WP ID | Activities / Items to be provided |
|---|---|
| WP.0.1.0 | a. Preparation and management of the Project and Quality Management Plan according to what specified in the Management and Quality Specification [RHCR-AD-002].<br>b. Project coordination / Project Management.<br>c. Monitor & Control of project schedule.<br>d. Contractual interactions with the Customer and management of subcontractor(s)/Supplier(s) activities. |

## 3.2 WP.1 - Hardware design and development

This Work Package comprises all the engineering efforts related to the production of the procedures, schemes, and documents necessary for the procurement, and assembly activities foreseen in the following WPs. Work Package WP.1 shall include at least the activities listed in Table 2.

**Table 2. WP.1 - Hardware design and development**

| Sub-Work Package | WP ID | Activities / Items to be provided |
|---|---|---|
| Design | WP.1.1.0 | a. Preparation of the executive hardware design.<br>b. This activity includes the review and correction of any inconsistency or inaccuracy in the proposed HW architecture and the integration of details and features necessary for the definition, and implementation of all the system parts. Moreover, in this phase the consistency with the SW modules defined by the requirements must be evaluated integrating the development phase with the SW development described in WP2. All points related to procurement and assembly fall under the Contractor's responsibility after contract signature. |
| | | c. Design, development of drawing, schemes, and documents. |
| Preparation | WP.1.2.0 | a. Preparation of the specifications for the purchase of materials and off-the-shelf products. |
| | | b. Definition and execution of all the activities necessary to qualify the implementation procedures and processes. |
| Implementation | WP.1.3.0 | a. Procurement of all hardware components to develop the control architecture of the control room. |
| Documentation | WP.1.4.0 | a. Subcontractor documentation. |
| | | b. Preparation of documents for assembly at the Contractor's factory. |
| | | c. Preparation of documents for tests foreseen at the Contractor's factory. |
| | | d. Preparation of the packing and transport specification for the delivery to the Site. |

The Contractor shall collect all the documents, drawings, and procedures prepared during WP.1 and include in a documents package. The document package provided has to be included in the Final Technical Report. Before starting any purchase activity of the following WP.2, the Contractor shall submit to the Customer for approval the relevant purchase documents prepared as part of WP.1, proving that it complies with all the technical requirements.

## 3.3 WP.2 – Software design and development

This Work Package comprises all the design and implementation efforts for the development of the software architecture. Work Package WP.2 shall include at least the activities listed in Table 3.

**Table 3. WP.2 - Software design and development**

| Sub-Work Package | WP ID | Activities / Items to be provided |
|---|---|---|
| Design | WP.2.1.0 | a. Provide a review and correction of any inconsistency or inaccuracy in the proposed SW architecture and the integration of details and features necessary for the definition, and implementation of all the software modules.<br>All these points related to procurement and assembly fall under the Contractor's responsibility after contract signature. |

| | | |
|---|---|---|
| | | b. Design, development of schemes, diagrams and technical documents foreseen among the software deliverables.<br>c. Design of a detailed test plan which will be conducted on each software module and on the whole architecture |
| Preparation | WP.2.2.0 | a. Definition and execution of all the activities necessary to qualify the implementation procedures and processes. |
| Implementation | WP.2.3.0 | a. Detailed design of all software modules<br>b. Implementation and coding of all the software modules<br>c. Preliminary testing of all software modules. Unit tests can be performed in this phase to evaluate each software modules |
| Documentation | WP.2.3.0 | a. Subcontractor documentation. |
| | | b. Preparation of documents for assembly at the Contractor's factory. |
| | | c. Preparation of documents for tests foreseen at the Contractor's factory. |
| | | d. Preparation of the packing and transport specification for the delivery to the Site. |

The Contractor shall collect all the documents, drawings, and procedures prepared during WP.2 and include in a document package. The document package provided has to be included in the Final Technical Report.

## 3.4 WP.3 - Assembly, testing at Contractor's factory (FAT)

This Work Package comprises the preparation and execution of the assembly and tests to be executed at the Contractor's factory prior to transportation as well as partial disassembly necessary before transportation (if needed). The auxiliary tools for the assembly and handling at Contractors' factory are included in this WP.

Work Package WP.3 shall be subdivided in a number of sub-Work Packages which are to be evaluated by the Contractor and approved by ENEA.

The Contractor shall include all the documents and certificates prepared and collected during WP.3 in the Factory Assembly & Acceptance Tests (FAT) Plan and Report and submit them to the Customer for approval.

The content of the Factory Assembly & Acceptance Tests (FAT) Plan and Report is described in the following.

Within this WP.3, the Contractor shall prepare the Final Technical Report.

## 3.5 WP.4 - Packing, transport and delivery

This Work Package comprises planning and executing measures to ensure safe cleaning and reliable handling during packing, temporary storage, transportation, delivery to site, unloading on Site.

Work Package WP.4 is subdivided in a number of sub-Work Packages which shall include in particular the activities listed in Table 4.

**Table 4. WP.4 - Packing, transport and delivery**

| Sub-Work Package | WP ID | Activities / Items to be provided |
|---|---|---|
| Packing and temporary storage | WP.4.1.0 | Packing and temporary storage: preparation of components and sub-assemblies for all components and the possible temporary storage at the Contractor's site before delivery if authorized by the Customer. |
| Transport and delivery | WP.4.2.0 | Transport and delivery:<br>a. uploading of all components, sub-assemblies, and equipment at the manufacturing/storage Site;<br>b. transportation to the Site;<br>c. unloading of all components, sub-assemblies, and equipment at the Site. |
| Tools | WP.4.3.0 | Procurement of transportation, handling, and delivery tools. |

The Contractor shall include all the documents and certificates prepared and collected during WP.4 in the and submit them to the Customer for approval.

## 3.6 WP.5 – Assistance on Site and SAT

This Work Package comprises the attendance to the execution of all the foreseen Acceptance Tests on Site. Work Package WP.5 shall include the activities according to the prescriptions of this Technical Specification and of the approved Site Assembly & Acceptance Tests (SAT) Plan. The content of the Site Assembly & Acceptance Tests (SAT) Plan is described in this document.

# 4 Input Documentation

A conceptual architecture of the Control Room is provided in the reference document "RHCR-REF-001: [CR_1] Control Room Architecture and Technical Requirements" and should be used for reference only.

The Contractor is fully responsible for ensuring that the concept is compliant with the requirements and constraints provided. The Contractor will develop and complete a final executive design of the Control Room, comprising all the hardware and software parts, ready for commissioning and followed by all the necessary tests. The Contractor will do so by following a progressive development process marked by intermediate stages that will be agreed with and approved by the Client. Should the Contractor consider appropriate, or indeed necessary, alternate design solutions, these will be submitted to and approved by the Client.

Further, the Contractor will implement a validation process, to be approved by the Client to ensure that the Control Room meets the needs of the Client.

While supporting the Contractor throughout the contractual period with relevant information about the conceptual architecture of the Control Room, the Client declines all responsibilities for providing erroneous or incomplete information, meaning that the Client will be fully responsible to verify, and fix where necessary, the correctness and applicability of any such information, or if the case ask for any additional information, to be treated as described above.

The input documentation includes:

- Technical Specifications: the present document
- Architecture and Requirements: document with the description of the conceptual architecture of the Control Room and the list of requirements
- Interface Control Document: description of the interfaces of the Control Room with the other systems.
- Quality and Management Specifications: specifications of all the issues related to Quality and Management, including Plans Documents.

# 5 General Requirements

In this section the general requirements are provided.

## 5.1 Basic provisions

The Contractor shall design, implement and test the hardware and software parts of the control room, including all the logics and networks, with the applicable standards, the best engineering practices and the state of the art in the corresponding technical areas.

## 5.2 Storage, packing, transportation and delivery

The Contractor shall ensure that all components to be shipped to the CeSMA site are properly stored until their delivery to site, to avoid possible damages and deterioration.

The Contractor shall organize and manage the transportation contract for goods delivery from and to the site. The packaging shall provide adeguate mechanical and environmental resistance during transport together. Packing system shall be in agreement with EU rules and with international sanitary rules.

The packaging shall ensure a clear identification by means of easily accessible documentation as well as traceability of transported components.

The Contractor shall inform the Client in the case of oversized loads. The Contractor shall take all possible precautions to avoid damages and consequent delays in the supply during delivery.

The Contractor shall allow Client access to inspect components packaging to check that packages adequate and intact before and after dispatching. The Contractor will be required to perform similar inspections once the packages are delivered to the DTT site. An official note documenting the list of checked packages and possible issues shall be prepared after each inspection.

The Contractor shall take any measure to ensure safe, clean, and reliable handling during packaging, transportation, delivery to Site, unloading, temporary storage to carry out SAT.

The Contractor shall inform ENEA of the near deliveries, according to requirements given in the Management and Quality Specification for the Supply of the DTT RH Facility Mock-ups.

**Protection during transport, delivery, and storage**

All the components to be delivered shall be separately packed together with their temporary fixtures, if any, to minimize the risk of damage and distortions during handling and transport.

Critical electronic components and parts shall be packed by using desiccant elements to insure low humidity during shipment and storage.

**Packaging**

Small items shall be wrapped and sealed in a suitable polyethylene bag. Desiccant elements shall be included inside all the packages to prevent condensation.

Each component and assembly shall be individually located in purpose-built reusable plywood containers/boxes to avoid damage during handling and transport and to provide medium term storage (up to 2-3 months) on Site. Suitable measures shall be taken to avoid the boxes be damaged by atmospheric events.

The boxes shall allow lifting during uploading and downloading operations.

The Contractor shall consider all the risks and the consequent safety rules to be adopted during all the phases of packing, transport, and unloading on Site.

**Transportation to the site**

The Contractor shall organise the transport of the Supply to the Site in compliance with all the applicable laws of the countries on the transport route and shall bear any relevant cost.

The Contractor shall be liable for the damages during transportation and must comply with requirements given in the Management and Quality Specification for the Supply of the DTT RH Facility Mockups.

**Delivery to the site**

The Contractor shall inform in advance ENEA of the deliveries.

The Contractor shall deliver all the components, assemblies, prototypes, and tools to the DTT RH Facility Mock-ups Site at the following address:

*Università degli Studi di Napoli Federico II - Scuola Politecnica e delle Scienze di Base - Complesso Napoli Est*
*Corso Nicolangelo Protopisani, 70*
*80146 Napoli (NA)*
*Italy*

NOTE: The precise building location for delivery and installation, the name of the contact person on site and access formalities will be communicated in advance to the Contractor prior to transport date.

## 5.3 General requirements about the tests

Before executing any test, the Contractor shall submit to ENEA for approval the test plan which shall contain at least the following data:

a. purpose of the test.
b. parts object of the test.
c. testing specifications and procedures.
d. conditions under which the test is to be carried out.
e. measurement instruments and relevant calibration reports, as applicable.
f. description/sketch of the testing set-up.
g. nomination of appropriate organization to accept the tests, where applicable.
h. documentation foreseen/data to be recorded that shall include as a minimum:

a. all the procedural, equipment, and calibration parameters necessary to provide a basis for comparison with later examinations.

All the test plans shall be included in the Factory Assembly & Acceptance Tests (FAT) Plan and in the Site Assembly & Acceptance Tests (SAT) Plan.

After the execution of each test, the complete set of obtained results against acceptance values, records, certificates, and performance curves shall be collected in a test report together with the final statement of positive or negative result (nonconformity) on the basis of detected defects or failures.

All the test reports shall be included in the Final Technical Report.

The Contractor shall carry out the tests ONLY after the relative test procedure is approved by ENEA and ONLY if ENEA or its representatives have been informed about the tests.

Activities related to cabling of electrical panels and/or hardware shall be carried out by personnel qualified and certified to the levels 2 and 3 in accordance with EN ISO 9712 and ANSI/NETA ETT "Standard for Certification of Electrical Testing Technicians" or other equivalent recognised standard or certification schemes. These test activities shall include:

1. setting up and verification of equipment settings.
2. performing and supervision of tests.
3. interpretation and evaluation of results.
4. performing of the test methods.
5. designation of the test methods, procedures, and test instructions to be used.

Test procedures and instructions shall be developed by the Contractor and approved by ENEA before any test can commence. The Contractor shall provide all test equipment, measuring and recording instrumentation, and qualified personnel.

Recommended safety practices regarding electrical hazards for all personnel dealing with high voltage applications and measurements are provided in IEEE Std 510-1983 "IEEE Recommended Practices for Safety in High Voltage and High-Power Testing".

Test failure shall be recorded as nonconformity of the component/sub-assembly to the technical specification and timely communicated to ENEA. The nonconformity shall be classified and managed according to the MQS [RHCR-REF-008].

After adjustment, modification or repair agreed with ENEA and performed by the Contractor, the Contractor shall submit the component to repeat the inspection and/or tests.

As normal management of nonconformities, the whole cost of the complete re-test shall be borne by the Contractor.

## 5.4 Warranty and equipment lifetime

A minimum of 5-year warranty shall cover all components listed in Scope of Supply against defects in design, construction, and installation. The warranty is limited to the direct costs of repair and component renovation. The quoted lifetime values above shall be confirmed or modified by the Contractor by implementing a maintenance and inspection program of the Control Room architecture system.

## 5.5 Spare parts

No spare parts are strictly required in the scope of this supply. If needed, the Contractor shall report it to the Client.

## 5.6 Staff training

The Contractor shall train (indicatively 6 people) indicated by the Client on the operation and maintenance of the Control Room by means of a training course to be held in person. The course content shall be presented to and agreed on by the Client and shall last at least five days. The course language shall be provided by the Contractor either in Italian or in English. As a guideline, the first part of the course shall focus on system architecture, usage, and maintenance. The second part shall focus on the operations and programming and be given at Contractor premises just before the delivery of the Supply to the site.

The Contractor shall grant access at agreed times, to its site to the Client throughout the period of the project. This may include visits by the Client to follow up crucial design, implementation and testing activities, allowing a natural transfer of project knowledge from the Contractor to the Client.

Dates and detailed content shall be agreed between the Contractor and Client during the preparation of the TDR and can be improved after the TDR. The Contractor shall bear course costs, the host Party shall cover logistics costs, and each Party will cover the expenses to compensate for its personnel away from its own premises.

# 6 Technical Requirements

Technical Requirements for the Control Room are reported in the document [RHCR-REF-001].

The technical-economic feasibility study is reported in the document [RHCR-REF-002].

The International System units shall be used. Should the Contractor identify inconsistencies or contradicting requirements between this Technical Specification and the other Applicable Documents, the Contractor shall seek clarification with the Customer at the earliest opportunity to ensure they consider the correct data.

To use a common frame of reference in software development, the contractor should take into account the frame of reference used for the DTT facility. The main frame of reference used for the DTT facility is the tokamak global coordinate system (TGCS), a three-dimensional Cartesian frame of reference where x is the radial direction located between sectors at positions #1 and #2, y passes through the middle position of sector #6, and z is the vertical direction with origin at the equatorial plane. The sector coordinate system (SCS) is a three-dimensional Cartesian frame of reference with origin (x'=0, y'=0, z'=0) located at x=2190 mm (the nominal plasma radius is R=2190 mm) and with equatorial plane (x', z'). Local coordinate systems can be defined for dimensional inspection during manufacturing. The Contractor should check with the Client that this frame is the definitive and desired frame.

# 7 Factory Acceptance Tests

All demountable parts shall be assembled at the factory. Some of the demountable parts can be pre-assembled, inspected as functional test, and then demounted if their integration is not compatible with transportation.

During FAT the necessary cabling to test that all the hardware components are correctly working, compatible with each other, and communication can be established. The control room cabling, with all sensors, server racks and additional components is considered necessary only in the SAT.

The installation of some items could be deferred or completed on site to avoid possible damage during handling and transport to DTT RH Facility site. Such deferrals or completions shall be agreed and approved by the Contractor.

The Contractor shall prepare a detailed plan about FAT. The minimum required FAT for the hardware and software parts are indicated in Table 5 and Table 6, respectively. Regarding the software, it is important to underline that the company shall hold a ISO 27001 certification, or equivalent.

The tests shall be carried out on all the components/subassemblies if applicable. The Contractor is recommended to perform intermediate tests.

Table 5. Summary of minimum required Factory Acceptance Tests (For Hardware).

| **Test description** | **FAT** |
|---|---|
| Visual inspection of hardware components to check the external state | FAT.01 |
| Validation of the electrical and logical operation of all off-the-shelf components. | FAT.02 |
| Electrical testing of safety and interface electrical panels. | FAT.03 |
| Verification of the operation of operating systems and software updates. | FAT.04 |
| Verification of the correct logical operation of PCs through a memtest cycle on RAM and hard drive. | FAT.05 |
| 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. | FAT.06 |
| Verification of the logical operation of the security system consisting of a safety panel and safety operator devices (Emergency Stop + Enable). | FAT.07 |
| Electrical isolation testing for safety panels and interfaces. | FAT.08 |

Table 6. Summary of minimum required Factory Acceptance Tests (For Software).

| **Test description** | **FAT** |
|---|---|
| Individual software module testing within a simulation context (simulated robots) to verify compliance with all project requirements. | FAT.09 |
| Integrated software module testing within a simulation context (simulated robots) to verify compliance with all project requirements. | FAT.10 |

| | |
|---|---|
| Usability testing. | FAT.11 |
| Software vulnerability testing in accordance with ISO 27001 standards: verifying vulnerabilities and ensuring that potentially vulnerability-causing actions have not been taken during the development cycle. | FAT.12 |

# 8 Site Acceptance Tests

The Contractor shall propose a Site Acceptance Test (SAT) plan to be approved by the Client. The plan shall address both the hardware and software components. The Contractor may attend all the Acceptance Tests on Site, according to the specified requirements and acceptance criteria.

Since the detailed design of the test sequences to verify the proper operation of software modules can only be carried out after the detailed design of the software itself, the detailed test plan shall be provided by the Contrator as a project document and shall be approved by the Client.

In Table 7 and Table 8 General SAT for the hardware and software parts are indicated, only as starting point.

For the tests, the Contractor shall observe any safety procedure of DTT RH Facility Site.

The Contractor shall propose and undertake all the necessary actions to resolve any possible problem identified during on-site acceptance tests in order to comply with all the requirements.

The results of the Acceptance Tests shall be integral part of the Final Technical Report and Acceptance Data Packages (ADPs).

The Contractor is responsible for carrying out any repair or modification required as a result of not meeting any of the Acceptance Criteria where the failure is directly attributable to Contractor's problems.

Table 7. General Site Acceptance Tests to consider (For Hardware).

| Test description | SAT |
|---|---|
| Visual inspection of hardware components to check the external condition of the equipment. | S.A.T.01 |
| Verification of the electrical and logical operation of all off-the-shelf components. | S.A.T.02 |
| Electrical testing of safety electrical panels and interfacing with the rest of the system. | S.A.T.03 |
| Verification of the logical operation of the safety system, consisting of a safety panel and operator safety devices (Emergency Stop + Enable). | S.A.T.04 |
| Electrical isolation testing for safety panels and their interface with the rest of the system. | S.A.T.05 |
| Electrical isolation testing for all components. | S.A.T.06 |
| Verification that network connectivity, communication between all modules, and latency respect the specifications. | S.A.T.07 |
| Verification on monitors and screens to ensure there are no display defects. | S.A.T.08 |
| Verification of power supply and UPS and checking the average operation times under UPS conditions when power disconnected. | S.A.T.09 |

Table 8. General Site Acceptance Tests to consider (For Software).

| Test description | SAT |
|---|---|
| Integrated testing of software modules in a real and simulated environment, as well as communication and movement of the robots in the mock-up area, to verify compliance with all project requirements. | S.A.T.10 |
| Usability testing. | S.A.T.11 |
| Software vulnerability testing in accordance with ISO 27001 standards. | S.A.T.12 |

# 9 Directives, Regulations, Codes and Standards

The following statutory acts shall be followed by the Contractor:

1. Machinery Directive 2006/42/EC (MD) for the design, fabrication of custom components, if expected.
2. CE marking for all off the shelf components;
3. CEI EN 60204-1:2018 Equipaggiamento elettrico macchine
4. ISO/IEC/IEEE 12207 Systems and software engineering – Software life cycle processes
5. ISO/IEC 9126 Software engineering

For each Work Package of the contract, the Contractor shall draw up a document in which all the applicable Laws, Directives, Regulations are referenced.

The Contractor shall indicate the number of protocols of the related internal documentation of the quality management system of the company, following directives, regulations, codes and standards.

The Contractor shall use the last applicable version of the Standards mentioned in this document at the date of the contract signature. In the case a Standard is superseded or withdrawn, the Contractor shall use the one that replaces the superseded/withdrawn.

Alternative International Standards based on specific former experience may be proposed by the Contractor for the different phases of the procurement. In case alternative standards are proposed, the Contractor shall submit them to ENEA for approval.

## 9.1 CE Marking

The Contractor shall determine EC/EU Directives and/or Regulations requiring CE Marking that apply to components/equipment/assemblies in the scope of the Contract.

The Contractor, or Subcontractor(s), is considered the Manufacturer of components/equipment/assemblies in the scope of the Contract. The Contractor, or Subcontractor(s), shall perform Conformity Assessment, affix the CE Marking and issue EC/EU Declaration(s) of Conformity where EC/ EU Directives and/or Regulations that require CE Marking apply.

The Contractor shall deliver components/equipment/assemblies certified and CE marked at the highest possible integration level, i.e. at the level of independent functional units (assemblies).

The Customer does not perform certification/CE marking or integration under national legislation of components/equipment/assemblies included in the Contractor's scope of Contract unless otherwise specified in the Contract.

The Contractor shall ensure that sub-contracted or purchased components/equipment/assemblies comply with EC/EU Directives and/or Regulations that require CE Marking where applicable. This includes verifying CE Marking, EC/EU Declarations of Conformity and operating and maintenance instructions.

Remark: Equipment/assemblies composed of CE marked components also require Conformity Assessment and CE marking on equipment/assembly level.

The Contractor shall provide the following documents for ENEA review and acceptance:

1. A Compliance Report with results of the Contractor's assessment regarding applicability of EC/EU Directives and/or Regulations to the scope of the Contract and a CE Marking strategy for the complete scope of the Contract at the level of independent functional units (assemblies).
2. Manufacturer's EC/EU Declaration(s) of Conformity and, if applicable, documents issued by Notified Bodies in the course of Conformity Assessment latest 15 working days prior to the transfer of ownership to ENEA (if not otherwise specified in the Contract);
3. Operating and maintenance instructions in English and in the national language of the country of destination latest 15 working days prior to the transfer of ownership to ENEA (if not otherwise specified in the Contract). Operating and maintenance instructions in Italian are waived for components/ equipment/ assemblies whose place of delivery is the DTT RH Facility Site, Napoli, Italy;
4. Technical documentation related to hazard identification, risk evaluation and risk mitigation of the component/equipment/assembly;
5. Upon request, other technical documentation related to design, manufacturing and erection of the component/equipment/assembly as necessary for integration into a higher level assembly and Conformity Assessment by another party.

NOTE: ENEA approval of the Compliance Report does not release the Contractor of its responsibility regarding the applicability of CE marking.

In case that no acceptance is granted by DTT, CE Marking applies. The same applies for any other exclusion from any EC/EU Directive or Regulation requiring CE Marking deemed applicable by the Contractor.

For information, the main EC/EU Directives and Regulations applicable to the scope of DTT Contracts are:

- Machinery Directive 2006/42/EC;
- Electromagnetic Compatibility Directive 2014/30/EU;
- Low Voltage Directive 2014/35/EU;
- Equipment and Protective Systems intended for use in Potentially Explosive Atmospheres (ATEX) Directive 2014/34/EU.

# 10 Milestones, deliverables and scheduling

## 10.1 Milestones

The reference Table of Milestones is shown in Table 9.

The approval by ENEA of the Final Technical Report shall be within 20 months after SoC.

The delivery of the Control Room is established at month 20 after SoC.

The Kick off Meeting (KoM) shall be set less than 1 month from SoC. The Contractor shall submit its proposal for modification, addition, and/or substitution of milestones no later than 2 weeks in advance of the KoM.

The Contractor shall prepare and implement MIPs (Manufacturing & Inspection Control Plans) to monitor both quality control and procurement tests, then shall submit the MIPs to ENEA for acceptance and mark up of interventions. The level of detail of the MIPs shall be agreed between ENEA and the Contractor. This level of detail shall be enough to allow for a proper follow-up of the activities by ENEA.

All the milestones shall be considered as Hold-Points for ENEA.

The rest of the control points will be defined and agreed at the beginning of the contract execution in accordance with the detailed schedule proposed by the Contractor and shall be in compliance with the milestones indicated in Table 9.

Assumption: the Months defined for the Milestones assume that software modules can be developed in parallel. The Contractor can propose to the Client a variation of the Milestones timeline after the definitive design, which must be then evaluated by the Client.

Table 9. List of milestones

| # | Deliverable | Milestone | Months after SoC |
|---|---|---|---|
| M.00 | - | KoM | 1 |
| M.01 | A.A | Completion of Executive hardware design | 2 |
| M.02 | A.B | Completion of Executive software design | 4 |
| M.03 | B.A | Software Development – Simulation and Visualization modules | 8 |
| | B.B | Software Development – Collision management module | 10 |
| | B.C | Software Development – Motion planning module | 12 |
| M.04 | C.A | SW+HW Development – Safety system | 13 |
| | C.B | Software Development – Operation module | 14 |
| | C.C | Software Development – Diagnostic module | 16 |
| | C.D | Software Development – HMI module | 16 |
| | C.E | Software Development – Cybersecurity module | 17 |
| M.5 | D.A | FAT | 18 |
| M.6 | E.A | Transportation of the equipment | 18 |
| | E.B | SAT | 19 |
| M.7 | F.A | Delivery of the Final Technical Report | 20 |

## 10.2 Deliverable

The Contractor shall create a Deliverable list to be approved by ENEA during the KoM. The Contractor Deliverable list shall include at least the deliverables shown in Table 10. The Contractor shall include in the monthly schedule submission the date of expected submission of each deliverable.

Table 10 contains specifics on the deliverable, the nomenclature of the ID is: “X” for the milestone, “Y” document, “N” the number of the document.

Table 10. List of deliverables

| ID | Deliverable | Date |
|---|---|---|
| - | Management documentation | |
| PQMP | Project and Quality Management Plan (PQMP) & related quality documentation | See Management and Quality Specification |
| MOM_DATE | Minutes of Meeting (including Kick-Off) | |
| ADP_X_Y | Acceptance Data Package | During contract |
| FTR | Final Technical Report | During contract |
| TR_X_Y | Test Report | See Management and Quality Specification |
| - | Technical Documentation | |
| FATP | Factory Assembly & Acceptance Tests (FAT) Plan | During contract |
| FATR | Factory Assembly & Acceptance Tests (FAT) Report | During contract |
| - | CAD Drawings, Wiring Diagrams and Electrical Schemes and Software Schemes | During contract |
| OMM_N | Operation and Maintenance Manual | During contract |
| CE_N | EU Directive declaration(s) of conformity | During contract |
| L_N | Codes, Standards, Law, Directives, Regulations document (for each WP) | Before starting of each WP |
| SATP | Site Acceptance Tests (SAT) Plan | See Management and Quality Specification |
| SATR | Site Acceptance Tests (SAT) Report | See Management and Quality Specification |
| - | Technical Documentation | |
| HW | All hardware components as described in CR1 | During contract |
| SW | All software modules as described in CR1 | During contract |

### 10.2.1 Management Documentation

Before the supply of each deliverable, the Contractor shall submit to ENEA for review the Acceptance Data Package (ADP) as documentation package linked with that deliverable (see the Management and Quality Specification) [RHCR-REF-008].

The Contractor shall prepare a Project and Quality Management Plan (PQMP) describing the management system developed, implemented, and maintained by the Contractor throughout the life-cycle of the Contract to ensure that the Contract Requirements are met and that evidence of such compliance is maintained (see the Management and Quality Specification) [RHCR-REF-008].

In particular, the Contractor shall include in the PQMP the management of nonconformities and Deviations.

The Contractor shall define in PQMP the methodology to ensure the traceability.

The Contractor shall describe in PQMP the methodology for the selection of procurement sources and Subcontractors.

The qualification strategy shall be documented in the PQMP and accepted by ENEA.

Management requirements specified in the Management and Quality Specification [RHCR-REF-008] apply.

## 10.2.2 Technical Documentation

The technical documents listed in this section will be elaborated and delivered in full as part of the Supply.

The Contractor shall prepare and deliver the following documents as a minimum during execution of the Contract according to the relevant schedule and work organization.

### 10.2.2.1 Plan and Report of Factory Assembly & Acceptance Tests (FAT)

The Contractor shall include all the tests made at the factory for the hardware and software of the control room in a Factory Assembly & Acceptance Tests (FAT) Plan, prepared according to the indications included in Section 7, and submit the plan to the Client for approval. The FAT shall include, if any, tests that are performed outside the Contractor premises. The FAT shall be performed using simulated robots.

The Contractor shall NOT start any of the assembly and/or testing activities at Contractor's factory or at subcontractors prior to approval of the Factory Assembly & Acceptance Tests (FAT) Plan by the Customer.

The Contractor shall collect in a Factory Assembly & Acceptance Tests (FAT) Report all the information and checks done during the integration and the measurements and results of tests carried out at the Contractor's factory or at subcontractors as well as the certification, qualification, inspection and quality records, certificates of conformity of each part, quality records and/or reports of nonconformities and submit the report to the Customer for approval.

The Contractor shall compare the results of the factory tests with the requirements given in this Technical Specifications and the Factory Assembly & Acceptance Tests (FAT) Plan.

### 10.2.2.2 Plan and Report of Site Assembly & Acceptance Tests (SAT)

The Contractor shall include all the tests for Control Room SAT in a Site Assembly & Acceptance Tests (SAT) Plan, according to the indications provided in Section 8, and submit the plan to the Customer for approval.

The Contractor shall NOT start any of the assembly and/or testing activities at Contractor's factory or at subcontractors prior to approval of the Site Assembly & Acceptance Tests (SAT) Plan by the Customer.

The Contractor shall collect in a Site Assembly & Acceptance Tests (SAT) Report all the information and checks done during the integration and the measurements and results of tests carried out at the Contractor's factory or at subcontractors as well as the certification, qualification, inspection and quality records, certificates of conformity of each part, quality records and/or reports of nonconformities and submit the report to the Customer for approval.

The Contractor shall compare the results of the factory tests with the requirements given in this Technical Specifications and the Site Assembly & Acceptance Tests (SAT) Plan.

#### 10.2.2.3 Operation and Maintenance Manual

The Contractor shall provide an Operation and Maintenance Manual for both the hardware and the software.

The hardware manual should include, but not limit to, the network description with all subnets and routing and a general description of all hardware components describing the control room, as well as the maintenance procedure, if necessary.

The software manual should include for all software modules, but not limited to:
- Installation, setup, update, and uninstallation
- System prerequisites
- Software configuration
- General use (e.g. launching and visualizing)
- Examples of use

The manuals shall be written in English.

#### 10.2.2.4 Final Technical Report

The Contractor shall issue a Final Technical Report at completion of the procurement.

The Final Technical Report shall include all the plans and reports required in this technical specification, in particular:

i. Electrical and network schemes;
ii. Software design;
iii. the Factory Assembly & Acceptance Tests (FAT) Plan and Report;
iv. plan and report of each test which is not requested for FAT and SAT;
v. the Packing, Transport and Delivery Plan and Report;
vi. the Site Assembly & Acceptance Tests (SAT) Plan and Report;
vii. the Operation and Maintenance Guide Manuals;

The Contractor shall create and submit either a single Final Technical Report clearly subdivided for each Block or a distinct Final Technical Reports, one for each Block.

# 11 Quality Assurance Provisions

The Contractor shall apply the Quality Assurance provisions as indicated in the Management and Quality Specification [RHCR-REF-008] issued for this Specific Contract for the procurement of the DTT RH Facility Control Room.

| Access: | ☐ contractual | ☐ open | ☐ restricted |
|---|---|---|---|

| | | |
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# Control Room Architecture and Requirements

| | | |
|---|---|---|
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# 1 Acronyms and definitions

## 1.1 Acronyms

| | |
|---|---|
| API | Application Programming Interface |
| A&A | Authentication & Authorization Software |
| CMM | Cassette Multifunctional Mover |
| CMS | Collision Management Software |
| CR | Control Room |
| DOF | Degree Of Freedom |
| DS | Diagnostic Software |
| DSI | Dynamic Simulation Interface |
| DTT | Divertor Tokamak Test |
| FRI | Fault Reporting Interface |
| FW | First Wall |
| HID | Human Interaction Device |
| HLCS | High Level Control System |
| HMI | Human Machine Interface |
| HO | Human Operator |
| HYRMAN | HYper Redundant MANipulator |
| IFW | Inner First Wall |
| LLCS | Low Level Control System |
| ME | Motion executor |
| MO | Manipulator Operator |
| MP | Motion Planner |
| OMS | Operation Management Software |
| RH | Remote Handling |
| RHE | Remote Handling Equipment |
| RHO | Remote Handling Operator |
| RHS | Remote Handling System |
| RO | Responsible Officer |
| SCM | Shared Control Mode |
| SL | Structured Language |
| SM | State Machine |
| S/S | Subsystem |
| TCP | Tool Center Point |
| TCS | Teleoperation Control Software |
| TF | Transform Frame |
| TR | Technical Requirement |
| RHF | Remote Handling Facility |
| UI | User Interface |
| UPS | Uninterruptible Power Supply |
| VR | Virtual Reality |
| VRS | Virtual Reality Software |
| VS | Visualization Software |
| VV | Vacuum Vessel |

## 1.2 Definitions

| | |
|---|---|
| Client | The entity that shall award the tender for the subject of the present Technical Specification and that shall be in charge of verifying the adherence to the required prescriptions |
| Fail-Safe | design feature that ensures the system minimizes the risk of harm and hazards. |
| Machine side | All the S/S located in the mock-up area. |
| Operator side | All the S/S located in the control room. |
| Real Camera | Camera View from the real mock-up area |
| Responsible Officer | A team leader operator named Responsible Officer (RO) that coordinates the different robotic machines operations and the actions taken by the operators of the lower levels. |
| Site | The location where the DTT RH facility will be installed (San Giovanni, Naples, Italy). |
| Tokamak | Toroidal shaped machine in which a hot and rarefied gas (usually of hydrogen and its isotopes, in the plasma state) is confined far enough from the internal walls thanks to a magnetic field created by electromagnets |
| Transform Frame | A three-dimensional coordinate system used to represent the position and orientation of objects with respect to a Cartesian reference frame (World Transform Frame) |
| Validation | The assurance that a product, service, or system meets the needs of the customer and other identified stakeholders |
| Verification | The evaluation of whether a product, service, or system complies with a regulation, requirement, specification, or imposed condition |
| Virtual Camera | Camera View from the virtual 3D visualization environment |

## 1.3 Identifiers

In order to simplify the reading of the text, we use identifiers with the following coding: [Identifier - Number]. For example the first requirement is indicated as: [RQ-001].

| **Identifier** | **Description** |
|---|---|
| M | Identifies a software module |
| RQ | Identifies a requirement |

# 2 Introduction

The DTT RH facility control room is responsible for the management, coordination and high-level control of all the robotic systems.

The purpose of this document is to provide the architecture and the technical requirements for the executive design and commissioning of the DTT RH facility control room (DTT RHF CR). The architecture and the technical requirements are reported in the same document for a better understanding of the technical requirements. First, the layout and the system architecture of the control room is presented. Then, the technical requirements of each subsystems are provided.

The rest of this document is therefore divided into the following chapters:

- **Chapter 3**: Description of the layout of the control room and definition of the operator roles within the control room.
- **Chapter 4:** System architecture of the control room.
- **Chapter 5:** Technical requirements associated with the networks
- **Chapter 6:** Technical requirements associated with the hardware
- **Chapter 7:** Technical requirements associated with the software

# 3 Layout of the control room

In this section we include the layout of the control room and the roles of the operators within the control room. This section is important to understand the subsequent architecture and relative technical requirements for the control room.

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

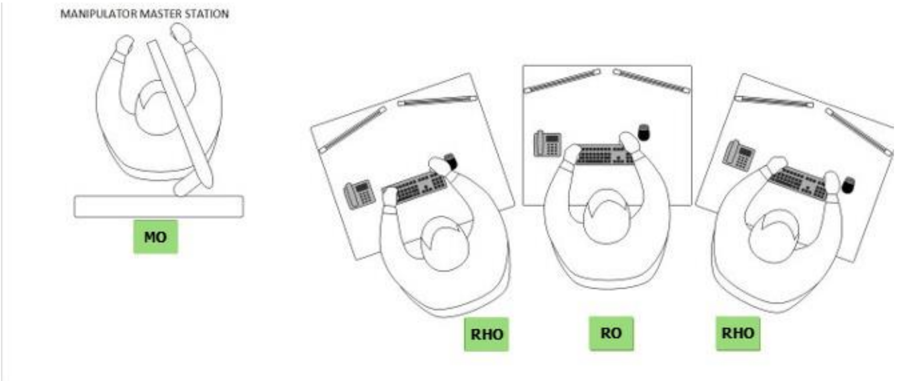


Figure 1: RH work-cell team composition.

During the remote handling operation, the Control Room foresees the presence of a team of operators with the following composition (see Figure 1: RH work-cell team composition.):

- 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.

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. In Table 2 is enlisted the minimum suggested number of hardware components for the workcell. Each component is specified in Chapter 8.

| Component | Q.ty |
|---|---|
| Wall-Monitor | 2 |
| Docking station | 1 |
| Manipulator master station monitor | 2 |
| Workdesk Monitors | 8 |
| Operator’s PC | 2 |
| Supervisor’s 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 |

Table 1: Minimum suggested number of hardware components for the workcell.

The CR will be hosted inside a two-storey prefabricated (see Figure 2). The ground floor will be used for the DTT RHF CR. Its planimetry is shown in Figure 3. The control room is divided in three main areas, which are described in the following: (1) Area A; (2) Area B; (3) Area WC.

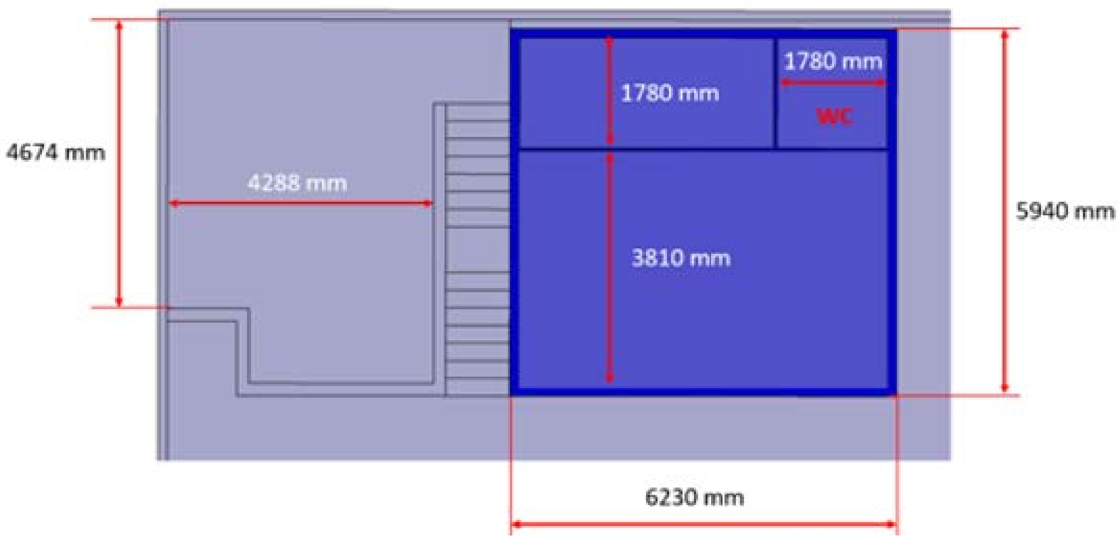


Figure 2: The control room is highlighted in blue and divided in three areas.

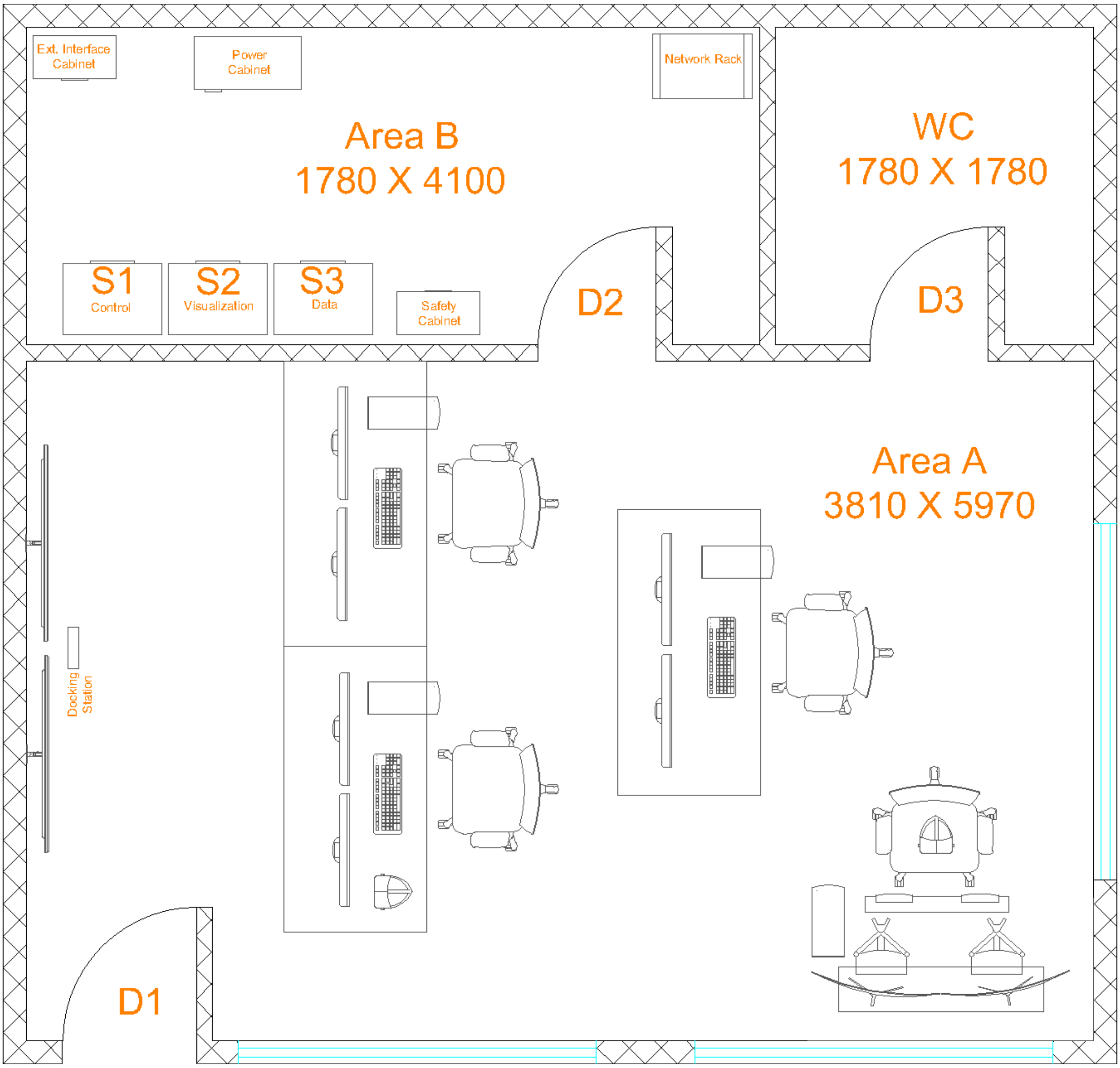


Figure 3: Floor Plan Control Room

**Area A – Workcell**

Area A is designated as the workcell and is intended to be the main area of operation. Dimensions for this area are 6200x3800mm. This area is already provided with windows facing the mock-up area. The workcell includes four operator workstations: one manipulator master station and three workdesks. An overview of the components needed for each workstation is provided in the following: a comprehensive summary of all the workcell hardware is in Table 1. 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 workdesk is composed of:

- Two or more workdesk monitors
- One ergonomic seat.
- One operator's PC

The workcell will also feature:

- A large wall-mounted monitor to facilitate clearer task status supervision.
- Two VR headsets with controllers.
- Two or more joysticks.

The only access door is located in this area; therefore, security measures must be provided to limit access only to authorized personal by ENEA. 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 – Storage**

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

**Area WC**

Area WC is designated as the toilet area. Dimensions for this area are 7800 mm x 1300 mm.

# 4 System architecture

This section reports the system architecture of the CR. The architecture is based on a Multi-Server/Multi-Clients communication system. The Clients represented by both the Machine side (all the S/S located in the mock-up area) and the Operator side (all the S/S in the control room) communicate with two central Servers: The Control server and the Visualization server. The operator's PC and the Servers will have to interface with a third Server which stores all data such as 3D models, task reports, and all the information regarding RH procedures in the DTT RHF.

The schematic of the proposed system architecture is illustrated in Figure 4, where, for completeness, the mock-up area has also been included, even though it is not directly relevant to this document.

The system architecture foresees three parts:

1. Network
2. Hardware
3. Software

They are described in the following.

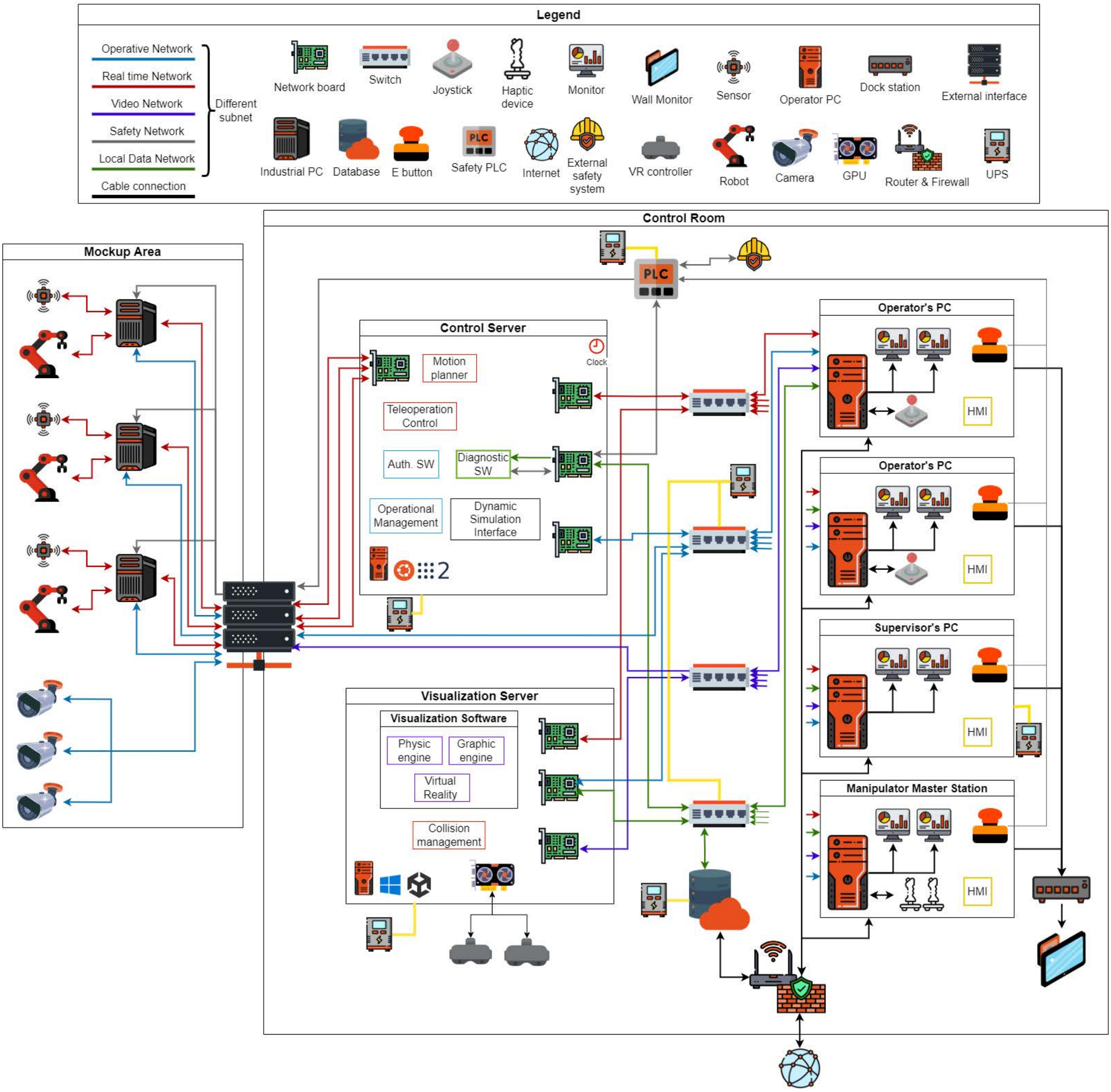


Figure 4. System Architecture Diagram. It is a Multi-Server/Multi-Clients system architecture.

## 4.1 Network

The architecture foresees **five distinct communication channels** to avoid interference during transmission. Within the system architecture diagram, the communication networks have been color-coded, based on the type of data and signals they carry, along with the specific requirements they must adhere to. The colour coding can be seen in the Legend on top of Figure 4. This legend also contains all symbols used in the schematic drawing. The RH networks are:

- The **Local Data Network**: handles the transferring diagnostic information and facilitating file and data transfer to and from the data server. Requirements are defined in 5.1.
- The **Real-Time Network**: handles the transmission of command signals and sensors signals with real-time requirements. Requirements are defined in Section 5.2
- The **Video Network**: designed to transmit video streams originating from the visualization server inside the Control Room. This network can serve as an alternative for video transmission, mitigating the risk of congestion on the Operative Network. Requirements are defined in Section 5.3.
- The **Operative Network**: handles the transferring non-critical information, including control set points, telemetry, and eventually video signals from external sources. Requirements are defined in Section 5.4
- The **Safety Network**: this setwork is composed of an analog hardwired network used for sending stop signals to the motors plus a dedicated safety network to send more structured safety data streams. It interfaces with the internal digital systems of the control room through a safety PLC. Requirements are defined in Section 5.5.

Additionally, an internet-based connection is foreseen to directly exchange data with the external ENEA centre. The connections between all S/Ss are specified in tables, including the particular sub-net of the connection.

The arrangement of networks and components within the control room has been assessed and is depicted in Figure 5. The estimation of the quantity of cables and their types, based on the dimensions and layout of the CR, is reported in Table 2 The cables considered are solely those within the CR. Connections involving cables originating from the external interface are not included in this assessment.

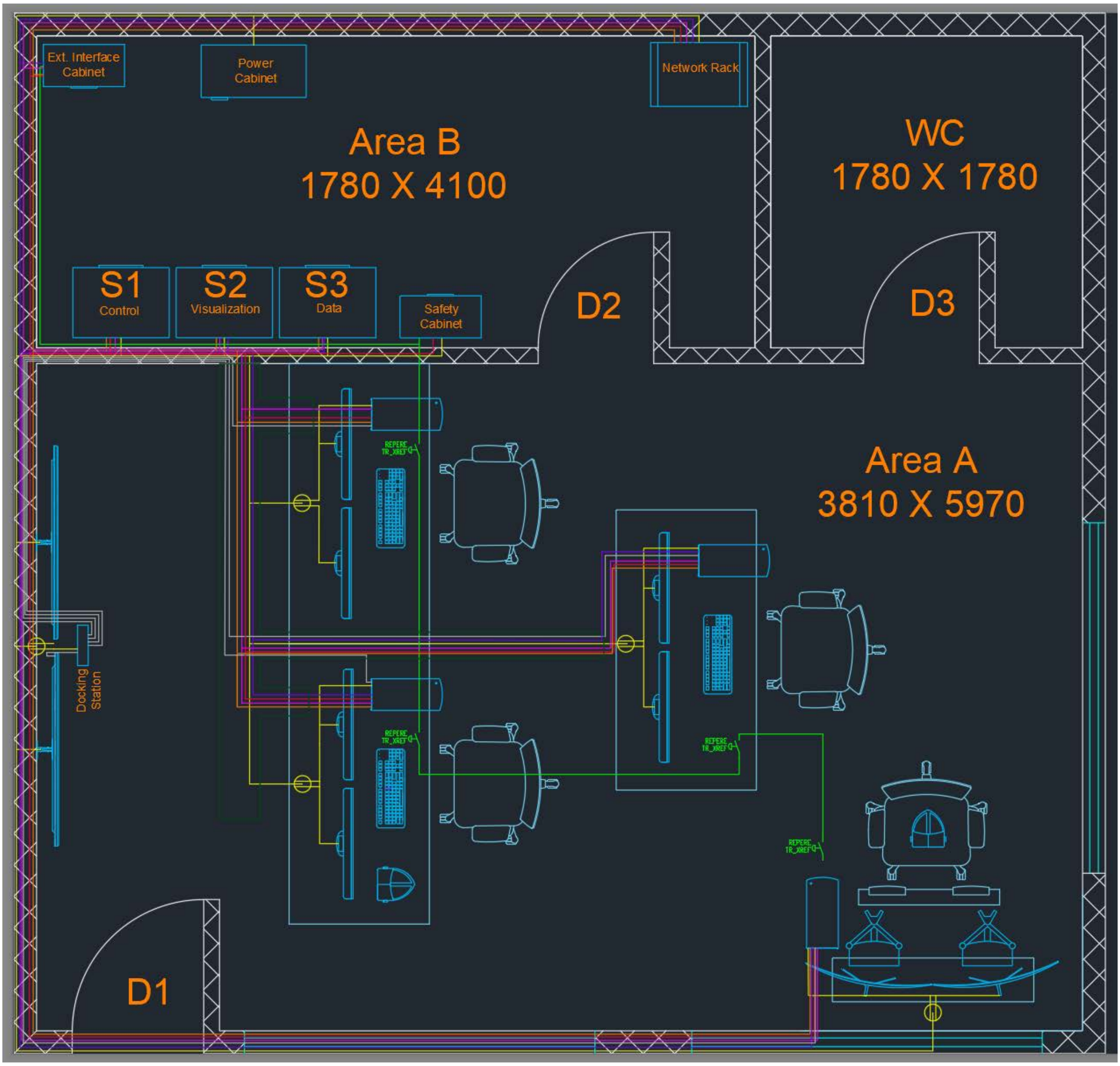


Figure 5. Architecture related to cable installation.

| Component | Q.ty/Meters |
|---|---|
| Wiring: Cable for real time protocol | 15 |
| Wiring: Ethernet cable | 500 |
| Wiring: DisplayPort 1.4 cable (5 meters) | 35 |
| Wiring: DisplayPort 1.4 cable (1 meters) | 6 |
| Wiring: USB cable | 10 |
| Wiring: floor cable channels type 1 | 10 |
| Wiring: Safety cable | 10 |
| Wiring: power cable | 150 |
| Wiring: power supply panel | 1 |
| Wiring: wall cable channels | 30 |
| Wiring: floor cable channels type 2 | 5 |
| Outlets | 15 |
| Vertical power outlets | 80 |
| Ethernet outlets | 8 |

Table 2. Estimation of quantity of cables based on the dimensions and layout of the CR.

## 4.2 Hardware

In this document with the term hardware we indicate all the hardware components within the CR, including displays, operator's PC, human interaction devices, standard network equipment (switch and routers), Uninterruptible Power Supply, and, of primary importance, the servers.

The architecture considers the following **displays**:

1. Workstation's monitor (x2)
2. Manipulator Master Station's Monitor (x2). The Manipulator master station's monitor must ensure complete and immersive visibility to the MO. It can be built as composition of monitor or as one large, curved monitor. In the first case it is crucial to avoid conjunction line in front of the operator.
3. Wall monitor (x2). To facilitate the execution of RH operations, it is foreseen to use a wall-mounted screen that enables a clear display of the ongoing task and critical information. An alternative solution is to create a wall monitor by combining two individual screens of smaller size. This dual-monitor configuration offers more adaptability and versatility. Unlike a fixed single-screen setup, this configuration provides the flexibility to switch between options, such as a single large screen composed of two monitors, two separate displays, each comprising one monitor, or any other preferred arrangement. This flexible arrangement empowers users to organize and manage the interface according to their needs, ensuring optimal clarity of information. To connect and display two monitors as a single cohesive display, the use of a docking station may be necessary.

The architecture foresees four **PCs**, that are grouped according to the four operators. All operators are connected to a docking station, enabling the control of the video signal on the wall monitor from any PC. In particular, we have two PC for the standard operators, one is the supervisor PC and one is the Manipulator Master Station.

The **human interaction devices** are:

1. Joystick (x2)

2. Force-feedback device (x1)
3. VR Headset & Controller (x2)

These devices contribute to the creation of the **Immersive control room**, developed to provide operators with a more immersive and engaging experience.

The most important part of the hardware is represented by the **servers**. Three servers are specified in the schematic diagram (Figure 4), each having multiple network cards. This stems from the proposed segmentation of the network into separate subnets, therefore requiring PCs with dedicated network cards. The servers communicate with operator PCs and among themselves via the highlighted networks and through four main switches, each responsible for managing data for a single network. The presence of servers reduces the computational burden on the operator's PCs, which are solely responsible for supervisory and high-level control tasks. The servers are: Control server, Visualization server, Data server.

The **Control server** takes on certain aspects of the control system, creating an intermediate-level control system that interfaces with the low-level control system executed on the robot's industrial PC. It also runs the diagnostic of all the components inside the Control Room and it interfaces with a Safety PLC to send a stop signal in case of critical failure of any component.

The **Visualization server** is the server devoted to visualization aspects.

The **Data Server** dedicated to collecting task data and maintaining 3D models can be implemented as an in-house server. However, it is also possible to rely on third-party cloud computing services. One of the significant advantages of having an in-house server is the physical control it provides over data backup. Critical data remains within the organization's premises, ensuring that no third party can access sensitive information. However, given the need for external connectivity, it remains essential to develop a robust data cybersecurity system. Another benefit of the in-house server is the independence from the Internet for accessing data, preventing interruptions in remote handling operations, while cloud-based servers are heavily reliant on internet connectivity. Additionally, over the long term, maintaining an in-house server setup can be more cost-effective compared to recurring cloud service fees. However, setting up and maintaining an in-house server requires a substantial capital investment in hardware and infrastructure. You'll need dedicated space for housing server racks or a server room, in addition to hiring and retaining IT support to manage and maintain the system. All this cost is avoided when using cloud services, which can be a more affordable solution in case of fluctuations in data storage needs. Cloud solutions are highly scalable, allowing organizations to expand their storage capacity as needed, often on a pay-as-you-go basis. Furthermore, in-house servers may be more susceptible to data loss during disaster situations since they are physically located within the organization. Natural disasters, power outages, or hardware failures can potentially disrupt data accessibility and compromise recovery efforts. Cloud-based servers offer the possibility of frequent data backups, sometimes as often as every 15 minutes, enhancing data security and minimizing potential losses during disaster scenarios. Additionally, in-house servers typically lack the uptime and recovery time guarantees provided by professional cloud service providers. Furthermore, cloud computing servers also provide additional capabilities for data analysis and AI-based solutions, which can be highly valuable for conducting task analysis and preventive maintenance. In conclusion, the choice between an in-house server and a cloud server depends on the specific needs and priorities. The high scalability and adaptability of the cloud-based server, coupled with the offered AI-based solutions, make the cloud server the preferred and envisioned solution. In this architecture we consider the **in-house Data Server solution**.

Furthermore, all PCs are connected to the internet through a router running a firewall and implementing all necessary cybersecurity measures.

The architecture foresees an **Uninterruptible Power Supply** (UPS) for each critical hardware component. In this architecture, there are six defined UPS units, each with names ranging from UPS1 to UPS6. These units belong to three distinct types, distinguished by their varying power sustainability capabilities. UPS types are:

- **Type 1**: With a suggested output wattage of 330 W. UPS Type 1 are associated with the networks (real-time, diagnostics and operative) – UPS 3 in Table 4 and Table 5 – and with the supervisor's PC – UPS5 in Table 4 and Table 5.
- **Type 2** With a suggested output wattage of 600 W. UPS Type 2 is associated with the Safety PLC - UPS4 in Table 4 and Table 5.
- **Type 3** With a suggested output wattage of 1000 W. UPS Type 3 are associated with the servers – UPS1, UPS2, and UPS 6 in Table 4 and Table 5.

## 4.3 Software

The software architecture of the CR is segmented into individual modular blocks. Each module performs a specific task, and necessary requirements and suggested functionalities have been documented for each one. The architecture foresees 9 **software modules**:

- **Human Machine Interface [M1]**
- **Diagnostic Software [M2]**
- **Dynamic Simulation Interface [M3]**
- **Motion Planner [M4]**
- **Teleoperation Control [M5]**
- **Collision Management [M6]**
- **Operation Management Software [M7]**
- **Authentication & Authorization Software [M8]**
- **Visualization Software [M9]**

This division is the result of this architecture. However, if it satisfies the requirements, multiple modules of this division can condensate under the same software module. They are in the following described, and divided according to their execution location:

On the Operators PCs runs:

- **Human Machine Interface [M1]:** This software module is responsible for implementing the user interface, collecting and displaying information from the system, and enabling user interaction with the software components.

On the Control Server runs:

- **Diagnostic Software [M2]:** This software module is responsible for monitoring the proper functioning of all system components. Furthermore, it can generate reports on executed task and identify all causes in the event of a fault. It interfaces with the safety network.

- **Dynamic Simulation Interface [M3]:** This software module is responsible for utilizing the manipulator models provided by the manufacturers and interfacing them with the modules present in the control and visualization server.
- **Motion Planner [M4]:** This software module is responsible for generating optimized trajectories for robots inside the VV, taking into account constraints and the actuators' capabilities, ensuring safe and efficient motion.
- **Teleoperation Control [M5]:** This software module is responsible to manage teleoperation, and transform input signal coming from the Human Interaction Device (HID) in control signals and provide feedback signal to the HID.
- **Operation Management Software [M7]:** This software module is responsible for managing RH operations, enabling the scheduling of tasks, generating reports, and planning activities. This module is further described in Section 7.8
- **Authentication & Authorization Software [M8]:** This software module is responsible for ensuring the proper authentication of each operator and granting them access to the functionalities they are authorized to use.

On the Visualization Server runs:

- **Visualization Software [M9]:** This software is responsible for providing a visualization of the scene using 2D images and 3D models. Additionally, it handles the implementation of the virtual reality environment and manages the interaction of the operator equipped with a VR headset.
- **Collision Management [M6]:** This software module is responsible of detecting any possible collision between the manipulator and the environment during RH operations.

All software should be developed in a way that includes three different *Session States*: **Planning State, Maintenance State** and **Operation State**. During the Operation State three different control modes should be available: Supervisor, Shared and Teleoperated.

- **Supervision mode** the human operator is only a supervisor of the ongoing procedures. The equipment executes autonomously the operations, while the operator monitors the completion level of the task, the flux of data collected by the sensors and the security status of the components. In case of failure or any unexpected behaviour, this mode should stop and prompt to switch to the "Teleoperation mode" in order to let the operator directly intervene and bring the interested S/S in a safe configuration.
- **Shared mode** part of the ongoing procedure is executed autonomously by the robotic system and part is manged by the Operator. The development of specific shared control strategies is out of scope of this project. The company should solely focus on developing an API to incorporate external forces, supplied by possible external module, that can be applied to the haptic interface.
- **Teleoperation mode** the user can remotely control the equipment in first person by providing a series of input commands, using joystick, headset controllers or force-feedback devices if the manipulator supports it.

Meanwhile, the Planning state is designed for operators' training and testing of solutions. During these instances, the real site is disconnected from its digital twin and the user exclusively interacts with the digital model. The control software does not directly command the manipulator but sends commands to a simulator, and everything is carried out in a virtual environment. In this mode, it is possible to plan trajectories and tasks and simulate them kinematically and dynamically. Once a task has been simulated and validated, it can be saved and executed on the real world. It also possible to simulate shared and teleoperated operation, controlling and visualizing the 3D model of the robotic system inside the VR environment.

The Maintenance State is designed for maintenance operations on the mock-up area. This is the only state in which operators might be near the machines, proved that all necessary safety measures and regulations have been implemented, such as the presence of emergency buttons near each robot, etc. During the maintenance state, the allowable operations are limited in order to comply with the technical requirements in Section 7. During this state the Control Room should be informed via the HMI and with physical light alerts. Maintenance are performed directly accessing the industrial cabinet, therefore no signals shall be sent from the Control Room when the maintenance state is activated.

For each software module, we provide in the following the list of the technical requirements.

It is expected that the development of software and hardware components will be coordinated to align data exchange interfaces and ensure seamless integration and collaboration between each module. Additionally, an intensive phase of testing and validation of the hardware and software systems within the DTT RHF is expected to ensure they precisely adhere to the specified requirements.

# 5 Technical Requirements for the Network

The connections between all S/Ss are specified in Table 3 to Table 6. In the following, we report all the requirements related to the Network part.

## 5.1 Basic Requirements

[RQ-001] The interfaces of the control room with the other systems are included in the ICD. In particular, a component referred to as "External interface" defines the interface between the elements in the control room and the elements within the other systems.

## 5.2 Local Data Network

The Local Data Network will be used to receive information about the status of connected systems, detect the causes of any malfunction, and act on it. Diagnostic information and task information elaborated from each component should be transmitted on this network. It should, therefore, respect the following specifications:

[RQ-002] The Local Data Network shall be designed to be fail-safe

[RQ-003] The Local Data Network shall ensure that each connected entity has a state that describes whether it is operating under nominal conditions. The state shall include at least include:

- Operational: The subsystem is turned on and functioning normally without issues.
- Disconnected: The subsystem is off and not visible on the network.
- Inactive: The subsystem is idle.
- Warning: The subsystem is operational, but there are conditions or parameters that require the operator's attention.
- Error: The subsystem is not working as expected and should be stopped. Known malfunctions/errors should be signalled to operators.

[RQ-004] The Local Data Network shall provide a network bandwidth of at least 10 Gbit

## 5.3 Real-time Network

The Real-time Network should respect the following specifications:

[RQ-005] The Real-time Network shall be used to retrieve force telemetries coming from the Robot S/S. It shall also be used to exchange data regarding:

- The robot state
- The control signals coming from the Operator's PC or the Control Server.
- The signals coming from sensors relevant for control purposes.

[RQ-006] The Real-Time Network shall be designed to guarantee connections from the industrial PC to the server using real-time protocols like EtherCAT or ProfiNet.

[RQ-007] The Real-Time Network shall ensure that operator PCs are connected to the server through a real-time protocol, such as EtherCAT, ProfiNet or RTP over UDP.

[RQ-008] The Real-time Network shall be designed in a way that the cables used can ensure reliable and real-time communications. Additionally, it shall include provisions for data to travel on a specific subnet.

[RQ-009] The Real-time Network shall comply with, but not limited to, the following conditions:

- Low Latency: Latency shall be consistent and predictable, assuring minimal delay in data transmission and processing. In particular, the frequency shall be at least 1000 Hz for ensuring real-time force control.
- High Bandwidth: The network shall have sufficient network capacity to handle the volume of data generated in real-time, including video, audio, and sensor data.
- Quality of Service (QoS): Real-Time data packets shall be prioritized to ensure timely delivery and minimal packet loss.
- Reliability: shall ensure minimal downtime for maintenance or repairs.
- Monitoring and Management: shall offer tools and systems for monitoring network performance and identifying issues in real-time.
- Traffic Prioritization: shall have the ability to prioritize different types of data traffic to ensure that critical data is delivered on time.
- Packet Loss Mitigation: shall foresee no packet loss.
- Jitter Control: shall foresee techniques to minimize variations in packet arrival times, which can impact real-time communication quality.
- Synchronization: shall ensure that devices and nodes within the network are time-synchronized to avoid timing discrepancies.
- Compatibility with Real-Time Protocols: Support for specialized real-time communication protocols like RTP (Real-time Transport Protocol), MQTT (Message Queuing Telemetry Transport), and others.

## 5.4 Video Network

The Video Network is designed for the transmission of video feeds from cameras and from the 3D visualization software. It should respect the following requirements:

[RQ-010] The Video Network shall be designed and tested to be reliable and to avoid disconnections during the video stream.

[RQ-011] The Video Network shall be exclusively dedicated to handling video stream data, including both video streams originating from the machine side and those from the Visualization Server. Eventually, video data from the machine side can be sourced from the Operative Network and then rerouted to the control room's Video Network.

[RQ-012] The Video Network shall ensure the ability to display all streams at the same resolution at which they were captured.

[RQ-013] The Video Network shall guarantee a maximum latency between the camera and operator monitor of 50 ms.

[RQ-014] The Video Network shall ensure a maximum of frames loss of 1% during transmission.

[RQ-015] The Video Network shall provide sufficient network bandwidth to transmit all the camera streams present in the mock-up area and at least three (3) different virtual cameras for each operator. This is intended to allow operators to simultaneously have different perspectives of the same operation, enabling them to be more aware of the ongoing movements. For example, this could include having a top view, a side view, and a front-facing view of the manipulator during the operation.

## 5.5 Operative Network

The Operative Network should respect the following specification:

[RQ-016] The Operative Network shall be designed and tested to be fail-safe.

[RQ-017] The Operative Network shall be dedicated to non-critical data regarding the RH operations that do not need real-time communication, such as robot telemetries.

[RQ-018] The Operative Network shall support the communication between heterogeneous applications by implementing a general-purpose communication mechanism and Protocol.

[RQ-019] The Operative Network shall ensure that no packet loss occurs during transmission.

[RQ-020] The Operative Network shall provide sufficient network bandwidth to transmit 3D models of the robot and of the environment to both the servers and the PC located within the control room. The bandwidth shall enable data transfer as fast as possible to reduce operation stop time, following the ALARA principle.

## 5.6 Safety Network

The Safety Network requirements are defined as follows:

[RQ-021] The Safety Network shall be designed and tested to be fail-safe and have a SIL 1 certification level.

[RQ-022] The Safety Network PLC shall poll at a minimum rate of 20Hz to detect loss of signal and shall take appropriate action in case of no response. This includes turning on emergency lights in the Control Room area and sending halt signals to the industrial cabinet of the robots.

[RQ-023] The Safety Network shall be developed as two network lines:

1. A digital hardwired network used to send stop and enable signals to the robots from the Control Room.
2. An Ethernet fail-safe network, such as the Fail-Safe over EtherCAT Network (FsOe), is utilized to facilitate the interconnection and secure transmission of safety data among all the safety PLCs within both the control room and the mock-up area.

[RQ-024] The Safety Network shall foresee hard-wired Emergency Stop System on each operator desk within arm's reach to stop the manipulator's execution.

[RQ-025] The Safety Network shall provide programmable an Emergency Stop System for each operator, except for the supervisor, to allow the exclusive stopping of individual manipulators rather than all of them. The supervisor shall have an Emergency Stop System capable of stopping all manipulators.

[RQ-026] The Safety Network shall ensure that each Emergency Stop Systems includes the capability to select and enable a manipulator using a dedicated and specific button for the exclusive connection to that manipulator. The emergency stop system will have the ability to stop only the manipulator to which it is connected.

[RQ-027] The Safety Network shall be designed in a way that prevents teleoperation of a specific manipulator unless the operator has previously configured the Emergency Stop Systems for that manipulator.

[RQ-028] The Safety Network shall foresee a Safety PLC to provide status updates to the Control Server.

[RQ-029] The Safety Network shall be designed to have the highest priority over any other network and can immediately activate the robot's brakes.

[RQ-030] The Safety Network shall include the activation of an audible alarm signal in the event of safety-critical situations. This signal can be bot visual or audible and shall be directly commanded by the safety PLC.

## 5.7 Maintenance State

The Maintenance State should adhere to the following requirements:

[RQ-031] The maintenance state shall be carried out in accordance with the CEI EN 6204-1 standard.

[RQ-032] During the Maintenance State, the diagnostic software shall inform the control room via the HMI, and activate physical visual warnings predisposed inside the control room. This signal alerts operators that maintenance is currently being performed. In particular, the signals are as follows: Green means planning, Orange means operation, Red means maintenance.

| Wiring Diagram | Interface Control Room - Mockup Area | Control server | Visualization server | Switch: Realtime Network | Switch: Diagnostic Network | Switch: Operation Network | Switch: Video Network | Emergency Stop System | Safety PLC | Docker Station | Wall Monitor | Desk Monitors | Operator's PC | Supervisor PC | Manipulator Master Station's PC | Data Server | Router with Firewall | Virtual Reality Device | Force-Feedback Device | Require UPS for recovery |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Interface Control Room - Mockup Area | | 1 EtherCAT for each robot | | | 1 Ethernet | | 1 Video Cable for each camera | | 1 Safety cable | | | | | | | | | | | |
| Control server | 1 EtherCAT for each robot | | | 1 Ethernet | 1 Ethernet | 1 Ethernet | | | 1 Cable | | | | | | | | | | | YES - UPS1 |
| Visualization server | | | | 1 Ethernet | 1 Ethernet | 1 Ethernet | 1 Ethernet | | | | | | | | | | | | | YES - UPS2 |
| Switch: Realtime Network | | 1 Ethernet | 1 Ethernet | | | | | | | | | | 2 Ethernet | 1 Ethernet | 1 Ethernet | | | | | YES - UPS3 |
| Switch: Diagnostic Network | 1 Ethernet | 1 Ethernet | 1 Ethernet | | | | | | | | | | 2 Ethernet | 1 Ethernet | 1 Ethernet | | | | | YES - UPS3 |
| Switch: Operation Network | | 1 Ethernet | 1 Ethernet | | | | | | | | | | 2 Ethernet | 1 Ethernet | 1 Ethernet | 1 Ethernet | | | | YES - UPS3 |
| Switch: Video Network | 1 Video Cable for each camera | | 1 Ethernet | | | | | | | | | | 2 Ethernet | 1 Ethernet | 1 Ethernet | | | | | |
| Emergency Stop System | | | | | | | | | 1 Safety cable for each button | | | | | | | | | | | |
| Safety PLC | 1 Safety cable | 1 Cable | | | | | | 1 Safety cable for each button | | | | | | | | | | | | YES- UPS4 |
| Docker Station | | | | | | | | | | | 4 HDMI/Displayport Cable | | 1 HDMI/Displayport Cable | 1 HDMI/Displayport Cable | 1 HDMI/Displayport Cable | | | | | |
| Wall Monitor | | | | | | | | | | 4 HDMI/Displayport Cable | | | | | | | | | | |
| Desk Monitor | | | | | | | | | | | | | 2 HDMI/Displayport cables for each PC | 2 HDMI/Displayport cables for each PC | 2 HDMI/Displayport cables for each PC | | | | | |
| Operator's PC | | | | 2 Ethernet | 2 Ethernet | 2 Ethernet | 2 Ethernet | | | 1 HDMI/Displayport Cable | | 2 HDMI/Displayport cables for each PC | | | | | 4 Ethernet | | | |
| Supervisor PC | | | | 1 Ethernet | 1 Ethernet | 1 Ethernet | 1 Ethernet | | | 1 HDMI/Displayport Cable | | 2 HDMI/Displayport cables for each PC | | | | | 4 Ethernet | | | YES- UPS5 |
| Manipulator Master Station's PC | | | | 1 Ethernet | 1 Ethernet | 1 Ethernet | 1 Ethernet | | | 1 HDMI/Displayport Cable | | 2 HDMI/Displayport cables for each PC | | | | | 4 Ethernet | 1 HDMI/Display cable + 1 USB | 1 Cable | |
| Data Server | | | | | | 1 Ethernet | | | | | | | | | | | 1 Ethernet | | | YES- UPS6 |
| Router with Firewall | | | | | | | | | | | | | 4 Ethernet | 4 Ethernet | 4 Ethernet | 1 Ethernet | | | | |
| Virtual Reality Device | | | | | | | | | | | | | | | 1 HDMI/Display cable + 1 USB | | | | | |
| Force-Feedback Device | | | | | | | | | | | | | | | 1 Cable | | | | | |
| Require UPS for recovery | | YES - UPS1 | YES - UPS2 | YES - UPS3 | YES - UPS3 | YES - UPS3 | | | YES- UPS4 | | | | | YES- UPS5 | | YES- UPS6 | | | | |

Table 3 : Network connections

| Component | Connected to | Network |
|---|---|---|
| Robot | Industrial PC | Realtime Network |
| External robot sensors | Industrial PC | Realtime Network |
| Industrial PC | Interface Control Room - Mock-up Area | Realtime Network |
| | | Operative Network |
| | | Safety Network |
| Cameras | Interface Control Room - Mock-up Area | Operative Network/Video Network |
| Interface Control Room-Mock-up Area | Industrial PC | Realtime Network |
| | | Operative Network |
| | | Safety Network |
| | Cameras | Operative Network/Video Network |
| | Control Server | Realtime Network |
| | Switch: Operative Network | Operative Network |
| | Switch: Video Network | Video Network |
| | Safety PLC | Safety Network |
| Control server | Interface Control Room - Mock-up Area | Realtime Network |
| | Switch: Realtime Network | Realtime Network |
| | Switch: Diagnostic Network | Diagnostic Network |
| | Switch: Operative Network | Operative Network |
| | Safety PLC | Safety Network |
| | UPS1 | Power Connection |
| Visualization server | Switch: Realtime Network | Realtime Network |
| | Switch: Diagnostic Network | Diagnostic Network |
| | Switch: Operative Network | Operative Network |
| | Switch: Video Network | Video Network |
| | UPS2 | Power Connection |
| Switch: Realtime Network | Control Server | Realtime Network |
| | Visualization Server | Realtime Network |
| | Operator's PC | Realtime Network |
| | Supervisor PC | Realtime Network |
| | Manipulator Master Station's PC | Realtime Network |
| | UPS3 | Power Connection |
| Switch: Diagnostic Network | Control Server | Diagnostic Network |
| | Visualization Server | Diagnostic Network |
| | Operator's PC | Diagnostic Network |
| | Supervisor PC | Diagnostic Network |
| | Manipulator Master Station's PC | Diagnostic Network |
| | UPS3 | Power Connection |

Table 4: Network connection - Part 1

| Component | Connected to | Network |
|---|---|---|
| Switch: Operative Network | Interface Control Room - Mock-up Area | Operative Network |
| | Control Server | Operative Network |
| | Visualization Server | Operative Network |
| | Operator's PC | Operative Network |
| | Supervisor PC | Operative Network |
| | Manipulator Master Station's PC | Operative Network |
| | Data Server | Operative Network |
| | UPS3 | Power Connection |
| Switch: Video Network | Interface Control Room - Mock-up Area | Video Network |
| | Visualization Server | Video Network |
| | Operator's PC | Video Network |
| | Supervisor PC | Video Network |
| | Manipulator Master Station's PC | Video Network |
| Emergency Stop System Safety PLC | Safety PLC | Safety Network |
| | Interface Control Room - Mock-up Area | Safety Network |
| | Control Server | Safety Network |
| | Emergency Stop System | Safety Network |
| | UPS4 | Power Connection |
| Docker Station | Wall Monitor | Cable Connection |
| | Operator's PC | Cable Connection |
| | Supervisor PC | Cable Connection |
| | Manipulator Master Station's PC | Cable Connection |
| Wall Monitor | Docker Station | Cable Connection |
| Desk Monitors | Operator's PC | Cable Connection |
| | Supervisor PC | Cable Connection |
| | Manipulator Master Station's PC | Cable Connection |
| Operator's PC | Switch: Realtime Network | Realtime Network |
| | Switch: Diagnostic Network | Diagnostic Network |
| | Switch: Operative Network | Operative Network |
| | Switch: Video Network | Video Network |
| | Docker Station | Cable Connection |
| | Desk Monitors | Cable Connection |
| | Router with Firewall | Cable Connection |
| Supervisor PC | Switch: Realtime Network | Realtime Network |
| | Switch: Diagnostic Network | Diagnostic Network |
| | Switch: Operative Network | Operative Network |
| | Switch: Video Network | Video Network |
| | Docker Station | Cable Connection |
| | Desk Monitors | Cable Connection |
| | Router with Firewall | Cable Connection |
| | UPS5 | Power Connection |

Table 5 : Network connection - Part 2

| Component | Connected to | Network |
|---|---|---|
| Manipulator Master Station's PC | Switch: Realtime Network | Realtime Network |
| | Switch: Diagnostic Network | Diagnostic Network |
| | Switch: Operative Network | Operative Network |
| | Switch: Video Network | Video Network |
| | Docker Station | Cable Connection |
| | Desk Monitors | Cable Connection |
| | Router with Firewall | Cable Connection |
| | Virtual Reality Device | Cable Connection |
| | Force-Feedback Device | Cable Connection |
| Data Server | Switch: Operative Network | Operative Network |
| | Router with Firewall | Cable Connection |
| | UPS6 | Power Connection |
| Router with Firewall | Operator's PC | Cable Connection |
| | Supervisor PC | Cable Connection |
| | Manipulator Master Station's PC | Cable Connection |
| | Data Server | Cable Connection |
| Virtual Reality Device | Manipulator Master Station's PC | Cable Connection |
| Force-Feedback Device | Manipulator Master Station's PC | Cable Connection |
| UPS1 | Control Server | Power Connection |
| UPS2 | Visualization Server | Power Connection |
| UPS3 | Switch: Realtime Network | Power Connection |
| | Switch: Diagnostic Network | Power Connection |
| | Switch: Operative Network | Power Connection |
| UPS4 | Safety PLC | Power Connection |
| UPS5 | Supervisor PC | Power Connection |
| UPS6 | Data Server | Power Connection |

Table 6: Network connection – part 3

# 6 Technical Requirements for the Hardware

In this section we report the technical requirements of the hardware components, which include:

- Displays: workstation's monitor, manipulator master station's monitor, wall monitor;
- Operator's PC;
- Human Interaction Devices: Joystick (>=2), Force-Feedback Devices (>=1), VR Headset and Controller (=2);
- Standard network equipment and UPS: switch for video network, switch for operative network, switch for real-time and local data networks, router, UPS Type 1, UPS Type 2, UPS Type 3;
- Servers: control server, visualization server, data server.

## 6.1 Displays

The technical requirements of the displays are in the following. Then, in 6.1.1 – 6.1.3 we report the specifications of suggested configurations.

[RQ-033] The workstation's monitor shall be with a full HD resolution and shall be greater than 27 inches. Specifications of a configuration that satisfy this requirement are included in Table 7.

[RQ-034] The manipulator master station's monitor shall be with a Ultra-Wide QHD resolution at minimum, and shall be greater than 34 inches. Specifications of a configuration that satisfy this requirement are included in Table 8.

[RQ-035] The wall monitors shall be two, they shall have a 4K UHD (3830x2160) resolution minimum with a 16:9 aspect ratio, shall be greater than 65 inches and with a refresh rate equal to or greater than 40 Hz. Specifications of a configuration that satisfy this requirement are included in Table 9.

### 6.1.1 Workstation's Monitor

| Workstation's Monitor Specifications | |
|---|---|
| **Display resolution** | Full HD resolution minimum with a 16:9 aspect ratio |
| **Screen size** | Greater than 27 inches |
| **Panel type** | IPS panel |
| **Refresh rate** | Equal to or greater than 30 Hz |
| **Response Time** | Less than 5ms (GtG) |
| **Brightness** | Minimum 200 cd/m² |
| **Viewing angle** | Greater than 160° |
| **Connectivity** | At least one HDMI port and one DisplayPort are required. |
| **Mount compatibility** | The monitor shall have VESA mount compatibility. |
| **Energy Efficiency** | Greater than or equal to G |
| **Ergonomics** | Adjustable tilt to achieve an optimal viewing angle |

| | |
|---|---|
| **Features** | Flicker-safe |

Table 7. Workstation's monitor specifications

The Monitor HP V27i has been identified as a monitor that meets these specifications.

### 6.1.2 Manipulator Master Station's Monitor

| Manipulator Master Station's Monitor Specifications | |
|---|---|
| **Display resolution** | Ultra-Wide QHD (UWQHD) resolution minimum with a 16:9 or 21:9 aspect ratio |
| **Screen size** | Greater than 34 inches |
| **Refresh rate** | Equal to or greater than 60 Hz |
| **Response Time** | Less than 5ms (GtG) |
| **Brightness** | Minimum 200 cd/m² |
| **Viewing angle** | Greater than 160° |
| **Connectivity** | At least one HDMI port and one DisplayPort are required. |
| **Mount compatibility** | The monitor shall have VESA mount compatibility. |
| **Energy Efficiency** | Energetic class greater than G |
| **Ergonomics** | Adjustable tilt to achieve an optimal viewing angle |
| **Features** | Flicker-safe, |

Table 8. Manipulator Master Station's Monitor Specifications

The Samsung odyssey g5-g55t has been identified as a monitor that meets these specifications.

### 6.1.3 Wall-Monitor

| Wall Monitor Specifications (to consider x2) | |
|---|---|
| **Display resolution** | 4K UHD (3830x2160) resolution minimum with a 16:9 aspect ratio |
| **Screen size** | Greater than 65 inches |
| **Refresh rate** | Equal to or greater than 40 Hz |
| **Brightness** | Minimum 200 cd/m² |
| **Connectivity** | HDMI 2.0 (3) |
| **Mount compatibility** | The monitor shall have VESA mount compatibility |
| **Energy Efficiency** | Energetic class greater than or equal to F |

Table 9. Wall Monitor specifications

The Samsung Series 7 Crystal 65" has been identified as a monitor that meets these specifications.

## 6.2 PC

[RQ-036] The operator's PC shall be at least two. Each operator's PC shall ensure the work of the operator. Specifications of a configuration that satisfy this requirement are included in the tables: Table 10 to Table 17.

[RQ-037] The supervisor PC shall be at least one. It shall ensure the work of the supervisor. Specifications of a configuration that satisfy this requirement are included in the tables: Table 10 to Table 17.

[RQ-038] The Manipulator Master Station shall be at least one. It shall ensure the connection on the real-time network. Specifications of a configuration that satisfy this requirement are included in the tables: Table 10 to Table 17, except for the video card, that shall be selected to ensure the connection on the real-time network.

A configuration that meets the requirements has been found on the Lenovo website. Therefore, it will be necessary to perform the same operation by selecting components that have at least the same performance as the components listed below (6.2.1 – 6.2.8).

### 6.2.1 CPU

| CPU Specifications | |
|---|---|
| **Total cores** | Greater than 18 |
| **Number of P-cores** | Greater than 8 |
| **Number of E-cores** | Greater than 10 |
| **Total threads** | Greater than 30 |
| **Minimum frequency** | Greater or equal to 2GHz |
| **Peak frequency** | Greater than 5.2 GHz |
| **Memory types** | Up to DDR5 5500 MT/s |
| $T_{Junction}$ | $< 100^{\circ}$ |
| **Features** | Adaptive boost technology,<br>Hyper-threading technology,<br>Thermal Monitoring Technologies |

Table 10. CPU specifications

The Intel® Core™ i9-13900 Processor has been identified as a CPU that meets these specifications.

### 6.2.2 GPU

| GPU Specifications | |
|---|---|
| **Suggested GPU chipset** | RTX A4500 or a higher tier. |
| **CUDA Core** | Greater than 7000 |
| **Boost clock** | Greater than 1.5 GHz |
| **PCI Express** | 4.0 16x |
| **GPU memory** | 20GB |
| **Memory velocity** | GDDR6 |
| **Memory Interface** | 320-bit |

| | |
|---|---|
| **Memory bandwidth** | 600 GB/s |
| **Supported APIs** | DirectX12 Ultimate, OpenGL4.6, Vulkan RT |
| **VR ready** | Yes |
| **Output port** | 3 x DisplayPort 1.4,<br>1 x HDMI® Connector |
| **Multivideo support** | Quad Display |
| **Features** | ECC |

Table 11. GPU specifications

The NVIDIA RTX A4500 has been identified as a GPU that meets these specifications.

### 6.2.3 Motherboard

| Motherboard specifications | |
|---|---|
| **Form factor** | ATX |
| **Expansion** | At least:<br>- 2 X PCI-E X16 slots for GPU<br>- 4 X PCI-E X4 for Network cards and expansions |
| **CPU support** | Supports 12th/13th Gen Intel® Core™ Processors, Pentium® Gold and Celeron® Processors |
| **Memory** | 4x DDR5, Maximum memory capacity greater than 120 GB,<br>Supports Intel® XMP 3.0 OC,<br>Supports Dual-Controller Dual-Channel mode |
| **Storage** | 2x M.2 slots,<br>3x SATA III |
| **RAID** | Supports RAID 0, RAID 1, RAID 5, and RAID 10 for SATA, M.2 storage devices |
| **USB** | At least:<br>- 4x USB 2.0,<br>- 2x USB 3.2 Gen1 Type A (Rear),<br>- 2x USB 3.2 Gen1 Type A (Front),<br>- 1x USB 3.2 Gen2 Type C |
| **LAN** | Intel® 2.5Gbps LAN |

Table 12. Motherboard specifications

### 6.2.4 RAM

| RAM specifications | |
|---|---|
| **Memory Type** | DDR5 |
| **Capacity** | Greater than 256GB |

| | |
|---|---|
| **Speed** | Greater than 4800MHz |
| **Features** | Intel XMP 3.0 Ready |

Table 13. RAM specifications

### 6.2.5 Cooling System

| **Cooling System specifications** | |
|---|---|
| **Socket compatibility** | Compatibility with the chosen CPU |
| **Max. TDP / NSPR** | Greater than 150 W / 130 |
| **Rotational speed** $\pm 10\%$ | 300 - 1500 rpm |
| **Max. airflow** | Greater than 130 $m^3/h$ |
| **Max. acoustical noise** | Less than 25 dB(A) |

Table 14. Cooling System specifications

### 6.2.6 Power supply

| **PSU specifications** | |
|---|---|
| **Type** | Fully modular |
| **Continuous Power (W)** | Greater than 900 Watts |
| **EPS Connector** | Greater than or equal to 2 |
| **SATA Connector** | Greater than or equal to 4 |
| **PCIe Connector** | Greater than or equal to 4 |
| **Certification** | 80 PLUS Efficiency Platinum |

Table 15. PSU specifications

### 6.2.7 Storage Modules

| **SSD** specifications | |
|---|---|
| **Number of** | 2 |
| **Form factor** | M.2 |
| **Capacity** | 2 TB |
| **Sequential read speed** | Up to 7,000 MB/s |
| **Sequential write speed** | Up to 5,100 MB/s |
| **Interface** | PCIe Gen 4.0 x4,<br>NVMe 1.3 |
| **Features** | Trim support,<br>Auto garbage collection algorithm,<br>S.M.A.R.T. support |

Table 16. SSD specifications

### 6.2.8 Network card

| Network card specifications | |
|---|---|
| **Ports** | The total number of ports shall be a minimum of 5 on every PC |
| **Bus Type** | PCI Express x4 |
| **Industry Standards** | IEEE 802.3 |
| **Supported Protocols** | IEEE 802.3ad (link aggregation),<br>IEEE 1588 (time sync) |
| **OS Compatibility** | Windows 10, 11<br>Linux |
| **Certification** | CE Mark |
| **Manipulator Master Station's PC** | At least on the MO's PC, there shall be a network card that allows the PC to connect to the real-time network using real-time protocol. |

Table 17. Network card specifications

## 6.3 Human Interaction Device

The technical requirements are reported the following. Then, in 6.3.1 – 6.3.3 we report the specifications of suggested device configurations.

[RQ-039] The joystick shall have a number of axes equal or greater than 2 and a number of button equal or greater than 10. Specifications of a configuration that satisfy this requirement are included in Table 18.

[RQ-040] The force-feedback device shall be used for real-time force control and shall ensure force feedback as accurate as possible. The requirements are such that the specifications are those included in Table 19.

[RQ-041] The VR Headset & Controller device shall be used for virtual reality simulations and training. The requirements are such that the specifications are those included in Table 20.

### 6.3.1 Joystick

| Joystick specifications | |
|---|---|
| **Number of** | 2 |
| **Number of Axes** | Greater than or equal to 2 |
| **Buttons** | Greater than or equal to 10 |
| **Compatibility** | Windows 10 |
| **Connectivity** | USB port |
| **Feature** | Programmable controls |

Table 18. Joystick specifications

The Thrustmaster T.16000M has been identified as a Joystick that meets these specifications.

### 6.3.2 Force-Feedback Device

| Force-feedback device specifications | |
|---|---|
| **Number of** | 1 |
| **Workspace** | Translation greater than 150 x 100 mm,<br>Rotation minimum 180 (yaw) x 140 (pitch) x 180 (roll) deg<br>Gripper greater than 20 mm |
| **Forces** | Forces: Translation greater than 19 N,<br>Rotation greater than 350 mNm,<br>Gripper greater than 6 N |
| **Resolution** | Translation less than 0.0015 mm,<br>Rotation less than 0.02 deg,<br>Gripper less than 0.01 mm |
| **Refresh rate** | Refresh rate: Greater than 1 KHz |

| | |
|---|---|
| **Software** | Software: It must provide clear and usable APIs for the development of the control system. |
| **Ergonomics** | Available in left- and right-hand Configuration, Ergonomic arms support |
| **Platforms** | Platforms: Microsoft, Linux |

Table 19. Force-Feedback Device specifications

The Force Dimension Sigma.7 has been identified as a force-feedback device that meets these specifications.

### 6.3.3 VR Headset & Controller

| **VR headset and controllers specifications** | |
|---|---|
| **Number of** | 2 |
| **Headset resolution** | 2448 × 2448 pixels per eye (4896 x 2448 pixels combined) |
| **Field of view** | Greater than or equal to 120° (horizontal) |
| **Refresh rate** | Greater than 90 Hz |
| **Connectivity** | Bluetooth, USB-C port for peripherals |
| **Sensors** | G-sensor, gyroscope, proximity,<br>IPD sensor |
| **Audio quality** | Certified Hi-Res audio |
| **Ergonomics** | Required lens distance adjustment for eye relief.<br>Adjustable head straps designed to be worn comfortably for extended periods. |
| **Durability** | Greater than 5 hours |

Table 20. VR Headset and controllers specifications

The HTC VIVE Pro 2 has been identified as a VR headset that meets these specifications.

## 6.4 Network Equipment and UPS

The technical requirements are reported the following. Then, in 6.4.1 – 6.4.5 we report the specifications of suggested device configurations.

[RQ-042] The switch of the video network shall consider the presence of at least 12 Full HD 30 Hz cameras in the mock-up areas. The requirements for the switch of the video network are such that the specifications are those included in Table 21.

[RQ-043] The requirements for the switch of the operative network are such that the specifications are those included in Table 22.

[RQ-044] The requirements for the switch of the real-time and local area networks are such that the specifications are those included in Table 23.

[RQ-045] The requirements for the router are such that the specifications are those included in Table 24.

[RQ-046] The UPS shall be chosen to provide enough time for the safe saving and exit in case of unexpected input power interruption (at least 30 min).

[RQ-047] The UPS shall be chosen so that a single UPS powers each critical component connected to it.

[RQ-048] The UPS shall be of three typologies: Type 1, Type 2, Type 3, with requirements that are satisfied by considering the specifications included in Table 25, Table 26 and Table 27, respectively.

### 6.4.1 Switch: Video Network

| **Switch: Video Network specifications** | |
|---|---|
| **Typology** | Managed |
| **Ports** | 16 Gbit Ethernet |
| **Switching capacity** | Greater than or equal to 30 Gbps |
| **Jumbo frame** | Greater than or equal to 8000 bytes |
| **Forwarding capacity** | Greater than or equal to 30 mpps |
| **Desirable features** | Cable diagnostics |
| **Standards** | IEEE 802.3 |
| **Certifications** | CE mark |

Table 21. Switch: Video Network specifications

The FS S3260-16T4FP has been identified as a Switch that meets these specifications.

### 6.4.2 Switch: Operative Network

| **Switch: Operative Network specifications** | |
|---|---|
| **Ports** | 10 x 10/100/1000M/2,5G/5G/10G Multi-gig RJ45 |
| **Jumbo frame** | Greater than or equal to 8000 bytes |
| **Forwarding capacity** | Greater than or equal to 300 Mpps |
| **Certifications** | CE mark |

Table 22. Switch: Operative Network specifications

The FS S5850-24XMG has been identified as a Switch that meets these specifications.

### 6.4.3 Switch: Real-Time and Local Data Networks

| **Switch: Real-Time and Local Data Networks specifications** | |
|---|---|
| **Ports** | 8 x 10/100/1000 Ethernet |
| **Switching capacity** | Greater than or equal to 1 Gbps |
| **Jumbo frame** | Greater than or equal to 8000 bytes |
| **Forwarding capacity** | Greater than or equal to 1.4 mpps |

| | |
|---|---|
| **Desirable features** | Cable diagnostics |
| **Standards** | IEEE 802.3 |
| **Certifications** | CE mark |

Table 23. Switch: Real-Time and Local Data Networks specifications

The FS S3270-10TM has been identified as a Switch that meets these specifications.

### 6.4.4 Router

| **Router specifications** | |
|---|---|
| **Networking standards** | IEEE 802.3 |
| **Ethernet LAN** | Yes |
| **Ethernet LAN data rates** | 10,100,1000 Mbit/s |
| **Quality of Service (QoS) support** | Yes |
| **Ethernet LAN (RJ-45) ports** | Greater than or equal to 8 |
| **Firewall** | Yes |

Table 24. Router specifications

The Cisco C1111-8P has been identified as a router that meets these specifications.

### 6.4.5 UPS

| **UPS Type 1 specifications** | |
|---|---|
| **Wattage** | 330 W |
| **Output nominal voltage** | 230V |
| **Output power factor** | Greater than 0.6 |
| **Battery classification** | 12 V / 5 Ah |
| **Battery management** | Replaceable batteries,<br>Automatic battery test,<br>deep-discharge protection,<br>cold-start capable |
| **Auto shutdown function** | Yes |
| **Efficiency** | 97 |
| **Surge protection** | Yes |
| **Noise level** | Less than 25 dB at 1 meter |
| **Phase (output)** | 1 |
| **Conformity** | CE mark |
| **Certification** | IEC/EN 62040-1, IEC/EN 62040-2, CE, EAC |

Table 25. USP Type 1 specifications

The EATON 5S550IBS has been identified as an UPS that meets these specifications.

| UPS Type 2 specifications | |
|---|---|
| **Wattage** | 600 W |
| **Output nominal voltage** | 230V |
| **Output power factor** | Greater than 0.6 |
| **Battery classification** | 12 V / 5 Ah |
| **Battery management** | Replaceable batteries,<br>Automatic battery test,<br>deep-discharge protection,<br>cold-start capable |
| **Auto shutdown function** | Yes |
| **Efficiency** | 97 |
| **Surge protection** | Yes |
| **Noise level** | Less than 25 dB at 1 meter |
| **Phase (output)** | 1 |
| **Conformity** | CE mark |
| **Certification** | IEC/EN 62040-1, IEC/EN 62040-2, CE, EAC |

Table 26. UPS Type 2 specifications

The EATON 5S1000I has been identified as an UPS that meets these specifications.

| UPS Type 3 specifications | |
|---|---|
| **Wattage** | 1000 W |
| **Output nominal voltage** | 230V |
| **Output power factor** | Greater than 0.6 |
| **Battery classification** | 12 V / 5 Ah |
| **Battery management** | Replaceable batteries,<br>Automatic battery test,<br>deep-discharge protection,<br>cold-start capable |
| **Auto shutdown function** | Yes |
| **Efficiency** | 97 |
| **Surge protection** | Yes |
| **Noise level** | Less than 25 dB at 1 meter |
| **Phase (output)** | 1 |
| **Conformity** | CE mark |
| **Certification** | IEC/EN 62040-1, IEC/EN 62040-2, CE, EAC |

Table 27. UPS Type 3 specifications

The EATON EL1600USBIEC has been identified as an UPS that meets these specifications.

## 6.5 Control server

The Control Server shall satisfy the following requirements:

[RQ-049] The Control Server shall connect to the robotic system in the mock up area with a Real-Time protocol such as EtherCAT or ProfiNet on the real-time network.

[RQ-050] Critical software that shall run in real-time will need to be specified and coded accordingly.

[RQ-051] The Control Server shall have a real-time communication link between the manipulator master and RH equipment controllers.

[RQ-052] The Control Server shall run a real-time OS which should be chosen according to the executive design of the control architecture. Moreover, a windows OS in dual boot must always be installed to run Windows OS based software (e.g. CAD prototyping).

[RQ-053] The Control Server shall have a full stack of real-time hardware, including the Operating System with a real-time kernel, suitable real-time drivers and motherboard.

[RQ-054] The Control Server shall interface with the industrial PC to receive robot state. The robot state shall encompass:

- The state of each joint including angular or linear position, velocity and if provided also torque information.
- The pose of the end-effector (xyz - RPY) in the world reference frame.
- The measured joint angular positions.
- The commanded joint angular positions.
- Module and direction of forces and torques acting on the robot if exteroceptive sensors are present on the manipulator.
- The robot state including useful information for diagnostic purposes.

[RQ-055] The Control Server shall incorporate all the required algorithms for robot manipulation within a framework that includes a set of utilities for planning, control etc such as the utilities provided by frameworks like ROS2.

[RQ-056] The Control Server shall automatically launch all the necessary software components for RH operations upon startup.

[RQ-057] The requirements on the control server are satisfied if the minimum control server hardware specifications (CPU, GPU, other components) listed in Table 28, Table 29 and Table 30 are satisfied.

| Control Server CPU specifications | |
|---|---|
| **Total cores** | Greater than 32 |
| **High Priority Cores** | Greater than 10 |
| **Total Threads** | Greater than 64 |

| | |
|---|---|
| **Max Turbo Frequency** | Greater than 4GHz |
| **Cache** | Greater than 60 MB |
| **Features** | Adaptive boost technology, Hyper-threading technology, Thermal Monitoring Technologies, ECC Memory Supported |

Table 28. Control Server CPU specifications

| Control Server GPU specifications | |
|---|---|
| **Suggested GPU chipset** | RTX A2000 or a higher tier. |
| **PCI Express** | 4.0 16x |
| **GPU memory** | >6GB |
| **Memory velocity** | GDDR6 |
| **Memory Interface** | 192-bit |
| **Memory bandwidth** | 250 GB/s |
| **Supported APIs** | DirectX12 Ultimate, OpenGL4.6, Vulkan RT |
| **Output port** | 3 x DisplayPort 1.4, 1 x HDMI® Connector |
| **Multivideo support** | Quad Display |
| **VR Ready** | Yes |

Table 29. Control Server GPU specifications

| Control Server other components - specifications | |
|---|---|
| **OS** | Ubuntu 22.04 & Windows 11 on separate disk drive |
| **RAM** | DDR5, 32GB, 3000MHz |
| **MOBO** | Dual Processor Intel Eagle Stream C741 |
| **SSD** | 2TB M.2 2280, PCIe Gen4, Performance TLC, Opal |
| **HDD** | Sata 6TB, 7200RPM, |
| **Connectivity** | Intel I350-T4, PCIex4, 1Gbps, high-profile |

Table 30. Control Server Other Components – specifications

## 6.6 Visualization Server

The Visualization Server shall satisfy the following requirements:

[RQ-058] The Visualization Server shall run on a OS compatible with graphic drivers and VR devices.

[RQ-059] The Visualization Server shall implement the 3D environment and manage the interaction with the VR equipment.

[RQ-060] The Visualization Server shall interface with Clients through the subnet.

[RQ-061] The Visualization Server shall offer the possibility to install proprietary software for cameras and motion capture. It also shall provide all the software necessary to acquire, analyse and transmit data taken from the proprietary software.

[RQ-062] The Visualization Server shall automatically launch all the necessary software components for RH operations upon startup.

[RQ-063] The visualization server must have high computational and graphic capabilities.

[RQ-064] The requirements on the visualization server are satisfied if the minimum visualization server hardware specifications (CPU, GPU, other components) listed in Table 31, Table 32 and Table 33 are satisfied.

| Visualization Server CPU specifications | |
|---|---|
| **Total cores** | Greater than 32 |
| **High Priority Cores** | Greater than 10 |
| **Total Threads** | Greater than 64 |
| **Max Turbo Frequency** | Greater than 4 GHz |
| **Cache** | Greater than 60 MB |
| **Features** | Adaptive boost technology,<br>Hyper-threading technology,<br>Thermal Monitoring Technologies,<br>ECC Memory Supported |

Table 31. Visualization Server CPU specifications

| Visualization Server GPU specifications | |
|---|---|
| **Suggested GPU chipset** | RTX A6000 or a higher tier. |
| **Number of CUDA Core** | Greater than 10,000 |
| **Number of Tensor Core** | Greater than 300 |
| **Single precision performance** | 35 TFLOPS |
| **RT Core performance** | 70 TFLOPS |
| **Tensor performance** | 280 TFLOPS |

| | |
|---|---|
| **PCI Express** | 4.0 16x |
| **GPU memory** | >45GB ECC |
| **Memory velocity** | GDDR6 |
| **Memory Interface** | > 384-bit |
| **Memory bandwidth** | > 700 GB/s |
| **Supported APIs** | DirectX12 Ultimate,<br>OpenGL4.6,<br>Vulkan RT |
| **VR ready** | Yes |
| **Output port** | 3 x DisplayPort 1.4,<br>1 x HDMI® Connector |
| **Multivideo support** | Quad Display |

Table 32. Visualization Server GPU specifications

| **Visualization Server Other Components - specifications** | |
|---|---|
| **OS** | Ubuntu 22.04 & Windows 11 on separate disk drive |
| **RAM** | DDR5, 256GB, 4800MHz |
| **MOBO** | Dual Processor Intel Eagle Stream C741 |
| **SSD** | 4TB M.2 2280, PCIe Gen4, Performance TLC, Opal |
| **HDD** | Sata Enterprise 6TB, 7200RPM, |
| **Connectivity** | Intel I350-T4, PCIex4, 1Gbps, high-profile |
| **Features** | Double Power Supply |

Table 33. Visualization Server Other components specifications

## 6.7 Data Server

The requirements of the data server, considering the in-house solution, are listed below:

[RQ-065] The Data Server shall provide enough storage space to store all described data including:

- Description of the RH operation, Task and procedures
- CAD model of every component inside the mock-up area
- 3D model library of the visualization software containing files regarding every component inside the mock-up area.
- Data regarding the kinematic and dynamic model of the robot and relevant mock-up modules
- Task report and log messages
- Video and Image captured from the operators.
- Other meaningful data loaded by the operator.

[RQ-066] The Data Server shall grant access and allow modification only to authorized personal.

[RQ-067] The Data Server shall interconnect with the external ENEA central system for data exchange, thus requiring suitable cybersecurity protection mechanism.

[RQ-068] The Data Server shall analyse data collected from task report to estimate equipment degradation and signal the need for preventive maintenance

[RQ-069] The Data Server shall implement a redundancy system, such as RAID5 or RAID-Z, to minimize the risk of data loss.

[RQ-070] The Data Server shall be able to manage multiple simultaneous data stream.

[RQ-071] The Data Server shall exchange all the data through the Operation Network.

[RQ-072] The requirements on the data server are satisfied if the minimum data server hardware specifications (CPU, GPU, other components) listed in Table 34, Table 35 and Table 36 are satisfied.

| Data Server CPU | |
|---|---|
| **Total cores** | Greater than 16 |
| **Total Threads** | Greater than 32 |
| **Max Turbo Frequency** | Greater than 4 GHz |
| **Cache** | Greater than 30 MB |
| **Features** | Adaptive boost technology,<br>Hyper-threading technology,<br>Thermal Monitoring Technologies,<br>ECC Memory Supported |

Table 34. Data Server CPU

| Data Server GPU | |
|---|---|
| **Suggested GPU chipset** | RTX A1000 or a higher tier. |
| **PCI Express** | 4.0 16x |
| **GPU memory** | >4GB |
| **Memory velocity** | GDDR6 |
| **Memory Interface** | 128-bit |
| **Memory bandwidth** | 150 GB/s |
| **Supported APIs** | DirectX12 Ultimate, OpenGL4.6, Vulkan RT |
| **Output port** | 3 x DisplayPort 1.4, 1 x HDMI® Connector |

| | |
|---|---|
| **Multivideo support** | Quad Display |

Table 35. Data Server GPU requirements

| **Data Server Other Components** | |
|---|---|
| **OS** | Windows |
| **RAM** | DDR5, 128GB, 3000MHz |
| **Controller RAID** | Intel VROC Premium+ Raid 5 |
| **SSD** | 2x4TB M.2 2280, PCIe Gen4, Performance TLC, Opal |
| **HDD** | 3xSata Enterprise12TB, 7200RPM |
| **Connectivity** | Intel I350-T4, PCIex4, 1Gbps, high-profile |

Table 36. Data Server Other Components

# 7 Technical Requirements for the Software

In this section we provide the list of technical requirements for the software. First, we provide the general technical requirements for the software modules. Then, we provide the technical requirements for all the nine software modules.

## 7.1 General Software Modules Requirements

All software modules inside the Control Room shall adhere to the following requirements:

[RQ-073] All software modules shall apply the "As Low As Reasonably Achievable" (ALARA) principle to optimize operations carried out from the software.

[RQ-074] All software modules shall follow a modular design, with each module delivering a defined functionality and interfacing with other modules through clearly defined interfaces.

[RQ-075] All software modules shall not have dependencies on the implementation details of other software modules. The interconnection of these modules shall be established through specific APIs associated with each individual software module.

[RQ-076] All software modules shall ensure that all PCs share the same Session State to avoid conflicts on data running on the network. The default state when the system starts shall be the Planning State, in which the real site is disconnected from its digital twin and the user exclusively interacts with the digital model. Switching state shall be possible only with the Supervisor's permission.

[RQ-077] All software shall be developed using a well-established reference framework. The suggested reference framework for the system architecture of the Control Room is ROS2. Other suggested control frameworks which have been already used for control architectures in research projects and in fusion energy include: EPICS and GENROBOT. This is not a comprehensive list; therefore, other frameworks can be considered.

[RQ-078] The software shall be developed in such a way that every module does not require a specific power-on or power-off sequence dependent on other modules. Nevertheless, each software module must implement a proper shutdown procedure that does not modify data within the system.

[RQ-079] The software must be developed in such a way that each module verifies the activation status of any other software module necessary for the specific task before initiating the task execution. For example, the Motion Planner shall check whether Collision Management is active before commencing its operation.

[RQ-080] The entire software architecture shall be developed following a lifecycle in accordance with ISO 12207, produced by the contractor and agreed upon with the customer.

[RQ-081] The software development shall include usability testing conducted by experienced technicians in line with ISO 9216

[RQ-082] The software framework shall be developed in such a way that additional modules can be easily added. No source code is required for proprietary libraries the Contractor has developed before the contract and implemented or customized.

## 7.2 Human Machine Interface [M1]

The operator workstations shall be equipped with a Human Machine Interface (HMI) software that will continuously relay precise and comprehensive information collected from the machine environment, empowering the operator to make informed decisions. Conversely, the HMI will enable the human operator to interact with and operate the robotic devices seamlessly and intuitively.
An illustrative example of the HMI concept is provided in Figure 6. HMI technical requirements are defined in the following.

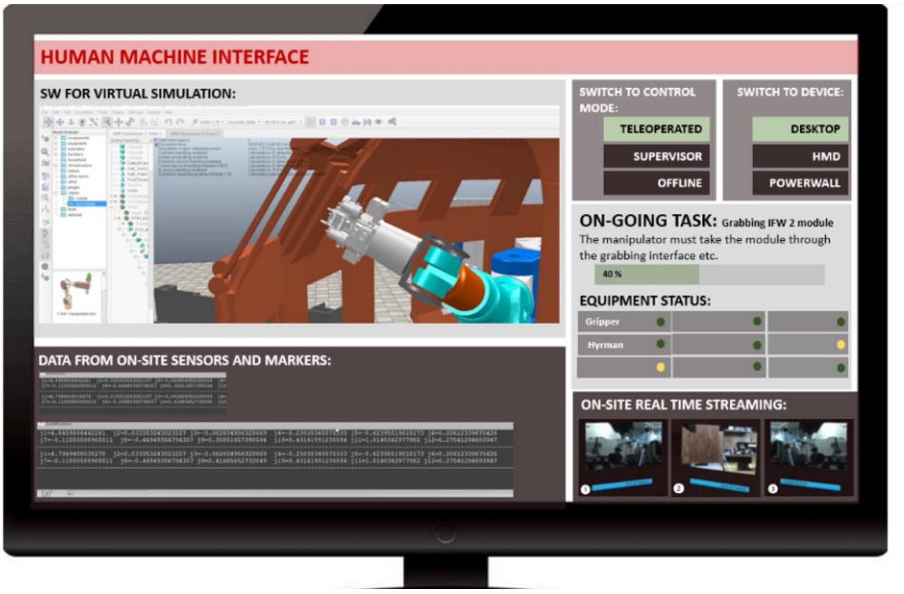


Figure 6: HMI initial concept

### 7.2.1 General requirements

**Execution**

[RQ-083] The HMI shall run on each PC independently. Each operator should be able to interact, modify and customize their own HMI software from the other operator's PC

**Testing**

[RQ-084] The development of the HMI shall include usability testing and validations by operators, as well as incorporating modifications based on the received feedback.

[RQ-085] The HMI software shall be developed to ensure it is smooth and provides lag-free interactions, with predefined maximum response times tailored to the adopted control methodology [3]. Specifically, the minimum refresh rate of the HMI shall be set to 30Hz.

**Authentication end authorization mechanism**

[RQ-086] The HMI software shall include the robust authentication and authorization mechanism implemented by the Operation SW.

**Data exchange**

[RQ-087] The HMI Software shall interface with other software and servers on the network to exchange all necessary information.

[RQ-088] The HMI Software shall be able to retrieve and display information synchronized with the other networks. Specifically, data shall avoid using buffer if possible. When buffers are suggested, the dimension shall guarantee a synchronous visualization with a refresh rate of at least 30Hz.

[RQ-089] The HMI Software shall ensure that the time between receiving information and displaying it is minimized to avoid introducing further delays.

[RQ-090] The HMI software shall ensure that the time between selecting a command on the user interface and its transmission is minimized to avoid introducing further delays.

### 7.2.2 User experience

**Layout**

[RQ-091] The User Interface (UI) shall organize and show the different features and data in specific panels or windows.

[RQ-092] The UI shall provide the operator with the option to open and close any desired windows or panel.

[RQ-093] The UI shall include, preferably, a settings menu allowing users to modify key bindings, visual settings, and other preferences.

[RQ-094] The UI shall enable users to view with the 3D environment in one or more windows, each representing a defined virtual camera framing within the 3D environment.

[RQ-095] The UI shall provide a pre-defined panel containing multiple cameras, both real and virtual, arranged in pre-defined layouts (e.g., vertical row, horizontal row, square). The operator shall be able to choose which camera streams to display.

**Displayed information and data**

[RQ-096] The UI shall effectively present the RH equipment status information retrieved from the diagnostic system. To display this information on the screen, it is advisable to consider accepted human factors conventions, such as colour coding and warning symbols.

[RQ-097] The UI shall clearly display the current session state. Possible states are Planning and Operation.

[RQ-098] The UI shall clearly display the current control mode.

[RQ-099] The UI shall clearly display the current Human Interaction Device (HID) (Standard mouse and keyboard - VR headset & controllers - Force-feedback device, if the manipulator supports it).

[RQ-100] The UI shall clearly display diagnostic data about each device status inside the room (Idle – Nominal – Hands-on – Commissioning – Recovery) and each controller status (Off – Safe-- Ready – Enabled). This is only intended as a visualization of the status data.

[RQ-101] The UI shall clearly display the operation status.

[RQ-102] The UI shall clearly display in a dedicated panel all the safety-related information coming from the Diagnostic Software, such as emergency stop status, system faults, and critical alarms.

[RQ-103] The UI shall visualize alerts and warnings prominently and shall clearly display instructions for operators.

[RQ-104] The UI shall display control data as time-stamped messages.

[RQ-105] The UI shall provide the possibility to show robot state retrieved by the Real-Time Network.

[RQ-106] The UI shall provide the possibility to show predefined sensors data.

[RQ-107] The UI shall provide, preferably, the possibility to show information elaborated by other software components (e.g., collision data, estimation of distances between robot's components and VV objects).

[RQ-108] The UI shall provide, preferably, the possibility to plot and export the provided data as log.

**RH controls**

[RQ-109] The UI shall provide, preferably, the possibility to move inside the 3D environment and utilize functions offered by the API of the visualization SW.

[RQ-110] The UI shall provide quick access to control commands (single click for safety related and most frequently used commands)

[RQ-111] The UI shall provide the possibility to switch between Session States, developing the necessary authentication and authorization mechanism.

[RQ-112] The UI shall provide the possibility to switch between control modes, considering the necessary authentication and authorization mechanism.

[RQ-113] The UI shall offer the option to select the desired HID to be used (Standard Mouse and Keyboard, Force-feedback device, VR headset & controllers) and specify the computer to which the HID is attached. The selection shall be confirmed through a dedicated prompt. This is done to prevent unintended control inputs on the remaining HIDs.

**Usability**

[RQ-114] The UI shall provide, preferably, the possibility to autonomously generate detailed task report.

[RQ-115] The UI shall provide, preferably, operators with access to the Operation Software's Fault Reporting Interface. This allows operators to comment about any fault, warning or problem detected during the task. It shall also provide an easy access to resolution guides if present in the documentation provided to the operator.

[RQ-116] The software shall also be able to operate if the connection with Data server is lost, allowing to use local stored data and functionalities independent from data server. The software shall inform the operator about the last synchronization.

**Camera settings**

[RQ-117] The UI shall provide, preferably, the possibility to modify each camera framing, if the camera is provided with motor to adjust orientation.

[RQ-118] The UI shall provide the possibility to modify, save, and load camera presets. This allows users to adjust the camera settings according to their preferences, save those configurations for future use, and load them when needed.

[RQ-119] The UI shall provide standard interface for camera control to modify the main parameters offered by the cameras control software.

[RQ-120] The UI shall provide the possibility to register and save and videos from the desired cameras.

## 7.3 Diagnostic Software [M2]

The Diagnostic Software (DS) should have the following main function: Collection of the performance data of all RH equipment connected to the local data Network for archiving purposes. The technical requirements are included in the following.

**State monitoring**

[RQ-121] The DS shall run a monitoring routine to gather data from all the devices and software connected to the diagnostic network to assess the health status of the system. It is suggested that such routine shall check the system status with a frequency of at least 50Hz.

[RQ-122] The DS shall detect any anomalies or malfunctions promptly and inform the operators through the HMI.

[RQ-123] The DS shall be able to pinpoint the origin of the detected fault or anomaly.

[RQ-124] The DS shall be able to generate alerts, warnings, or notifications for operators and administrators when abnormalities are detected.

[RQ-125] In case of critical failures, the software must integrate with the Safety Network to trigger appropriate safety protocols, such as stopping the robot and control software.

[RQ-126] The DS shall provide a classification of the detected errors and corresponding actions, encompassing at least the following three severity levels:
1. Critical Fail: The DS triggers the Emergency System via the safety PLC.
2. Fault: The robot's motors are halted through control without utilizing the safety PLC.
3. Warning: The controller is set to a SAFE state, awaiting supervisor confirmation to acknowledge the warning and proceed with operations.

[RQ-127] Severity levels shall be colour coded and easily recognizable.

[RQ-128] The DS shall provide to the Operation Software detected errors using an univocal error code.

[RQ-129] The DS shall collect the status of the connected Human Interaction Device (HID) and make available the information through the API. The possible status of the HID is:
1. OFF: the HID is not ready to be utilized.
2. IDLE: the HID is in an idle state and is ready to be utilized. It doesn't send and receive any signal.
3. HANDS-ON: the HID is operated and is exchanging signals with the control system.

**State analysis**

[RQ-130] The DS shall be able to retrieve the last commanded signal sent from the low-level and forward it to the Operator's PC to evaluate possible differences with the nominal commands sent by the high-level control.

**Data report**

[RQ-131] The DS shall write in a log file all the detailed information regarding system diagnostics elaborated during RH operations.

[RQ-132] The DS shall store detailed logs in the data server for analysis and historical records. The supervisor operator must decide how much time the data server shall store the diagnostic log file before its elimination.

[RQ-133] The DS shall make available the gathered diagnostic data through an implemented API.

## 7.4 Dynamic Simulation Interface [M3]

The Dynamic Simulation Interface (DSI) technical requirements are included in the following:

**General requirements**

[RQ-134] The DSI shall ensure soft real-time requirements when using the simulator in Operation State. If, due to the complexity of the simulation, this requirement cannot be met, the operator shall be notified, and the system shall be halted (paused). The halt of the system on "non-real-time" events shall be disabled by the user. *With soft real-time is intended that the simulation is computed in the same time sequence of the time in the real world*

[RQ-135] The DSI shall offer the possibility to include non-real-time simulations during Planning State, where the real-time factor, indicating the ratio between simulation time and real time, is displayed to the operator.

[RQ-136] The DSI shall be able to run in all session states.

**Interfaces**

[RQ-137] The DSI shall be able to accept kinematic and dynamic models (If the model is elastic at the joints and/or links) of the RH equipment described in unified formats. If the model is provided of dynamic model and information regarding the controller dynamics, the DSS could be develop interaction simulation.

[RQ-138] The DSI shall fetch updated data regarding the robot, the sensors, the VV modules, and the environment from the data server.

[RQ-139] The DSI shall interface with Visualization Software to display the manipulator's pose and behaviour during the simulation.

[RQ-140] The DSI shall be able to accept joint commands (position, velocity) from the Motion Planner and the Teleoperation Control to simulate RH Operations.

[RQ-141] The DSI shall be able to handle simulations involving multiple robots, at least 4.

**Simulations**

[RQ-142] The DSI shall be able to run robot kinematic and dynamic simulations.

[RQ-143] The DSI shall support soft real-time simulation of the real system's behaviour and enable a time-aware visualization of data from the simulation. For time-aware visualization is intended that the software shall complete tasks within a reasonable timeframe, emphasizing responsiveness and predictability while mitigating the risk of failure and errors. For the DSI this mean that each time step *ts* of the simulation shall be calculated in a time t <= ts.

[RQ-144] The DSI shall enable offline simulation of complex models in a non-real-time mode. In this case the operator shall be informed through the HMI that the simulation is not in real-time. Additional useful data shall also be shown (e.g., the simulation integration time).

[RQ-145] The DSI shall be able to also accept data from models including flexible behaviour at joints and/or links level. In this way DSI will act as an interface between the model (e.g., FMU or equivalent) and the visualization module.

For the scope of this project, the flexible behaviour of the robots must be considered only for long reach robots. According to this project the only long-reach robot the control room shall consider is the HYRMAN.

[RQ-146] The DSI shall be able, preferably, to simulate data streams coming from proprioceptive and exteroceptive robot's sensors and additional sensors inside the environment.

[RQ-147] The DSI shall offer the possibility to add or remove predefined end effectors and update the kinematic chain accordingly and load the new dynamic model.

[RQ-148] The DSI shall offer the possibility, preferably, to apply external forces and torques (impulsive, constant, or variable) at specific positions on the simulated manipulator.

[RQ-149] The DSI shall allow for straightforward modification of parameters to fine-tune simulation accuracy.

[RQ-150] The DSI shall allow for straightforward modification of solver parameters, such as simulation timestep, max number of iterations, and solver tolerance.

[RQ-151] The DSI shall provide the capability to record simulation data, including the robot status, sensor outputs, robot trajectory, and robot interactions.

[RQ-152] The DSI shall be able to generate, preferably, a comprehensive report about the simulation containing: the simulated robot, the simulated task, time of simulation, faults and log messages, type of inputs, and parameters of the simulation.

## 7.5 Requirements of the Motion Planner [M4]

The motion planner(MP) is responsible for generating optimized trajectories for robots inside the VV, considering physical constraints from the environment, the actuators' capabilities, ensuring safe and efficient motion. The requirements are included in the following.

**General Requirements**

[RQ-153] The MP shall communicate on the Operative Network with the robots and the operator's PC.

[RQ-154] The MP shall have the capability to switch between the Planning state and Operation State, with the ability to send position and velocity commands to the robot to execute the trajectory selected by the operator.

**Motion executor**

[RQ-155] The MP shall contain a “Motion executor (ME)” module which is responsible for forwarding the collected information from the industrial PC to the Operator's PC, on the Real-Time network or on the Operative Network, depending on the data to be transmitted.

[RQ-156] The ME shall be able to accept the robot state and sensor data as input coming from the industrial PC.

[RQ-157] The ME shall be able to switch between the Planning state and Operation State. In planning state, the digital twin version of the robot is used to test the trajectories.

[RQ-158] The ME shall inform the operator when a joint is working near its limits.

[RQ-159] The ME shall interface with the robot to exchange trajectory-related data, ensuring that the motions sent by the motion planner are synchronized with the manipulator's movement. The ME shall, therefore, have the capability to halt a trajectory in progress through control signals.

**Interconnection and API**

[RQ-160] The MP shall be able to accept the robot model and adopt the rigid link hypothesis if it aligns with the received model.

[RQ-161] The MP shall generate trajectories and make them available to other software modules through the API, optimized for visualization in the VR environment. The trajectory description shall include position, velocity, acceleration, torques of joints, and the pose of each link and the end-effector, expressed in Cartesian space as xyz-rpy or quaternions.

[RQ-162] The MP shall transmit robot commands sent to the industrial PC to the operator's PC over the Operative Network.

[RQ-163] The MP shall be able to extract obstacle positions and environmental constraints from the 3D model of the environment retrieved from the Data Server.

**Trajectory Generation**

[RQ-164] The MP shall provide continuous trajectories in the joint space.

[RQ-165] The MP shall provide trajectories defined in the Cartesian space that do not exceed actuators' safe limits (e.g., velocities and accelerations) and joint limits.

[RQ-166] The MP shall provide the operator with the possibility to define trajectories by interpolating a set of user-defined reference frames (TF).

[RQ-167] The MP shall provide trajectories that respect limits imposed by the robot, the environment, and any external constraints provided by the manufacturer.

[RQ-168] The MP shall allow for the modification of trajectory parameters (e.g., velocity, acceleration, time) for the desired trajectory.

[RQ-169] The MP shall offer the possibility to use different path planning algorithms, with modifiable parameters by the operator.

[RQ-170] The MP shall accept various types of constraints: position, orientation, visibility, joint, and external constraints.

[RQ-171] The MP shall be able to find the optimum trajectory to reach any desired user-defined TF, considering environmental and user-defined constraints.

[RQ-172] The MP shall use the cost function provided by the Collision Software during trajectory generation to evaluate possible collision with the environment.

[RQ-173] The MP shall optimize robot movements to avoid operating the manipulator in singular configurations or near its limits, as well as in configurations defined as critical for the system.

[RQ-174] The MP shall be capable, preferably, of optimizing the trajectory taking into account the redundancy of the robot. In the case of robots with micro-macro configurations (comprising two independent serial kinematic chains), the MP must have the ability to optimize the configuration of the basic kinematic chain (macro), considering user-specified constraints related to the micro kinematic chain. During this optimization the MP shall always avoid collisions.

[RQ-175] The MP shall offer the possibility, preferably, for redundant chains to reconfigure the internal elements of the chain while keeping the end effector's pose unchanged

**User Experience (UX)**

[RQ-176] The MP shall provide a confirmation mechanism before executing any autonomous motion, including the possibility to send trajectories to the visualization software for pre-visualization.

[RQ-177] The MP shall interface with VR controllers and the visualization software to visualize planning information during immersive operations in virtual reality.

[RQ-178] The MP shall offer information on the completion percentage of the current trajectory.

## 7.6 Teleoperation Control [M5]

The Teleoperation Control Software (TCS) is responsible for enabling teleoperation of remote handling equipment, ensuring efficient and safe control of robots within the VV. The requirements are included in the following.

[RQ-179] The TCS shall be able to interface with the ME, enabling the initiation, pausing, and termination of trajectories in both the foreseen Session States

[RQ-180] The TCS shall be able to communicate on the Real-Time Network, ensuring Hard Real-Time communication between the robots and the master station operator's PC.

[RQ-181] The TCS shall provide the possibility to switch between the Planning state and Operation State, with the following differences:

- In the Planning State, the TCS shall be able to forward the trajectory information to the simulation and to the visualization software.
- In the Operation State, the TCS shall be able to forward the trajectory information to the simulation, to the visualization software, and to the real robot.

[RQ-182] The TCS shall oversee the teleoperation for all robots, ensuring that a single robot is teleoperated exclusively by one operator and facilitating the transfer of control between operators through a confirmation by the Supervisor.

[RQ-183] The TCS shall be able to interface with the industrial PC to send control signals, which can be commands in terms of position and velocity.

[RQ-184] The TCS shall ensure that the use of HID generates the same command inputs in both simulation and on real manipulators (e.g., scale factors, key binds, motion axis).

[RQ-185] The TCS shall be able to accept kinematic and dynamic model of the RH equipment described in unified formats.

[RQ-186] The TCS shall allow for the selection of only a sub-section of the kinematic chain of the manipulator while keeping the remaining parts stationary in the Cartesian space.

**Shared Mode**

[RQ-187] The TCS shall foresee a Shared Control Mode (SCM) to assist RH operations.

[RQ-188] The SCM shall provide, preferably, the capability to create custom virtual constraints for the operator defined as specific external wrenches (force-torque) on the master device. The implementation of specific virtual constraint strategies is out of scope of this tender

## 7.7 Collision Management [M6]

The Collision Management Software (CMS) is responsible for managing and preventing collisions between remote handling equipment and objects within the Virtual Vacuum Vessel (VV) environment. The software module is based on a precise correspondence between the 3D models of the manipulators and the environment and the real-world elements and their relative poses. The requirements are listed in the following.

**General Requirements**

[RQ-189] The CMS shall be able to communicate on the Operative Network.

[RQ-190] The CMS shall be able to work in both Planning State and Operation State.

**Model Data**

[RQ-191] The CMS shall be able to accept the kinematic and dynamic model of the remote handling equipment described in unified formats.

[RQ-192] The CMS must possess the capability to perform collision detection for the manipulator's links in relation to both the environment and other manipulators.

[RQ-193] The CMS shall be capable, preferably, of executing collision detection, encompassing, if the rigid-model hypothesis is not valid, at least the flexible behaviour of the manipulator at the joint level

[RQ-194] The CMS shall be able to accept different types of objects, including meshes, 3D models, primitive shapes, with a minimum resolution of 2^16 (65536) nodes or 65535 triangles per represented object and update the pose of each object based on data provided by the mock-up area.

[RQ-195] The CMS shall be able to import model of the robots and the environment and extract necessaries information to run collision management.

[RQ-196] The CMS shall allow the operator to choose, for each object in the scene, the level of accuracy with which the meshes and colliders shall replicate the geometric characteristics of the objects. The required level of accuracy will depend on the minimum dimensions of the components that can potentially collide with the environment and robots.

[RQ-197] The CMS shall foresee a final topology of the 3D model compatible with the graphic and physical engine offered by the Visualization Software

**Collision detection**

[RQ-198] The CMS shall interface with the Motion Planner, providing a cost function to evaluate possible collision between the robot and the environment during planning.

[RQ-199] The CMS shall be able to retrieve robot state from the Operative Network, both in the Planning State and Operative State, to update the cost function.

[RQ-200] The CMS shall ensure that movements inside the environment can be executed without unexpected collision.

[RQ-201] The CMS shall be able to evaluate collisions between object under a minimum distance determined from the foreseen operation inside the environment.

[RQ-202] The CMS shall check for self-collisions and collisions with the environment using the robot model, the robot state, and information from additional sensors.

[RQ-203] The CMS shall offer, preferably, a cost function that can take into account any flexible components declared by the manufacturer

[RQ-204] The CMS could implement an algorithm for collision detection to identify collisions that can be reported by sensors on the robotic arm.

[RQ-205] The CMS shall trigger the Diagnostic Software to switch the controller into SAFE mode in case of any undesired collision detected.

## 7.8 Operation Management Software [M7]

The Operation Management Software (OMS) is responsible for managing and overseeing procedures for remote handling (RH) operations. It ensures that maintenance tasks are performed safely, efficiently, and with consistent quality. The OMS requirements are defined as follows.

**State Machine**

[RQ-206] The OMS shall provide a State Machine (SM) to enable proper task planning, handle state transition conditions, and supervise transitions across different operational modes.

[RQ-207] The SM shall communicate on the Operative Network.

[RQ-208] The SM shall be the same for both Planning and Operation States

[RQ-209] The SM shall be designed to accommodate a division into two states for robot control: the "approach state" and the "telemanipulation state," each serving distinct control requirements. The first state is employed for trajectory planning toward a target, utilizing the motion planning module, and is utilized for approaching the target. The second state is used for direct teleoperation of the target in either full teleoperation or shared mode.

[RQ-210] The SM shall interface with other modules to ensure time synchronization within the network.

**Structured Language**

[RQ-211] The OMS shall describe tasks unambiguously.

[RQ-212] The OMS shall describe tasks using a Structured Language (SL) where each operation step has the format: [Subject] - [Action] - [ActionObject] - [QualifierObject], allowing precise and structured task descriptions.

[RQ-213] The SL shall support mathematical operations (<, >, =), conditional statements (IF-ELSE), repetitive statements (WHILE/FOR LOOPS), and event statements (WAIT UNTIL).

[RQ-214] The OMS shall store SL data objects in a database implemented on the data server.

**Operation Scheduling & Management**

[RQ-215] The OMS shall include graphical interfaces for operation planning, execution, and analysis. This graphical interface can be integrated within the Human-Machine Interface (HMI) module or be a separate executable.

[RQ-216] The OMS shall enable detailed planning and scheduling of RH operations.

[RQ-217] The OMS shall allow users to create, delete, and modify procedures and tasks, with authorization from the Supervisor.

[RQ-218] The OMS shall provide the possibility to define a task as a sequence of saved procedures or as a sequence of user-defined trajectories, with Supervisor authorization.

[RQ-219] The OMS shall allow the verification of task procedures, including the consistency of multiple concatenated procedures or trajectories using the simulation module.

[RQ-220] The OMS shall monitor that RH operations adhere to stored procedures.

[RQ-221] The OMS shall keep track of RH operations, highlighting the current action.

[RQ-222] The OMS shall verify that the conditions for starting procedure and task execution are met.

[RQ-223] The OMS shall support the development of different parts of procedures by multiple users simultaneously.

[RQ-224] The OMS shall have the capability to send structured tasks, including pre-planned and approved RH operations, either to the real robot or to the robot simulation without the necessity of routing through the Motion Planner.

[RQ-225] The OMS shall interface with the industrial PC to receive, save and execution of robotic jobs.

[RQ-226] The OMS shall interface with the industrial PC to start, abort, and pause the execution of a robotic job.

[RQ-227] The OMS shall allow to send a sequence of user-defined coordinate frames to the be reinterpreted as robotic job

**Fault Reporting Interface**

[RQ-228] The OMS shall provide a Fault Reporting Interface (FRI) dedicated to signalling, reporting, and describing any faults, problems, or difficulties experienced by users during RH operations. This module is associated to the OMS to synchronize the fault or report to the specific task.

[RQ-229] The FRI shall offer a detailed fault description, allowing users to include any relevant data retrieved during task operations.

[RQ-230] The FRI shall provide documentation to address expected problems.

[RQ-231] The FRI shall categorize reports as OPEN and ARCHIVED, with OPEN reports requiring investigation and ARCHIVED reports indicating resolved issues.

## 7.9 Authentication & Authorization Software [M8]

The Authentication & Authorization Software (A&A) is responsible for managing all authentication and authorization mechanisms for the network and all software applications, ensuring the security and privacy of the system. The A&A requirements are defined as follows.

[RQ-232] The A&A shall manage all authentication and authorization mechanisms for the network.

[RQ-233] The A&A shall develop cybersecurity mechanisms to protect against unauthorized access.

[RQ-234] The A&A shall implement a hierarchical authorization structure, with the Supervisor having the highest level of privileges, granting access to all functionalities, while lower-level users have restricted access. By default, lower-level users shall be restricted from modifying task scheduling, managing authentication and authorization, altering interconnection settings, manipulating manipulators' movements, and changing operational settings without the presence and approval of an authorized supervisor.

[RQ-235] The A&A shall provide the Supervisor with the ability to add, modify, and delete different types of users.

[RQ-236] The A&A shall allow the Supervisor to manage access authorization for defined user types.

[RQ-237] The A&A shall provide each user with a clear and detailed list of operations and privileges they possess.

[RQ-238] The A&A shall provide the Supervisor with the ability to add and delete users from the authentication system.

[RQ-239] The safety of hardware and software systems must be ensured by adhering to the standards of ISO 27001. Precautionary measures can be implemented to enhance the security of the control room, such as:

- Employing specific hardware firewalls at all network access points to the external internet.
- Disabling any Wi-Fi networks connected to the main networks and control PCs.
- Managing access permissions to USB ports and other interface ports through supervisor authentication.
- Utilizing MAC addresses instead of IP addresses.
- Regulating access to external ENEA servers through authentication procedures.
- Enabling either VPN or FPS alternatively on the network.
- Monitoring access to all PC ports, blocking high-risk ports, such as port 80, for example.

## 7.10 Visualization Software [M9]

The Visualization Software (VS) is responsible for providing the operator with a faithful 3D representation of the environment and the manipulators, accurately reproducing the real-world scenario. The requirements for the Visualization Software are defined as follows.

### 7.10.1 General Requirements

**Accessibility**

[RQ-240] The VS shall include accessibility options that allow users to modify settings such as language, text dimension, and more to suit their preferences and needs.

[RQ-241] The VS shall offer, preferably, adjustable lighting or shading options for specific panels and windows in order to enhance the visual quality of the representation

**Model Management**

[RQ-242] The VS shall establish communication with a data server to periodically synchronize the model library and automatically update the 3D world environment

[RQ-243] The VS shall establish communication with a data server and allow the user to load model and manually update the 3d world environment.

[RQ-244] The VS shall, preferably, synchronize the model library with the data server once every workday, as the VS is turned on.

[RQ-245] The VS shall, preferably, provide the possibility to force a synchronization with the data server.

[RQ-246] The VS shall, preferably, provide information on the last synchronization, such as date, number, and name of changed files

**Compatibility**

[RQ-247] The VS shall be compatible with at least the chosen VR headset, preferably with the most common VR headset, ideally with any VR headset.

[RQ-248] The VS shall evaluate the option of using commercially established 3D visualization and simulation environments within the robotics sector, such as Unity or Unreal. The VS shall also consider the use of VTK.

**Visualization**

[RQ-249] The VS shall incorporate soft real-time rendering of the environment and the robots, guaranteeing reliable and up-to-date visualization. Achieving soft real-time implementation involves providing a reliable system visualization at a minimum and constant update frequency (suggested minimum is 30 Hz). This ensures that the operator has a fluid and responsive visual representation of both the environment and the robot manipulator during the task execution.

[RQ-250] The VS shall deliver good graphical performance with all S/S's 3D models (suggested minimum refresh rate is 30Hz).

### 7.10.2 3D Environment

**Digital Twin**

[RQ-251] The VS shall incorporate a digital twin of both the robot manipulators and the environment. This digital twin shall be created using the 3D model of the robot. The robot model shall accurately replicate the robot's geometries at a 1:1 scale, enabling precise remote handling operations that rely solely on the digital twin.

[RQ-252] The VS module shall ensure that each 3D model of manipulators and objects located within the VV is described using meshes with a minimum of 2^16 (65536) nodes or 65535 triangle per represented object to ensure a high degree of detail and precision during simulations.

[RQ-253] The VS module shall also provide simplified CAD starting from the CAD library models. These simplified models shall have all the necessary features for correct and precise visualization but be light enough to enable real-time/time-aware features.

[RQ-254] The VS shall implement a digital twin that replicates the movements of the S/Ss inside the mock-up. The digital twin will rely on data from sensors and the kinematic/dynamic models provided along with the S/Ss. Latency shall be minimized in order to provide good performances in terms of easiness of teleportation and precision. A maximum latency of 30ms is suggested.

[RQ-255] The VS shall provide a visually clear and intuitive representation of the robot's and other components movement before task execution, including an accurate depiction of its planned path.

**Physical Engine**

[RQ-256] The VS shall integrate with the collision module to correctly simulate collision physics.

**Rendering**

[RQ-257] The VS shall use Vulkan-based graphic rendering software for all 2D and 3D rendering operations. The implementation of Vulkan must be compatible with the target hardware and fully leverage the capabilities of the graphics cards to ensure optimal performance. The use of Vulkan should facilitate efficient management of graphic resources and low latency, thus contributing to the provision of an advanced and highly performing graphic rendering platform for the VS system.

[RQ-258] The VS shall offer a faithful 3D representation of the environment and the manipulators. It shall guarantee precise spatial understanding of the environment and robot manipulators. This includes maintaining accurate proportions, distances, and angles to create a faithful representation of the real-world scenario.

[RQ-259] The VS shall implement transparent object rendering to improve visibility and understanding within the visualization.

[RQ-260] The VS shall provide options to customize the visualization of robot components such as joints, links, frames, and other relevant parts.

[RQ-261] The VS shall achieve realistic rendering of any sensor data foreseen for the Mock-up area, encompassing available sensors such as cameras, lidar point clouds, and depth maps.

**World Management**

[RQ-262] The VS shall give the possibility to modify the 3D world environment only to authorized personnel.

[RQ-263] The VS shall offer access to 3D models from the model library in order to modify the 3D environment.

**Virtual Camera Framing**

[RQ-264] The VS shall provide an API for the HMI software to modify settings of the virtual camera.

[RQ-265] The VS shall provide the possibility to create and delete virtual cameras, giving operators the possibility to have different points of view streaming simultaneously.

[RQ-266] The VS shall provide each operator with access to any virtual camera view, enabling operators to have a custom layout of views independent from each other.

[RQ-267] The VS shall provide controls to manipulate the viewpoint and virtual camera angle.

[RQ-268] The VS shall provide the possibility to switch between different virtual camera views and perspectives, previously created by the operator and saved.

[RQ-269] The VS shall offer the possibility to capture screenshots, record videos, and export custom layouts of operator windows for documentation or sharing purposes.

### 7.10.3 Virtual Reality Software (VRS)

[RQ-270] The VS software shall provide a Virtual Reality Software (VRS) to manage the interaction between operators and machines inside the Virtual Reality (VR) environment.

[RQ-271] The VRS shall provide soft real-time visualization of the 3D environment and of the digital twins.

[RQ-272] The VRS shall support the simultaneous display of multiple views, both from virtual and real cameras, arranged in a grid layout around the main view. This layout shall enable operators to gain a comprehensive understanding of the scenario from various angles.

[RQ-273] The VRS shall grant operators the ability to select which camera streams (virtual or real) to display and where to position them within the grid layout.

[RQ-274] The VRS shall provide the operator with access to all the task's information available to the other operator's PC for better situational awareness.

[RQ-275] The VRS shall be able to visualize the desired task information in windows and panels that can be arranged in a grid layout around the main view. The VS shall provide the operators with the possibility to create, delete, and move the panel inside the layout.

[RQ-276] The VRS shall foresee panel and layout of predefined size and ratio to visualize data and camera streams. The VS shall allow the operator to change the size of any panel choosing between the predefined ones.

[RQ-277] The VRS shall offer the possibility to create, save, and load custom layouts of camera views, windows, and panels.

[RQ-278] The VRS shall offer the possibility to visualize plots of data streams.

[RQ-279] The VRS shall offer a visually clear and intuitive representation of the robot's movement before task execution. This allows for the evaluation of the trajectory and the identification of potential conflicts with environmental constraints.

[RQ-280] The VRS shall implement trajectory preview (eg. as a semi-transparent replay of the manipulator performing the trajectory in a continuous loop). It shall also allow the operator to control the preview by adjusting the playback speed, pausing, or slowing it down. The playback could be initiated and controlled by continuous trigger pressure on the HID controllers. This functionality enables the operator to thoroughly examine the trajectory and precision movements from various perspectives.

[RQ-281] The VRS shall offer the possibility to visualize the actual joint state through clearly visible text near each joint. The joint state shall encompass:

- The angular position of the joint.
- The link position (XYZ-RPY) in the world reference frame.
- The joint limits.

[RQ-282] The VRS shall offer the possibility to visualize the estimation of distances between robot's components and VV objects. The VRS could provide the option to select desired points on the manipulator and the VV component for which to visualize the distance estimation. The VRS could visualize the information through clearly visible text and a line connecting the referenced points.

[RQ-283] The VRS shall implement interactive controls that enable manipulation of the viewpoint and camera angles.

# 8 References

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# 9 Annex A: List of Technical Requirements

| Legend | |
|---|---|
| **I** | Inspection of the functionality |
| **T** | Test |
| **A** | Analysis in the design phase |

| **Req ID** | **Requirement text** | **Value** | **Category** | **Verification** | **Comments** |
|---|---|---|---|---|---|
| RQ-001 | The interfaces of the control room with the other systems are included in the ICD. In particular, a component referred to as "External interface" defines the interface between the elements in the control room and the elements within the other systems | | General Requirement | I | |
| RQ-002 | The Local Data Network shall be designed to be fail-safe | | Network:<br>Local Data Network | T | |
| RQ-003 | The Local Data Network shall ensure that each connected entity has a state that describes whether it is operating under nominal conditions. | | Network:<br>Local Data Network | T | |
| RQ-004 | The Local Data  Network shall provide a network bandwidth of at least 1/10 Gbit | 1/10 Gbit | Network:<br>Local Data Network | T | |

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| RQ-005 | The Real-time Network shall be used to retrieve force telemetries coming from the Robot S/S | | Network:<br>Real-Time Network | T | |
| RQ-006 | The Real-Time Network shall be designed to guarantee connections from the industrial PC to the server using real-time protocols like EtherCAT or ProfiNet. | | Network:<br>Real-Time Network | T | |
| RQ-007 | The Real-Time Network shall ensure that operator PCs are connected to the server through a real-time protocol, such as EtherCAT, ProfiNet or RTP over UDP. | | Network:<br>Real-Time Network | T | |
| RQ-008 | The Real-time Network shall be designed in a way that the cables used can ensure reliable and real-time communications. Additionally, it shall include provisions for data to travel on a specific subnet. | | Network:<br>Real-Time Network | T | |
| RQ-009 | The Real-time Network shall comply with, but not limited to, the following conditions:<br>• Low Latency<br>• High Bandwidth<br>• Quality of Service (QoS)<br>• Reliability<br>• Monitoring and Management<br>• Traffic Prioritization<br>• Packet Loss Mitigation<br>• Jitter Control<br>• Synchronization<br>• Compatibility with Real-Time Protocols | | Network:<br>Real-Time Network | A | |

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| | In particular, the frequency shall be at least 1000 Hz for ensuring real-time force control. | | | | |
| RQ-010 | The Video Network will be designed and tested to be reliable and to avoid disconnections during the video stream. | | Network: Video Network | T | |
| RQ-011 | The Video Network shall be exclusively dedicated to handling video stream data, including both video streams originating from the machine side and those from the Visualization Server. It should be considered that video data from the machine side can be sourced from the Operative Network and then rerouted to the control room's Video Network. | | Network: Video Network | I | |
| RQ-012 | The Video Network shall ensure the ability to display all streams at the same resolution at which they were captured. | | Network: Video Network | T | |
| RQ-013 | The Video Network shall guarantee a maximum latency between the camera and operator monitor of 50 ms. | 50ms | Network: Video Network | T | |
| RQ-014 | The Video Network shall ensure a maximum of frames loss of 1% during transmission. | 1% | Network: Video Network | T | |
| RQ-015 | The Video Network shall provide sufficient network bandwidth to transmit all the camera streams present in the mock-up area and at least three (3) different virtual cameras for each operator. | | Network: Video Network | T | |
| RQ-016 | The Operative Network shall be designed and tested to be fail-safe. | | Network: Operative Network | T | |

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| RQ-017 | The Operative Network shall be dedicated to non-critical data regarding the RH operations that do not need real-time communication, such as robot telemetries. | | Network: Operative Network | I | |
| RQ-018 | The Operative Network shall support the communication between heterogeneous applications by implementing a general-purpose communication mechanism and Protocol. | | Network: Operative Network | I | |
| RQ-019 | The Operative Network shall ensure that no packet loss occurs during transmission. | | Network: Operative Network | T | |
| RQ-020 | The Operative Network shall provide sufficient network bandwidth to transmit 3D models of the robot and of the environment to both the servers and the PC located within the control room. The bandwidth shall enable data transfer as fast as possible to reduce operation stop time, following the ALARA principle. | ALARA | Network: Operative Network | T | |
| RQ-021 | The Safety Network shall be designed and tested to be fail-safe and have a SIL 1 certification level. | | Network: Safety Network | A | |
| RQ-022 | The Safety Network PLC shall poll at a minimum rate of 20Hz to detect loss of signal and shall take appropriate action in case of no response. This includes turning on emergency lights in the Control Room area and sending halt signals to the industrial cabinet of the robots. | 20Hz | Network: Safety Network | T | |

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| RQ-023 | The Safety Network shall be developed as two network lines | | Network: Safety Network | I | |
| RQ-024 | The Safety Network shall foresee hard-wired Emergency Stop System on each operator desk within arm's reach to stop the manipulator's execution. | | Network: Safety Network | I | |
| RQ-025 | The Safety Network shall provide programmable an Emergency Stop System for each operator, except for the supervisor, to allow the mutually exclusive stop of individual manipulators. The supervisor shall have an Emergency Stop System capable of stopping all manipulators. | | Network: Safety Network | T | |
| RQ-026 | The Safety Network shall ensure that each Emergency Stop Systems includes the capability to select and enable a manipulator using a dedicated and specific button for the exclusive connection to that manipulator. The emergency stop system will have the ability to stop only the manipulator to which it is connected. | | Network: Safety Network | T | |
| RQ-027 | The Safety Network shall be designed in a way that prevents teleoperation of a specific manipulator unless the operator has previously configured the Emergency Stop Systems for that manipulator. | | Network: Safety Network | A,T | |
| RQ-028 | The Safety Network shall foresee a Safety PLC to provide status updates to the Control Server. | | Network: Safety Network | I | |

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| RQ-029 | The Safety Network shall be designed to have the highest priority over any other network and can immediately activate the robot's brakes. | | Network: Safety Network | T | |
| RQ-030 | The Safety Network shall include the activation of an audible alarm signal in the event of safety-critical situations. This signal can be bot visual or audible and shall be directly commanded by the safety PLC. | | Network: Safety Network | T | |
| RQ-031 | The maintenance state shall be carried out in accordance with the CEI EN 6204-1 standard. | | Network: Maintenance | A | |
| RQ-032 | During the Maintenance State, the diagnostic software shall inform the control room via the HMI, and activate physical visual warnings predisposed inside the control room. This signal alerts operators that maintenance is currently being performed. In particular, the signals are as follows: Green means planning, Orange means operation, Red means maintenance. | | Network: Maintenance | T | |
| RQ-033 | The workstation’s monitor shall be with a full HD resolution and shall be greater than 27 inches. Specifications of a configuration that satisfy this requirement are included in Table 7 | | Hardware: Displays | I | |
| RQ-034 | The manipulator master station’s monitor shall be with a Ultra-Wide QHD resolution at minimum, and shall be greater than 34 inches. Specifications of a configuration | | Hardware: Displays | I | |

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| | that satisfy this requirement are included in Table 8. | | | | |
| RQ-035 | The wall monitors shall be two, they shall have a 4K UHD (3830x2160) resolution minimum with a 16:9 aspect ratio, shall be greater than 65 inches and with a refresh rate equal to or greater than 40 Hz. Specifications of a configuration that satisfy this requirement are included in Table 9 | | Hardware: Displays | I | |
| RQ-036 | The operator's PC shall be at least two. Each operator's PC shall ensure the work of the operator. Specifications of a configuration that satisfy this requirement are included in the tables: Table 10 to Table 17. | | Hardware: PCs | I | |
| RQ-037 | The supervisor PC shall be at least one. It shall ensure the work of the supervisor. Specifications of a configuration that satisfy this requirement are included in the tables: Table 10 to Table 17 | | Hardware: PCs | I | |
| RQ-038 | The Manipulator Master Station shall be at least one. It shall ensure the connection on the real-time network. Specifications of a configuration that satisfy this requirement are included in the tables: Table 10 to Table 17, except for the video card, that shall be selected to ensure the connection on the real-time network | | Hardware: PCs | I | |

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| RQ-039 | The joystick shall have a number of axes equal or greater than 2 and a number of button equal or greater than 10. Specifications of a configuration that satisfy this requirement are included in Table 18 | | Hardware:<br>Human Interaction Device | I | |
| RQ-040 | The force-feedback device shall be used for real-time force control and shall ensure force feedback as accurate as possible. The requirements are such that the specifications are those included in Table 19 | | Hardware:<br>Human Interaction Device | I | |
| RQ-041 | The VR Headset & Controller device shall be used for virtual reality simulations and training. The requirements are such that the specifications are those included in Table 20 | | Hardware:<br>Human Interaction Device | I | |
| RQ-042 | The switch of the video network shall consider the presence of at least 12 Full HD 30 Hz cameras in the mock-up areas. The requirements for the switch of the video network are such that the specifications are those included in Table 21 | | Hardware:<br>Network Equipment and UPS | I | |
| RQ-043 | The requirements for the switch of the operative network are such that the specifications are those included in Table 22. | | Hardware:<br>Network Equipment and UPS | I | |
| RQ-044 | The requirements for the switch of the real-time and local area networks are such that the specifications are those included in Table 23 | | Hardware:<br>Network Equipment and UPS | I | |

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| RQ-045 | The requirements for the router are such that the specifications are those included in Table 24. | | Hardware:<br>Network Equipment and UPS | I | |
| RQ-046 | The UPS shall be chosen to provide enough time for the safe saving and exit in case of unexpected input power interruption (at least 30 min) | | Hardware:<br>Network Equipment and UPS | I | |
| RQ-047 | The UPS shall be chosen so that a single UPS powers each critical component connected to it | | Hardware:<br>Network Equipment and UPS | I | |
| RQ-048 | The UPS shall be of three typologies: Type 1, Type 2, Type 3, with requirements that are satisfied by considering the specifications included in Table 25, Table 26 and Table 27, respectively | | Hardware:<br>Network Equipment and UPS | I | |
| RQ-049 | The Control Server shall connect to the robotic system in the mock up area with a Real-Time protocol such as EtherCAT or ProfiNet on the real-time network. | | Hardware:<br>Control Server | I | |
| RQ-050 | Critical software that shall run in real-time will need to be specified and coded accordingly. | | Hardware:<br>Control Server | I,T | |
| RQ-051 | The Control Server shall have a real-time communication link between the manipulator master station and RH equipment controllers. | | Hardware:<br>Control Server | I | |
| RQ-052 | The Control Server shall run a real-time OS which should be chosen according to the executive design of the control | | Hardware:<br>Control Server | I | |

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| | architecture. Moreover, a windows OS in dual boot must always be installed to run Windows OS based software (e.g. CAD prototyping). | | | | |
| RQ-053 | The Control Server shall have a full stack of real-time hardware, including the Operating System with a real-time kernel, suitable real-time drivers and motherboard. | | Hardware: Control Server | I | |
| RQ-054 | The Control Server shall interface with the industrial PC to receive robot state. | | Hardware: Control Server | I | |
| RQ-055 | The Control Server shall incorporate all the required algorithms for robot manipulation within a framework that includes a set of utilities for planning, control etc such as the utilities provided by frameworks like ROS2. | | Hardware: Control Server | I | |
| RQ-056 | The Control Server shall automatically launch all the necessary software components for RH operations upon startup. | | Hardware: Control Server | T | |
| RQ-057 | The requirements on the control server are satisfied if the minimum control server hardware specifications (CPU, GPU, other components) listed in Table 28, Table 29 and Table 30 are satisfied | | Hardware: Control Server | I | |
| RQ-058 | The Visualization Server shall run on a OS compatible with graphic drivers and VR devices. | | Hardware: Visualization Server | I | |
| RQ-059 | The Visualization Server shall implement the 3D environment and manage the interaction with the VR equipment. | | Hardware: Visualization Server | I | |

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| RQ-060 | The Visualization Server shall interface with Clients through subnet. | | Hardware: Visualization Server | I | |
| RQ-061 | Visualization Server shall offer the possibility to install proprietary software for cameras and motion capture. It also shall provide all the software necessary to acquire, analyse and transmit data taken from the proprietary software. | | Hardware: Visualization Server | I | |
| RQ-062 | The Visualization Server shall automatically launch all the necessary software components for RH operations upon startup. | | Hardware: Visualization Server | T | |
| RQ-063 | The visualization server must have high computational and graphic capabilities. | | Hardware: Visualization Server | I | |
| RQ-064 | The requirements on the visualization server are satisfied if the minimum visualization server hardware specifications (CPU, GPU, other components) listed in Table 31, Table 32 and Table 33 are satisfied | | Hardware: Visualization Server | I | |
| RQ-065 | The Data Server shall provide enough storage space to store all described data | | Hardware: Data Server | I | |
| RQ-066 | The Data Server shall grant access and allow modification only to authorized personal. | | Hardware: Data Server | T | |
| RQ-067 | The Data Server shall interconnect with the external ENEA central system for data exchange, thus requiring suitable cybersecurity protection mechanism. | | Hardware: Data Server | I,T | |

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| RQ-068 | The Data Server shall analyse data collected from task report to estimate equipment degradation and signal the need for preventive maintenance | | Hardware: Data Server | I | |
| RQ-069 | The Data Server shall implement a redundancy system, such as RAID5 or RAID-Z, to minimize the risk of data loss. | | Hardware: Data Server | I | |
| RQ-070 | The Data Server shall be able to manage multiple simultaneous data stream. | | Hardware: Data Server | T | |
| RQ-071 | The Data Server shall exchange all the data through the Operation Network | | Hardware: Data Server | I | |
| RQ-072 | The requirements on the data server are satisfied if the minimum data server hardware specifications (CPU, GPU, other components) listed in Table 34, Table 35 and Table 36 are satisfied | | Hardware: Data Server | I | |
| RQ-073 | All software modules shall apply the "As Low As Reasonably Achievable" (ALARA) principle to optimize operations carried out from the software. | ALARA | Software: General Requirement | I | |
| RQ-074 | All software modules shall follow a modular design, with each module delivering a defined functionality and interfacing with other modules through clearly defined interfaces. | | Software: General Requirement | A | |
| RQ-075 | All software modules shall not have dependencies on the implementation details of other software modules. The interconnection of these modules shall be | | Software: General Requirement | A | |

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| | established through specific APIs associated with each individual software module. | | | | |
| RQ-076 | All software modules shall ensure that all PCs share the same Session State to avoid conflicts on data running on the network. The default state when the system starts shall be the Planning State, in which the real site is disconnected from its digital twin and the user exclusively interacts with the digital model. Switching state shall be possible only with the Supervisor's permission. | | Software: General Requirement | T | |
| RQ-077 | All software shall be developed using a well-established reference framework. The suggested reference framework for the system architecture of the Control Room is ROS2/DDS. Other suggested control frameworks which have been already used for control architectures in research projects and in fusion energy include: EPICS and GENROBOT. This is not a comprehensive list; therefore, other frameworks can be considered. | | Software: General Requirement | A | |
| RQ-078 | The software shall be developed in such a way that every module does not require a specific power-on or power-off sequence dependent on other modules. Nevertheless, each software module must implement a proper shutdown procedure | | Software: General Requirement | I | |

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| | that does not modify data within the system. | | | | |
| RQ-079 | The software must be developed in such a way that each module verifies the activation status of any other software module necessary for the specific task before initiating the task execution. For example, the Motion Planner shall check whether Collision Management is active before commencing its operation. | | Software: General Requirement | T | |
| RQ-080 | The entire software architecture shall be developed following a lifecycle in accordance with ISO 12207, produced by the contractor and agreed upon with the customer. | | Software: General Requirement | T | |
| RQ-081 | The software development shall include usability testing conducted by experienced technicians in line with ISO 9216 | | Software: General Requirement | A,T | |
| RQ-082 | The software framework must be developed in such a way that more modules can be easily added. No source code is required for proprietary libraries the Contractor has developed before the contract and implemented or customized. | | Software: General Requirement | I | |
| RQ-083 | The HMI shall run on each PC independently. Each operator should be able to interact, modify and customize their own HMI software from the other operator's PC | | Software: HMI | I | |

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| RQ-084 | The development of the HMI shall include usability testing and validations by operators, as well as incorporating modifications based on the received feedback | | Software: HMI | I | |
| RQ-085 | The HMI software shall be developed to ensure it is smooth and provides lag-free interactions, with predefined maximum response times tailored to the adopted control methodology [3]. Specifically, the minimum refresh rate of the HMI shall be set to 30Hz. | 30Hz | Software: HMI | T | |
| RQ-086 | The HMI software shall include the robust authentication and authorization mechanism implemented by the Operation SW in Section 7.8 | | Software: HMI | T | |
| RQ-087 | The HMI Software shall interface with other software and servers on the network to exchange all necessary information. | | Software: HMI | I | |
| RQ-088 | The HMI Software shall be able to retrieve and display information synchronized with the other networks. Specifically, data shall avoid using buffer if possible. When buffers are suggested, the dimension shall guarantee a synchronous visualization with a refresh rate of at least 30Hz. | 30Hz | Software: HMI | T | |
| RQ-089 | The HMI Software shall ensure that the time between receiving information and displaying it is minimized to avoid introducing further delays. | | Software: HMI | I | |

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| RQ-090 | The HMI software shall ensure that the time between selecting a command on the user interface and its transmission is minimized to avoid introducing further delays. | | Software: HMI | I | |
| RQ-091 | The User Interface (UI) shall organize and show the different features and data in specific panels or windows. | | Software: HMI | I | |
| RQ-092 | The UI shall provide the operator with the option to open and close any desired windows or panel. | | Software: HMI | T | |
| RQ-093 | The UI shall enable users to view with the 3D environment in one or more windows, each representing a defined virtual camera framing within the 3D environment. | | Software: HMI | T | |
| RQ-094 | The UI shall provide a pre-defined panel containing multiple cameras, both real and virtual, arranged in pre-defined layouts (e.g., vertical row, horizontal row, square). The operator shall be able to choose which camera streams to display. | | Software: HMI | T | |
| RQ-095 | The UI shall effectively present the RH equipment status information retrieved from the diagnostic system. To display this information on the screen, it is advisable to consider accepted human factors conventions, such as colour coding and warning symbols. | | Software: HMI | T,A | |
| RQ-096 | The UI shall effectively present the RH equipment status information retrieved | | Software: HMI | T | |

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| | from the diagnostic system. To display this information on the screen, it is advisable to consider accepted human factors conventions, such as colour coding and warning symbols | | | | |
| RQ-097 | The UI shall clearly display the current session state. Possible states are Planning and Operation (described in Section 6) | | Software: HMI | T | |
| RQ-098 | The UI shall clearly display the current control mode. | | Software: HMI | T | |
| RQ-099 | The UI shall clearly display the current Human Interaction Device (HID) (Standard mouse and keyboard - VR headset & controllers - Force-feedback device, if the manipulator supports it). | | Software: HMI | T | |
| RQ-100 | The UI shall clearly display diagnostic data about each device status inside the room (Idle – Nominal – Hands-on – Commissioning – Recovery) and each controller status (Off – Safe-- Ready – Enabled). This is only intended as a visualization of the status data. These states are described in Section 7.3 | | Software: HMI | T | |
| RQ-101 | The UI shall clearly display the operation status | | Software: HMI | T | |
| RQ-102 | The UI shall clearly display in a dedicated panel all the safety-related information coming from the Diagnostic Software, such as emergency stop status, system faults, and critical alarms | | Software: HMI | T | |

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| RQ-103 | The UI shall visualize alerts and warnings prominently and shall clearly display instructions for operators. | | Software: HMI | T | |
| RQ-104 | The UI shall display control data as time-stamped messages. | | Software: HMI | T | |
| RQ-105 | The UI shall provide the possibility to show robot state retrieved by the Real-Time Network. | | Software: HMI | T | |
| RQ-106 | The UI shall provide the possibility to show predefined sensors data. | | Software: HMI | T | |
| RQ-107 | The UI shall provide, preferably, the possibility to show information elaborated by other software components (e.g., collision data, estimation of distances between robot's components and VV objects). | | Software: HMI | T | |
| RQ-108 | The UI shall provide, preferably, the possibility to plot and export the provided data as log | | Software: HMI | T | |
| RQ-109 | The UI shall provide, preferably, the possibility to move inside the 3D environment and utilize functions offered by the API of the visualization SW | | Software: HMI | T | |
| RQ-110 | The UI shall provide quick access to control commands (single click for safety related and most frequently used commands) | | Software: HMI | T | |
| RQ-111 | The UI shall provide the possibility to switch between Session States, developing the necessary authentication and authorization mechanism. | | Software: HMI | T | |

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| RQ-112 | The UI shall provide the possibility to switch between control modes, considering the necessary authentication and authorization mechanism. | | Software: HMI | T | |
| RQ-113 | The UI shall offer the option to select the desired HID to be used (Standard Mouse and Keyboard, Force-feedback device, VR headset & controllers) and specify the computer to which the HID is attached. The selection shall be confirmed through a dedicated prompt. This is done to prevent unintended control inputs on the remaining HIDs. | | Software: HMI | T | |
| RQ-114 | The UI shall provide, preferably, the possibility to autonomously generate detailed task report | | Software: HMI | T | |
| RQ-115 | The UI shall provide, preferably, operators with access to the Operation Software's Fault Reporting Interface. This allows operators to comment about any fault, warning or problem detected during the task. It shall also provide an easy access to resolution guides if present in the documentation provided to the operator | | Software: HMI | T | |
| RQ-116 | The software shall also be able to operate if the connection with Data server is lost, allowing to use local stored data and functionalities independent from data | | Software: HMI | T | |

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| | server. The software shall inform the operator about the last synchronization. | | | | |
| RQ-117 | The UI shall provide, preferably, the possibility to modify each camera framing, if the camera is provided with motor to adjust orientation. | | Software: HMI | T | |
| RQ-118 | The UI shall provide the possibility to modify, save, and load camera presets. This allows users to adjust the camera settings according to their preferences, save those configurations for future use, and load them when needed. | | Software: HMI | T | |
| RQ-119 | The UI shall provide standard interface for camera control to modify the main parameters offered by the cameras control software. | | Software: HMI | T | |
| RQ-120 | The UI shall provide the possibility to register and save and videos from the desired cameras. | | Software: HMI | T | |
| RQ-121 | The DS shall run a monitoring routine to gather data from all the devices and software connected to the diagnostic network to assess the health status of the system. It is suggested that such routine shall check the system status with a frequency of at least 50Hz. | 50Hz | Software: Diagnostic Software | T | |
| RQ-122 | The DS shall detect any anomalies or malfunctions promptly and inform the operators through the HMI. | | Software: Diagnostic Software | T | |

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| RQ-123 | The DS shall be able to pinpoint the origin of the detected fault or anomaly. | | Software: Diagnostic Software | T | |
| RQ-124 | The DS shall be able to generate alerts, warnings, or notifications for operators and administrators when abnormalities are detected. | | Software: Diagnostic Software | T | |
| RQ-125 | In case of critical failures, the software must integrate with the Safety Network to trigger appropriate safety protocols, such as stopping the robot and control software. | | Software: Diagnostic Software | T | |
| RQ-126 | The DS shall provide a classification of the detected errors and corresponding actions, encompassing at least the following three severity levels: (1). Critical Fail: The DS triggers the Emergency System via the safety PLC. (2). Fault: The robot's motors are halted through control without utilizing the safety PLC. (3). Warning: The controller is set to a SAFE state, awaiting supervisor confirmation to acknowledge the warning and proceed with operations. | | Software: Diagnostic Software | T | |
| RQ-127 | Severity levels shall be colour coded and easily recognizable. | | Software: Diagnostic Software | I | |
| RQ-128 | The DS shall provide to the Operation Software detected errors using an univocal error code. | | Software: Diagnostic Software | T | |
| RQ-129 | The DS shall collect the status of the connected Human Interaction Device (HID) and make available the information through the API | | Software: Diagnostic Software | T | |

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| RQ-130 | The DS shall be able to retrieve the last commanded signal sent from the low-level and forward it to the Operator's PC to evaluate possible differences with the nominal commands sent by the high-level control. | | Software: Diagnostic Software | T | |
| RQ-131 | The DS shall write in a log file all the detailed information regarding system diagnostics elaborated during RH operations. | | Software: Diagnostic Software | T | |
| RQ-132 | The DS shall store detailed logs in the data server for analysis and historical records. The supervisor operator must decide how much time the data server shall store the diagnostic log file before its elimination. | | Software: Diagnostic Software | T | |
| RQ-133 | The DS shall make available the gathered diagnostic data through an implemented API. | | Software: Diagnostic Software | T | |
| RQ-134 | The DSI shall ensure soft real-time requirements when using the simulator in Operation State. If, due to the complexity of the simulation, this requirement cannot be met, the operator shall be notified, and the system shall be halted (paused). The halt of the system on “non-real-time” events shall be disabled by the user. With soft real-time is intended that the simulation is computed in the same time sequence of the time in the real world | | Software: Dynamic Simulation Interface | T | |

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| RQ-135 | The DSI shall offer the possibility to include non-real-time simulations during Planning State, where the real-time factor, indicating the ratio between simulation time and real time, is displayed to the operator. | | Software: Dynamic Simulation Interface | T | |
| RQ-136 | The DSI shall be able to run in all session states. | | Software: Dynamic Simulation Interface | T | |
| RQ-137 | The DSI shall be able to accept kinematic and dynamic models (If the model is elastic at the joints and/or links) of the RH equipment described in unified formats. If the model is provided of dynamic model and information regarding the controller dynamics, the DSS could be develop interaction simulation. | | Software: Dynamic Simulation Interface | T | |
| RQ-138 | The DSI shall fetch updated data regarding the robot, the sensors, the VV modules, and the environment from the data server. | | Software: Dynamic Simulation Interface | T | |
| RQ-139 | The DSI shall interface with Visualization Software to display the manipulator's pose and behaviour during the simulation. | | Software: Dynamic Simulation Interface | T | |
| RQ-140 | The DSI shall be able to accept joint commands (position, velocity) from the Motion Planner and the Teleoperation Control to simulate RH Operations. | | Software: Dynamic Simulation Interface | T | |
| RQ-141 | The DSI shall be able to handle simulations involving multiple robots (at least 4). | 4 | Software: Dynamic Simulation Interface | T | Test should be performed with 2 hyrman and 2 CMM. |
| RQ-142 | The DSI shall be able to run robot kinematic and dynamic simulations. | | Software: Dynamic Simulation Interface | T,A | |

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| RQ-143 | The DSI shall support soft real-time simulation of the real system's behaviour and enable a time-aware visualization of data from the simulation. For time-aware visualization is intended that the software shall complete tasks within a reasonable timeframe, emphasizing responsiveness and predictability while mitigating the risk of failure and errors. For the DSI this mean that each time step ts of the simulation shall be calculated in a time t <= ts. | | Software: Dynamic Simulation Interface | T | |
| RQ-144 | The DSI shall enable offline simulation of complex models in a non-real-time mode. In this case the operator shall be informed through the HMI that the simulation is not in real-time. Additional useful data shall also be shown (e.g., the simulation integration time). | | Software: Dynamic Simulation Interface | T | |
| RQ-145 | The DSI shall be able to also accept data from models including flexible behaviour at joints and/or links level. In this way DSI will act as an interface between the model (using the FMU standard) and the visualization module. | | Software: Dynamic Simulation Interface | T | |
| RQ-146 | The DSI shall be able, preferably, to simulate data streams coming from proprioceptive and exteroceptive robot's sensors and additional sensors inside the environment | | Software: Dynamic Simulation Interface | T | |

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| RQ-147 | The DSI shall offer the possibility to add or remove predefined end effectors and update the kinematic chain accordingly and load the new dynamic model. | | Software: Dynamic Simulation Interface | T | |
| RQ-148 | The DSI shall offer the possibility, preferably, to apply external forces and torques (impulsive, constant, or variable) at specific positions on the simulated manipulator | | Software: Dynamic Simulation Interface | T | |
| RQ-149 | The DSI shall allow for straightforward modification of parameters to fine-tune simulation accuracy. | | Software: Dynamic Simulation Interface | T | |
| RQ-150 | The DSI shall allow for straightforward modification of solver parameters, such as simulation timestep, max number of iterations, and solver tolerance. | | Software: Dynamic Simulation Interface | T | |
| RQ-151 | The DSI shall provide the capability to record simulation data, including the robot status, sensor outputs, robot trajectory, and robot interactions. | | Software: Dynamic Simulation Interface | T | |
| RQ-152 | The DSI shall be able to generate, preferably, a comprehensive report about the simulation containing: the simulated robot, the simulated task, time of simulation, faults and log messages, type of inputs, and parameters of the simulation | | Software: Dynamic Simulation Interface | T | |
| RQ-153 | The MP shall communicate on the Operative Network with the robots and the operator's PC | | Software: Dynamic Simulation Interface | I | |

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| RQ-154 | The MP shall have the capability to switch between the Planning state and Operation State, with the ability to send position and velocity commands to the robot to execute the trajectory selected by the operator. | | Software: Dynamic Simulation Interface | T | |
| RQ-155 | The MP shall contain a "Motion executor (ME)" module which is responsible for forwarding the collected information from the industrial PC  to the Operator's PC, on the Real-Time network or on the Operative Network, depending on the data to be transmitted. | | Software: Dynamic Simulation Interface | A | |
| RQ-156 | The ME shall be able to accept the robot state and sensor data as input coming from the industrial PC. | | Software: Dynamic Simulation Interface | T | |
| RQ-157 | The ME shall be able to switch between the Planning state and Operation State. In planning state, the digital twin version of the robot is used to test the trajectories. | | Software: Dynamic Simulation Interface | T | |
| RQ-158 | The ME shall inform the operator when a joint is working near its limits. | | Software: Dynamic Simulation Interface | T | |
| RQ-159 | The ME shall interface with the robot to exchange trajectory-related data, ensuring that the motions sent by the motion planner are synchronized with the manipulator's movement. The ME shall, therefore, have the capability to halt a trajectory in progress through control signals. | | Software: Dynamic Simulation Interface | T | |

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| RQ-160 | The MP shall be able to accept the robot model and adopt the rigid link hypothesis if it aligns with the received model. | | Software: Motion Planner | T | |
| RQ-161 | The MP shall generate trajectories and make them available to other software modules through the API, optimized for visualization in the VR environment. The trajectory description shall include position, velocity, acceleration, torques of joints, and the pose of each link and the end-effector, expressed in Cartesian space as xyz-rpy or quaternions. | | Software: Motion Planner | T | |
| RQ-162 | The MP shall transmit robot commands sent to the industrial PC to the operator's PC over the Operative Network. | | Software: Motion Planner | T | |
| RQ-163 | The MP shall be able to extract obstacle positions and environmental constraints from the 3D model of the environment retrieved from the Data Server. | | Software: Motion Planner | T | |
| RQ-164 | The MP shall provide continuous trajectories in the joint space. | | Software: Motion Planner | T | |
| RQ-165 | The MP shall provide trajectories defined in the Cartesian space that do not exceed actuators' safe limits (e.g., velocities and accelerations) and joint limits. | | Software: Motion Planner | T | |
| RQ-166 | The MP shall provide the operator with the possibility to define trajectories by interpolating a set of user-defined reference frames (TF). | | Software: Motion Planner | T | |

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| RQ-167 | The MP shall provide trajectories that respect limits imposed by the robot, the environment, and any external constraints provided by the manufacturer. | | Software: Motion Planner | T | |
| RQ-168 | The MP shall allow for the modification of trajectory parameters (e.g., velocity, acceleration, time) for the desired trajectory. | | Software: Motion Planner | T | |
| RQ-169 | The MP shall offer the possibility to use different path planning algorithms, with modifiable parameters by the operator. | | Software: Motion Planner | T | |
| RQ-170 | The MP shall accept various types of constraints: position, orientation, visibility, joint, and external constraints. | | Software: Motion Planner | T | |
| RQ-171 | The MP shall be able to find the optimum trajectory to reach any desired user-defined TF, considering environmental and user-defined constraints. | | Software: Motion Planner | T | |
| RQ-172 | The MP shall use the cost function provided by the Collision Management Software during trajectory generation to evaluate possible collision with the environment. | | Software: Motion Planner | A | |
| RQ-173 | The MP shall optimize robot movements to avoid operating the manipulator in singular configurations or near its limits, as well as in configurations defined as critical for the system. | | Software: Motion Planner | T | |
| RQ-174 | The MP shall be capable, preferably, of optimizing the trajectory taking into account the redundancy of the robot. In the | | Software: Motion Planner | T | |

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| | case of robots with micro-macro configurations (comprising two independent serial kinematic chains), the MP must have the ability to optimize the configuration of the basic kinematic chain (macro), considering user-specified constraints related to the micro kinematic chain. During this optimization the MP shall always avoid collisions | | | | |
| RQ-175 | The MP shall offer the possibility, preferably, for redundant chains to reconfigure the internal elements of the chain while keeping the end effector's pose unchanged | | Software:<br>Motion Planner | T | |
| RQ-176 | The MP shall provide a confirmation mechanism before executing any autonomous motion, including the possibility to send trajectories to the visualization software for pre-visualization. | | Software:<br>Motion Planner | T | |
| RQ-177 | The MP shall interface with VR controllers and the visualization software to visualize planning information during immersive operations in virtual reality. | | Software:<br>Motion Planner | T | |
| RQ-178 | The MP shall offer information on the completion percentage of the current trajectory. | | Software:<br>Motion Planner | T | |
| RQ-179 | The TCS shall be able to interface with the ME, enabling the initiation, pausing, and termination of trajectories in both the foreseen Session States | | Software:<br>Teleoperation Control | T | |

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| RQ-180 | The TCS shall be able to communicate on the Real-Time Network, ensuring Hard Real-Time communication between the robots and the master station operator's PC. | | Software: Teleoperation Control | I,A | |
| RQ-181 | The TCS shall provide the possibility to switch between the Planning state and Operation State. | | Software: Teleoperation Control | T | |
| RQ-182 | The TCS shall oversee the teleoperation for all robots, ensuring that a single robot is teleoperated exclusively by one operator and facilitating the transfer of control between operators through a confirmation by the Supervisor. | | Software: Teleoperation Control | T | |
| RQ-183 | The TCS shall be able to interface with the industrial PC to send control signals, which can be commands in terms of position and velocity. | | Software: Teleoperation Control | T | |
| RQ-184 | The TCS shall ensure that the use of HID generates the same command inputs in both simulation and on real manipulators (e.g., scale factors, key binds, motion axis). | | Software: Teleoperation Control | T | |
| RQ-185 | The TCS shall be able to accept kinematic and dynamic model of the RH equipment described in unified formats. | | Software: Teleoperation Control | T | |
| RQ-186 | The TCS shall allow for the selection of only a sub-section of the kinematic chain of the manipulator while keeping the remaining parts stationary in the Cartesian space. | | Software: Teleoperation Control | T | |
| RQ-187 | The TCS shall foresee a Shared Control Mode (SCM) to assist RH operations. | | Software: Teleoperation Control | T | |

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| RQ-188 | The SCM shall provide, preferably, the capability to create custom virtual constraints for the operator defined as specific external wrenches (force-torque) on the master device. The implementation of specific virtual constraint strategies is out of scope of this tender | | Software:<br>Teleoperation Control | | |
| RQ-189 | The CMS shall be able to communicate on the Operative Network. | | Software:<br>Collision Management | I | |
| RQ-190 | The CMS shall be able to work in both Planning State and Operation State. | | Software:<br>Collision Management | T | |
| RQ-191 | The CMS shall be able to accept the kinematic and dynamic model of the remote handling equipment described in unified formats. | | Software:<br>Collision Management | T | |
| RQ-192 | The CMS must possess the capability to perform collision detection for the manipulator's links in relation to both the environment and other manipulators. | | Software:<br>Collision Management | T | |
| RQ-193 | The CMS shall be capable, preferably, of executing collision detection, encompassing, if the rigid-model hypothesis is not valid, at least the flexible behaviour of the manipulator at the joint level | | Software:<br>Collision Management | T | |
| RQ-194 | The CMS shall be able to accept different types of objects, including meshes, 3D models, primitive shapes, and Octomap, with a minimum resolution of 2^16 (65536) nodes or 65535 triangles per represented object, and update the pose of each object | | Software:<br>Collision Management | T | |

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| | based on data provided by the mock-up area. | | | | |
| RQ-195 | The CMS shall be able to import model of the robots and the environment and extract necessaries information to run collision management. | | Software: Collision Management | T | |
| RQ-196 | The CMS shall allow the operator to choose, for each object in the scene, the level of accuracy with which the meshes and colliders shall replicate the geometric characteristics of the objects. The required level of accuracy will depend on the minimum dimensions of the components that can potentially collide with the environment and robots. | | Software: Collision Management | T | |
| RQ-197 | The CMS shall foresee a final topology of the 3D model compatible with the graphic and physical engine offered by the Visualization Software | | Software: Collision Management | T | |
| RQ-198 | The CMS shall interface with the Motion Planner, providing a cost function to evaluate possible collision between the robot and the environment during planning. | | Software: Collision Management | A | |
| RQ-199 | The CMS shall be able to retrieve robot state from the Operative Network, both in the Planning State and Operative State, to update the cost function. | | Software: Collision Management | T | |
| RQ-200 | The CMS shall ensure that movements inside the environment can be executed without unexpected collision. | | Software: Collision Management | T | |

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| RQ-201 | The CMS shall be able to evaluate collisions between object under a minimum distance determined from the foreseen operation inside the environment. | | Software:<br>Collision Management | T | |
| RQ-202 | The CMS shall check for self-collisions and collisions with the environment using the robot model, the robot state, and information from additional sensors. | | Software:<br>Collision Management | T | |
| RQ-203 | The CMS shall offer, preferably, a cost function that can take into account any flexible components declared by the manufacturer | | Software:<br>Collision Management | T | |
| RQ-204 | The CMS could implement an algorithm for collision detection to identify collisions that can be reported by sensors on the robotic arm. | | Software:<br>Collision Management | T | |
| RQ-205 | The CMS shall trigger the Diagnostic Software to switch the controller into SAFE mode in case of any undesired collision detected. | | Software:<br>Collision Management | T | |
| RQ-206 | The OMS shall provide a State Machine (SM) to enable proper task planning, handle state transition conditions, and supervise transitions across different operational modes. | | Software:<br>Operation Management Software | A | |
| RQ-207 | The SM shall communicate on the Operative Network. | | Software:<br>Operation Management Software | I | |
| RQ-208 | The SM shall be the same for both Planning and Operation States | | Software:<br>Operation Management Software | A | |

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| RQ-209 | The SM shall be designed to accommodate a division into two states for robot control: the "approach state" and the "telemanipulation state," each serving distinct control requirements. The first state is employed for trajectory planning toward a target, utilizing the motion planning module, and is utilized for approaching the target. The second state is used for direct teleoperation of the target in either full teleoperation or shared mode. | | Software: Operation Management Software | A | |
| RQ-210 | The SM shall interface with other modules to ensure time synchronization within the network. | | Software: Operation Management Software | A | |
| RQ-211 | The OMS shall describe tasks unambiguously. | | Software: Operation Management Software | A | |
| RQ-212 | The OMS shall describe tasks using a Structured Language (SL) where each operation step has the format: [Subject] - [Action] - [ActionObject] - [QualifierObject], allowing precise and structured task descriptions. | | Software: Operation Management Software | A | |
| RQ-213 | The SL shall support mathematical operations (<, >, =), conditional statements (IF-ELSE), repetitive statements (WHILE/FOR LOOPS), and event statements (WAIT UNTIL). | | Software: Operation Management Software | A | |
| RQ-214 | The OMS shall store SL data objects in a database implemented on the data server. | | Software: Operation Management Software | I | |

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| RQ-215 | The OMS shall include graphical interfaces for operation planning, execution, and analysis. This graphical interface can be integrated within the Human-Machine Interface (HMI) module or be a separate executable. | | Software: Operation Management Software | A | |
| RQ-216 | The OMS shall enable detailed planning and scheduling of RH operations. | | Software: Operation Management Software | A | |
| RQ-217 | The OMS shall allow users to create, delete, and modify procedures and tasks, with authorization from the Supervisor. | | Software: Operation Management Software | T | |
| RQ-218 | The OMS shall provide the possibility to define a task as a sequence of saved procedures or as a sequence of user-defined trajectories, with Supervisor authorization. | | Software: Operation Management Software | T | |
| RQ-219 | The OMS shall allow the verification of task procedures, including the consistency of multiple concatenated procedures or trajectories using the simulation module. | | Software: Operation Management Software | T | |
| RQ-220 | The OMS shall monitor that RH operations adhere to stored procedures. | | Software: Operation Management Software | T | |
| RQ-221 | The OMS shall keep track of RH operations, highlighting the current action. | | Software: Operation Management Software | T | |
| RQ-222 | The OMS shall verify that the conditions for starting procedure and task execution are met. | | Software: Operation Management Software | T | |
| RQ-223 | The OMS shall support the development of different parts of procedures by multiple users simultaneously. | | Software: Operation Management Software | T | |

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| RQ-224 | The OMS shall have the capability to send structured tasks, including pre-planned and approved RH operations, either to the real robot or to the robot simulation without the necessity of routing through the Motion Planner. | | Software: Operation Management Software | T | |
| RQ-225 | The OMS shall interface with the industrial PC to receive, save and execution of robotic jobs. | | Software: Operation Management Software | T | |
| RQ-226 | The OMS shall interface with the industrial PC to start, abort, and pause the execution of a robotic job. | | Software: Operation Management Software | T | |
| RQ-227 | The OMS shall allow to send a sequence of user-defined coordinate frames to the be reinterpreted as robotic job | | Software: Operation Management Software | T | |
| RQ-228 | The OMS shall provide a Fault Reporting Interface (FRI) dedicated to signalling, reporting, and describing any faults, problems, or difficulties experienced by users during RH operations. This module is associated to the OMS to synchronize the fault or report to the specific task. | | Software: Operation Management Software | T | |
| RQ-229 | The FRI shall offer a detailed fault description, allowing users to include any relevant data retrieved during task operations. | | Software: Operation Management Software | T | |
| RQ-230 | The FRI shall provide documentation to address expected problems. | | Software: Operation Management Software | I | |
| RQ-231 | The FRI shall categorize reports as OPEN and ARCHIVED, with OPEN reports requiring | | Software: Operation Management Software | A,T | |

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| | investigation and ARCHIVED reports indicating resolved issues. | | | | |
| RQ-232 | The A&A shall manage all authentication and authorization mechanisms for the network. | | Software: Authorization & Authentication Software | A | |
| RQ-233 | The A&A shall develop cybersecurity mechanisms to protect against unauthorized access. | | Software: Authorization & Authentication Software | T | |
| RQ-234 | The A&A shall implement a hierarchical authorization structure, with the Supervisor having the highest level of privileges, granting access to all functionalities, while lower-level users have restricted access. By default, lower-level users shall be restricted from modifying task scheduling, managing authentication and authorization, altering interconnection settings, manipulating manipulators' movements, and changing operational settings without the presence and approval of an authorized supervisor. | | Software: Authorization & Authentication Software | A | |
| RQ-235 | The A&A shall provide the Supervisor with the ability to add, modify, and delete different types of users. | | Software: Authorization & Authentication Software | T | |
| RQ-236 | The A&A shall allow the Supervisor to manage access authorization for defined user types. | | Software: Authorization & Authentication Software | T | |
| RQ-237 | The A&A shall provide each user with a clear and detailed list of operations and privileges they possess. | | Software: Authorization & Authentication Software | I | |

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| RQ-238 | The A&A shall provide the Supervisor with the ability to add and delete users from the authentication system. | | Software: Authorization & Authentication Software | T | |
| RQ-239 | The safety of hardware and software systems must be ensured by adhering to the standards of ISO 27001. | | Software: Authorization & Authentication Software | A | |
| RQ-240 | The VS shall include accessibility options that allow users to modify settings such as language, text dimension, and more to suit their preferences and needs. | | Software: Visualization Software | T | |
| RQ-241 | The VS shall offer, preferably, adjustable lighting or shading options for specific panels and windows in order to enhance the visual quality of the representation | | Visualization Software | T | |
| RQ-242 | The VS shall establish communication with a data server and allow the user to load model and manually update the 3d world environment. | | Visualization Software | T | |
| RQ-243 | The VS shall establish communication with a data server and allow the user to load model and manually update the 3d world environment | | Software: Visualization Software | T | |
| RQ-244 | The VS shall, preferably, synchronize the model library with the data server once every workday, as the VS is turned on | | Software: Visualization Software | T | |
| RQ-245 | The VS shall, preferably, provide the possibility to force a synchronization with the data server | | Software: Visualization Software | T | |

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| RQ-246 | The VS shall, preferably, provide information on the last synchronization, such as date, number, and name of changed files | | Software: Visualization Software | T | |
| RQ-247 | The VS shall be compatible with at least the chosen VR headset, preferably with the most common VR headset, ideally with any VR headset. | | Software: Visualization Software | T | |
| RQ-248 | The VS shall evaluate the option of using commercially established 3D visualization and simulation environments within the robotics sector, such as Unity or Unreal. The VS shall also consider the use of VTK. | | Software: Visualization Software | A | |
| RQ-249 | The VS shall incorporate soft real-time rendering of the environment and the robots, guaranteeing reliable and up-to-date visualization. Achieving soft real-time implementation involves providing a reliable system visualization at a minimum and constant update frequency (suggested minimum is 30 Hz). This ensures that the operator has a fluid and responsive visual representation of both the environment and the robot manipulator during the task execution. | 30 Hz | Software: Visualization Software | T | |
| RQ-250 | The VS shall deliver good graphical performance with all S/S's 3D models (suggested minimum refresh rate is 30Hz). | 30Hz | Software: Visualization Software | T | |

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| RQ-251 | The VS shall incorporate a digital twin of both the robot manipulators and the environment. This digital twin shall be created using the 3D model of the robot provided by the manufacturing company. The robot model shall accurately replicate the robot's geometries at a 1:1 scale, enabling precise remote handling operations that rely solely on the digital twin. | | Software: Visualization Software | T | |
| RQ-252 | The VS module shall ensure that each 3D model of manipulators and objects located within the VV (Vacuum Vessel) is described using meshes with a minimum of 2^16 (65536) nodes to ensure a high degree of detail and precision during simulations. | 65536 nodes | Software: Visualization Software | A,T | |
| RQ-253 | The VS module shall also provide simplified CAD starting from the CAD library models. These simplified models shall have all the necessary features for correct and precise visualization but be light enough to enable real-time/time-aware features. | | Software: Visualization Software | T | |
| RQ-254 | The VS shall implement a digital twin that replicates the movements of the S/Ss inside the mock-up. The digital twin will rely on data from sensors and the kinematic/dynamic models provided along with the S/Ss. Latency shall be minimized in order to provide good performances in terms of easiness of teleportation and | 30ms | Software: Visualization Software | T | |

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| | precision. A maximum latency of 30ms is suggested. | | | | |
| RQ-255 | The VS shall provide a visually clear and intuitive representation of the robot's and other components movement before task execution, including an accurate depiction of its planned path | | Software: Visualization Software | T | |
| RQ-256 | The VS shall integrate with the collision module to correctly simulate collision physics. | | Software: Visualization Software | T | |
| RQ-257 | The VS shall use Vulkan-based graphic rendering software for all 2D and 3D rendering operations. The implementation of Vulkan must be compatible with the target hardware and fully leverage the capabilities of the graphics cards to ensure optimal performance. The use of Vulkan should facilitate efficient management of graphic resources and low latency, thus contributing to the provision of an advanced and highly performing graphic rendering platform for the VS system | | Software: Visualization Software | A | |
| RQ-258 | The VS shall offer a faithful 3D representation of the environment and the manipulators. It shall guarantee precise spatial understanding of the environment and robot manipulators. This includes maintaining accurate proportions, | | Software: Visualization Software | A | |

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| | distances, and angles to create a faithful representation of the real-world scenario. | | | | |
| RQ-259 | The VS shall implement transparent object rendering to improve visibility and understanding within the visualization. | | Software: Visualization Software | T | |
| RQ-260 | The VS shall provide options to customize the visualization of robot components such as joints, links, frames, and other relevant parts. | | Software: Visualization Software | T | |
| RQ-261 | The VS shall achieve realistic rendering of any sensor data foreseen for the Mock-up area, encompassing available sensors such as cameras, lidar point clouds, and depth maps. | | Software: Visualization Software | T | |
| RQ-262 | The VS shall give the possibility to modify the 3D world environment only to authorized personnel. | | Software: Visualization Software | T | |
| RQ-263 | The VS shall offer access to 3D models from the model library in order to modify the 3D environment. | | Software: Visualization Software | T | |
| RQ-264 | The VS shall provide an API for the HMI software to modify settings of the virtual camera. | | Software: Visualization Software | T | |
| RQ-265 | The VS shall provide the possibility to create and delete virtual cameras, giving operators the possibility to have different points of view streaming simultaneously. | | Software: Visualization Software | T | |

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| RQ-266 | The VS shall provide each operator with access to any virtual camera view, enabling operators to have a custom layout of views independent from each other. | | Software: Visualization Software | T | |
| RQ-267 | The VS shall provide controls to manipulate the viewpoint and virtual camera angle. | | Software: Visualization Software | T | |
| RQ-268 | The VS shall provide the possibility to switch between different virtual camera views and perspectives, previously created by the operator and saved. | | Software: Visualization Software | T | |
| RQ-269 | The VS shall offer the possibility to capture screenshots, record videos, and export custom layouts of operator windows for documentation or sharing purposes. | | Software: Visualization Software | T | |
| RQ-270 | The VS software shall provide a Virtual Reality Software (VRS) to manage the interaction between operators and machines inside the Virtual Reality (VR) environment. | | Software: Visualization Software | A | |
| RQ-271 | The VRS shall provide soft real-time visualization of the 3D environment and of the digital twins. | | Software: Visualization Software | A | |
| RQ-272 | The VRS shall support the simultaneous display of multiple views, both from virtual and real cameras, arranged in a grid layout around the main view. This layout shall enable operators to gain a comprehensive understanding of the scenario from various angles. | | Software: Visualization Software | T | |

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| RQ-273 | The VRS shall grant operators the ability to select which camera streams (virtual or real) to display and where to position them within the grid layout. | | Software: Visualization Software | T | |
| RQ-274 | The VRS shall provide the operator with access to all the task's information available to the other operator's PC for better situational awareness. | | Software: Visualization Software | T | |
| RQ-275 | The VRS shall be able to visualize the desired task information in windows and panels that can be arranged in a grid layout around the main view. The VS shall provide the operators with the possibility to create, delete, and move the panel inside the layout. | | Software: Visualization Software | T | |
| RQ-276 | The VRS shall foresee panel and layout of predefined size and ratio to visualize data and camera streams. The VS shall allow the operator to change the size of any panel choosing between the predefined ones. | | Software: Visualization Software | I | |
| RQ-277 | The VRS shall offer the possibility to create, save, and load custom layouts of camera views, windows, and panels. | | Software: Visualization Software | T | |
| RQ-278 | The VRS shall offer the possibility to visualize plots of data streams. | | Software: Visualization Software | T | |
| RQ-279 | The VRS shall offer a visually clear and intuitive representation of the robot's movement before task execution. This allows for the evaluation of the trajectory | | Software: Visualization Software | T | |

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| | and the identification of potential conflicts with environmental constraints. | | | | |
| RQ-280 | The VRS shall implement trajectory preview (eg. as a semi-transparent replay of the manipulator performing the trajectory in a continuous loop). It shall also allow the operator to control the preview by adjusting the playback speed, pausing, or slowing it down. The playback could be initiated and controlled by continuous trigger pressure on the HID controllers. This functionality enables the operator to thoroughly examine the trajectory and precision movements from various perspectives. | | Software: Visualization Software | T | |
| RQ-281 | The VRS shall offer the possibility to visualize the actual joint state through clearly visible text near each joint. | | Software: Visualization Software | T | |
| RQ-282 | The VRS shall offer the possibility to visualize the estimation of distances between robot's components and VV objects. The VRS could provide the option to select desired points on the manipulator and the VV component for which to visualize the distance estimation. The VRS could visualize the information through clearly visible text and a line connecting the referenced points. | | Software: Visualization Software | T | |

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| RQ-283 | The VRS shall implement interactive controls that enable manipulation of the viewpoint and camera angles. | | Software: Visualization Software | T | |

# DTT RH FACILITY Control Room Interface Control Document

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# DTT RH FACILITY
# Control Room
# Interface Control Document

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# Index

# 1 Acronyms and definitions

## 1.1 Acronyms

| | |
|---|---|
| CoM | Center of Mass |
| DIV | Divertor |
| DTT | Divertor Tokamak Test |
| FTS | Force Torque sensor |
| FW | First Wall |
| HLCS | High-level Control System |
| HMI | Human Machine Interface |
| IFW | Inboard First Wall |
| IFWL | Inboard First Wall Lifter |
| IS | Interface Sheet |
| LLCS | Low-level Control System |
| OFW | Outboard First Wall |
| OSS | Occupational Safety System |
| PBS | Product Breakdown Structure |
| PID | Plant Integration Document |
| RH | Remote Handling |
| RHTF | Remote Handling Training Facility |
| TEM | Tool Exchange Mechanism |
| TFW | Top First Wall |
| TR | Technical Requirement |
| TS | Technical Specification |
| VV | Vacuum Vessel |
| WBS | Work Breakdown Structure |

## 1.2 Definitions

| | |
|---|---|
| Plasma-facing components | Tokamak components which directly interact with the plasma and are subject to high heat fluxes. |
| Tokamak | Toroidal shaped machine in which a hot and rarefied gas (usually of hydrogen and its isotopes, in the plasma state) is confined far enough from the internal walls thanks to a magnetic field created by electromagnets |

## 1.3 Applicable Documents

[AD1] "Hyrman to High Level Control System Interface Sheet", ICD Annex n. HYR-IS-004

[AD2] "CMM to High Level Control System Interface Sheet", ICD Annex n. CMM -IS-002

RHCR-REF-000: [CR_0] Control Room Technical Specification
RHCR-REF-001: [CR_1] Control Room Technical Requirements
RHCR-REF-002: [CR_2] Control Room Technical and Economical relation
RHCR-REF-003: [CR_3] Interface Control Document
RHCR-REF-004: [CR_4] ControlRoom-IS-001-Power
RHCR-REF-005: [CR_5] ControlRoom-IS-002-Internet
RHCR-REF-006: [CR_6] ControlRoom-IS-003-HYRMAN
RHCR-REF-007: [CR_7] ControlRoom-IS-004-CMM
RHCR-REF-008: [CR_8] Management and Quality Specification

## 2 Introduction

DTT is one of the largest superconducting tokamak under construction with the mission to get scientific and technological proofs of power exhaust in prospect of the first nuclear fusion power plant. The two major objectives of the DTT are:

- Testing alternative divertor cassette solutions.
- Improvement of the experimental knowledge in the scientific area of heat discharge for parameter ranges that cannot be addressed by current devices.

The DTT Remote Handling (DTT RH) plays a crucial role in the successful realization of the project. For testing and validation of the DTT RH, a special facility called DTT Training and Test Facility (DTT TTF) is in the pipeline to be developed. DTT TTF has the major objectives of:

- Testing and validation of the RH procedures and equipment design, verifying the correct integration between robots and surrounding environment.
- Training the Human Operators (HOs) to control the RH equipment and perform the RH procedures.
- Validation of proof of concept for design solutions and control algorithms and acceptance test for new RH procedures, equipment and tooling that may be developed during the lifetime of DTT: the TTF shall also offer a collaborative platform for testing and validating several alternatives for new RH equipment and its control algorithms, having the possibility to verify their compatibility with the entire machine.

DTT TTF will contain the following robotic systems:

- The Hyper Redundant MANipulator (HRYMAN).
- The Inboard First Wall (IFW) Lifting S/S.
- The Divertor Handling (DH) S/S.

An essential system of the DTT TTF is the control room, which is responsible for the management, coordination and high-level control of all the robotic systems.

The purpose of this document is to define the interface information between the Control Room and the other subsystems (S/S). This document is intended to be used for the design & installation of the systems.

In this document, an interface is defined as *"a common boundary or co-function between two items which must interact and fit each other to meet a given requirement or to satisfy a constraint"*

## 3 Interfaces overview

The Control Room is conceived to perform RH operations. The interfaces between the Control Room and the external Substations (S/S) are composed of:

1. The interfaces with the Remote handling equipment, which include:
    a. HYRMAN S/S
    b. CMM S/S
2. The interfaces with the site utilities, which include:
    a. Power supply system

b. Internet supply system

3. The interfaces with the software of the Remote handling equipment
4. The interfaces with the civil work
5. The (suggested) interface with the mock-up area, in terms of the availability of a motion capture system which is a desirable system to have.

For the main identified interface (1 and 2), a dedicated Interface Sheet (IS) is provided in the Annex, with the purpose of defining the interfaces data to be used for the design of the interfacing systems.

# 4 Interfaces with remote handling equipment

The Control Room serves the role of HLCS for the control of robotic system and includes a component, known as the "External Interface", through which it connects to the external S/S within the mock-up area. The "External interface" is intended as a panel with all plugs required to connect the HLCS to the external S/S. This means that the systems within the control room interface with the systems in the mock-up area through this component referred to as "External interface".

The primary development philosophy of the control room is to make it highly adaptable and capable of accommodating various external S/S. Within the control room, there are the following five networks:

- The **Real-Time Network**: handles the transmission of command signals and sensors signals with real-time requirements.
- The **Operative Network**: handles the transferring non-critical information, including control set points, telemetry, and eventually video signals from external sources.
- The **Local Data Network**: handles the transferring diagnostic information and facilitating file and data transfer to and from the data server.
- The **Visualization Network**: designed to transmit video streams originating from the visualization server inside the Control Room. This network can serve as an alternative for video transmission, mitigating the risk of congestion on the Operative Network.
- The **Safety Network**: this setwork is composed of an digitalhardwired network used for sending stop signals to the motors plus a dedicated safety network to send more structured safety data streams. It interfaces with the internal digital systems of the control room through a safety PLC.

## 4.1 Interfaces with HYRMAN

The interface with Hyrman will utilize the following three networks routed to the HLCS as described follows:

1. **The Real-Time network:** is used to transmit primarily force information from the robot force sensors to be utilized for haptic. Moreover, the real-time network can be used to transmit high-frequency or hard real-time set points for the manipulator to implement advanced control algorithms.
2. **The Operative network:** is used for all data which can be considered at low frequency and not real-time. This includes robot set points, diagnostics, and video. video information can be routed to the internal **visualization network** to avoid congestions on the operative network whether the number of video streams inside the S/S increases.
3. **The Safety Network:** is used to manage all safety aspects related to the robot. It interfaces directly with the digital hardwired network and with the real-time safety network of the HLCS

This interface includes the following aspects:

1) Command function, from HLCS to HYRMAN controller
2) Telemetry function, from HYRMAN Controller to HLCS
3) Handshake protocol for Commands and Telemetries functions
4) Hardware network connection to HLCS functions
5) Safety commands from HLCS functions

These points are described in detail in the Interface Sheet [RHCR-REF-006]

### 4.2 Interfaces with CMM

The interface with CMM will utilize the following three networks routed to the HLCS as described follows:

1. **The Real-Time network:** is used to transmit primarily force information from the robot force sensors to be utilized for haptic. Moreover, the real-time network can be used to transmit high-frequency or hard real-time set points for the manipulator to implement advanced control algorithms.
2. **The Operative network:** is used for all data which can be considered at low frequency and not real-time. This includes robot set points, diagnostics, and video. video information can be routed to the internal **visualization network** to avoid congestions on the operative network whether the number of video streams inside the S/S increases.
3. **The Safety Network:** is used to manage all safety aspects related to the robot. It interfaces directly with the digital hardwired network and with the real-time safety network of the HLCS

This interface includes the following aspects:

1) Command function, from HLCS to CMM controller
2) Telemetry function, from CMM Controller to HLCS
3) Handshake protocol for Commands and Telemetries functions
4) Hardware network connection to HLCS functions
5) Safety commands from HLCS functions

These points are described in detail in the Interface Sheet [RHCR-REF-007]

### 4.3 Data Routing

The transmitted data packets must be routed as follows:

- Robot telemetry data shall be sent to the Operative Network.
- Video signals from cameras shall have the flexibility to be routed either to the Operative Network or to the Video Network
- Data stream with real-time requirements shall be sent to the Real-Time network.

## 5 Interfaces with site utilities

### 5.1 Interfaces with Power supply System

This interface includes the following aspects:

1) Minimum Power to be provided to major components inside the Control Room

These points are described in detail in the Interface Sheet [RHCR-REF-004]

### 5.2 Interfaces with Internet Supply System

This interface includes the following aspects:

1) Internet connection provided to the router inside the Control Room

These points are described in detail in the Interface Sheet [RHCR-REF-005]

# 6 Interfaces with the software of the remote handling equipment

The control room must be independent of the specifics of the robotic systems it needs to manage and, therefore, must be easily interfaced with any possible robotic system in the mock-up. Therefore, it is the responsibility of the manufacturer of each robot to provide a comprehensive and detailed kinematic and dynamic description of the robot. Standard robot representation, such as URDF, can be suitable if the system's flexibility remains below a predefined threshold, which doesn't interfere with RH operations. However, when this threshold is surpassed, the framework of the control room shall be designed to accommodate data related to the robot's state and engage with the robot model through more refined models, such as FMUs or equivalent model descriptions. In such cases, the models must be accurate and realistic, going beyond rigid approximations, for instance, by incorporating sensor data fusion to enhance their precision. In this case, the realistic robot model should provide as output the robot state in a univocal and clear manner, and it should be robot specific.

# 7 Interfaces with civil works

The interfaces with the civil works are divided in three main areas:

1. Wiring (Section 8.1)
2. Safety (Section 8.2)
3. Ventilation (Section 8.3)

## 7.1 Wiring

[INT-RQ-01] The industrial cabinets for the Low-level control shall be placed in the proximity of the robot. This limits the number and length of wires from the mock-up area to the Control Room.

[INT-RQ-02] To connect devices for real-time communication, Ethernet connections with cables and connectors rated at a minimum of category 5 (Cat5) shall be used, following the standards EN 50173 or ISO/IEC 11801.

[INT-RQ-03] All cables used with real time protocol must not exceed 100m. This results from the FastEthernet technology, which, above all for reasons of signal attenuation over the length of the cable, allows a maximum link length of 5 + 90 + 5 m if cables with appropriate properties are used. Specifically, these cables shall cover a maximum distance of 90 meters from the industrial PCs to the control room, allowing for a 10-meter allowance for internal cabling.

[INT-RQ-04] Cable routes shall be made in accordance with IEC 60092 and CEI 11/17 standards. For instance, cables shall maintain a minimum bending radius greater than 10 times the cable diameter.

[INT-RQ-05] Cable routes shall include cable trays to ensure the safety of operators and the preservation of cables.

[INT-RQ-06] All cable trays shall always be accessible for inspections and maintenance.

[INT-RQ-07] Inside the control room work area (Area A), there shall be a minimum of 8 Ethernet outlets connecting the control room elements to the router in the server room. Additionally, there shall be at least 15 electrical outlets, correctly placed considering operators desk position.

[INT-RQ-08] To manage the wiring of the safety network between control room and the robots, one hardwired cable with 6 poles for each robot must be routed from the control room to each robot cabinet (4 cables in total). This cable must be used to connetct directly the safety PLC and devices in the control room to the safety input of each robot allowing the emergency stop and enable signal.

**Suggestions:**

[INT-SG-01] Data transfer cables shall follow the shortest path from the industrial PCs to the control room, when possible.

[INT-SG-02] All wiring, including power and data cables, shall be color-coded and labelled clearly for easy identification and troubleshooting.

[INT-SG-03] Cable management systems, such as cable conduits and cable ties, shall be installed to keep the wiring organized and to prevent tripping hazards.

[INT-SG-04] Cable trays and conduits shall be designed to prevent excessive cable bundling, which can cause overheating and signal degradation.

[INT-SG-05] All cable routes shall be documented with clear, up-to-date diagrams, indicating cable types, connections, and routing pathways.

## 7.2 Ventilation

[INT-RQ-09] The control room shall be equipped with an air conditioning system that allows operators to work with a comfortable temperature.

[INT-RQ-10] The server room shall have a ventilation system in place to maintain the servers within an optimal temperature range between 19 – 21°. Moreover, the humidity level shall be between 40 – 60%.

**Suggestions:**

[INT-SG-06] In environments where dust or airborne particles are prevalent, the control room's ventilation system shall include high-efficiency particulate air (HEPA) filters to maintain clean and dust-free air quality.

## 7.3 Safety

[INT-RQ-11] The control room shall include safety visual and audio devices such as emergency lights, alarms. Additionally, it shall have an emergency lighting system with three states that indicate the normal functioning of the robots inside the mock-up area, the fault status, and the maintenance status.

[INT-RQ-12] The control room shall be equipped with fire safety devices, including fire extinguishers, and appropriate signals.

[INT-RQ-13] Civil works shall ensure the proper functioning of the sanitary facilities located within the control room.

[INT-RQ-14] Civil works shall ensure panic doors in compliance with local regulations regarding workplace safety standards.

[INT-RQ-15] The control room shall be equipped with safety signage and clear markings to indicate emergency exits, fire extinguisher locations, first aid stations, and other safety resources.

[INT-RQ-16] Adequate ergonomic seating and workstations shall be provided to ensure the comfort and well-being of control room operators during long shifts.

# 8 Suggested interfaces with mock-up area

The presence of a motion capture system (optical cameras to track the 3D motion of passive markers) is suggested in the mock-up area of the TTF, to be used for multiple purposes, and in particular for the control room. Despite the absence of a motion capture system in the real VV of the DTT, the motion capture system could be useful in the TTF to:

1. Validate task procedures performed inside the VV.
2. Evaluate displacement of the robotic system during motion
3. Evaluate module displacement caused by remote handling operations.

The motion capture system should be fixed in the training facility space and calibrated. It is suggested to fix it to the mock-up. The number of motion capture cameras and their positions should be studied in such a way to:

- Ensure precise measures of all the module poses inside the VV.
- Guarantee the availability of measures during remote handling operations without obstruction by the manipulator itself or from VV components.

The motion capture system should be interfaced with the visualization server on the Video Network, using suitable software. One widely used solution for motion capture is Vicon and can be used as a reference.

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# Control Room to Power Supply Interface Sheet

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# Index



# Applicable Documents

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RHCR-REF-003: [CR_3] Interface Control Document
RHCR-REF-004: [CR_4] ControlRoom-IS-001-Power
RHCR-REF-005: [CR_5] ControlRoom-IS-002-Internet
RHCR-REF-006: [CR_6] ControlRoom-IS-003-HYRMAN
RHCR-REF-007: [CR_7] ControlRoom-IS-004-CMM
RHCR-REF-008: [CR_8] Management and Quality Specification

# 1 Scope

The scope of this document is to identify the interface points between:

- **Control Room system**

  and

- **DTT Remote Handling Facility**

in terms of:

  - Power supply for each component inside the Control Room

# 2 Interfaces requirement data

## 2.1 Description of the interface points

The Control Room components receive power from the electrical substation located within the control room. The following section identifies the minimum power characteristics for each component of the Control Room. Nevertheless, is good practice to expect other electrical loads not considered further.

In this document are described the general interfaces between components. The number of components should be retrieved from the document in Annex.

## 2.2 Identification of the Control Room Components / Facility Site- Power Supply

| | **Control Room Components** | **Facility Site - Power Supply** |
|---|---|---|
| **IP n.** | **IP designation** | **IP designation** |
| IP1 | Operator's PC | Facility Power supply |
| IP2 | Server | Facility Power supply |
| IP3 | Switch | Facility Power supply |
| IP4 | Monitor | Facility Power supply |
| IP5 | Manipulator Master Station | Facility Power supply |
| IP6 | VR Headset | Facility Power supply |

Table 1 - List of the functional interfaces between Control Room Components and Facility for power supply

### 2.2.1 IP1 - Operator's PC

Each Operator's PC requires as a minimum the following electrical supply and characteristics:

1) Power consumption at max operative conditions: 650 W

Moreover, it is required that the power supply for the Supervisor’s PC shall be under UPS providing the max power for at least 30 minutes. The UPS will be part of the HLCS furniture.

### 2.2.2 IP2 - Server

Each server inside the Control Room requires as a minimum the following electrical supply and characteristics:

1) Power consumption at max operative conditions: 1000 W

Moreover, it is required that the power supply for each server shall be under UPS providing the max power for at least 30 minutes.

### 2.2.3 IP3- Switch

Each switch inside the Control Room requires as a minimum the following electrical supply and characteristics for each switch:

1) Power consumption at max operative conditions: 250W

Moreover, it is required that the power supply for 2 switches (Operation and Local Data Network) shall be under UPS providing the max power for at least 30 minutes.

### 2.2.4 IP4- Monitor

Each monitor inside the Control Room requires as a minimum the following electrical supply and characteristics:

1) Power consumption equivalent to European Energy class G

This includes all desk pc monitor, wall tv and other display defined in [RHCR-REF-001].

### 2.2.5 IP5 – Manipulator Master Station

The Manipulator Master Station inside the Control Room requires as a minimum the following electrical supply and characteristics:

1) Supply voltage: 1400W

### 2.2.6 IP6 – VR Headset

Each VR Headset inside the Control Room requires as a minimum the following electrical supply and characteristics:

1) Power consumption at max operative conditions: 20W

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| **Authors & Contributors** | Grazioso S., Fontanelli G.A., Fimiani A., Sofia A. | |
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| **Abstract** | *This Interface Sheet defines the interface data of a specific interface between the Control Room and the Internet Supply system of the DTT RH facility.* | |

# Index



## *Applicable Documents*

RHCR-REF-000: [CR_0] Control Room Technical Specification
RHCR-REF-001: [CR_1] Control Room Technical Requirements
RHCR-REF-002: [CR_2] Control Room Technical and Economical relation
RHCR-REF-003: [CR_3] Interface Control Document
RHCR-REF-004: [CR_4] ControlRoom-IS-001-Power
RHCR-REF-005: [CR_5] ControlRoom-IS-002-Internet
RHCR-REF-006: [CR_6] ControlRoom-IS-003-HYRMAN
RHCR-REF-007: [CR_7] ControlRoom-IS-004-CMM
RHCR-REF-008: [CR_8] Management and Quality Specification

# 1 Scope

The scope of this document is to identify the interface points between:

- **Control Room system**

  and

- **DTT Remote Handling Facility**

in terms of:

  - Internet Supply for components inside the Control Room

# 2 Interfaces requirement data

## 2.1 Description of the interface points

The Control Room components receive Internet from attachments provided inside the Control Room. The following section identifies the characteristics for the Internet connection of the Control Room.

## 2.2 Identification of the Control Room Components / Facility Site- Internet Supply

| | **Control Room Components** | **Facility Site - Internet Supply** |
|---|---|---|
| **IP n.** | **IP designation** | **IP designation** |
| IP1 | Router | Internet Supply System |

Table 1 - List of the functional interfaces between Control Room Components and Facility for internet supply

## 2.3 IS requirements

In this section the requirements for the IS are detaleid.

The requirement of the internet connection must be calculated starting from the following assumption:

- Each operator PC must have a minimum bandwidth of 10Mbps in download with a latency of a maximum 50ms
- Each operator PC must have a minimum bandwidth of 10Mbps in upload of a latency of a maximum of 50ms
- The Data server must have a minimum bandwidth of 10Mbps in download with a latency of a maximum 50ms
- The Data server must have a minimum bandwidth of 10 Mbps in upload with a latency of a maximum 50ms
- The manipulator master station's PC must have a minimum bandwidth of 10Mbps in download with a latency of a maximum 50ms

- The manipulator master station's PC must have a minimum bandwidth of 10Mbps in upload with a latency of a maximum 50ms
- All PCs can access the network at the same time

| Access: | ☐ contractual | ☐ open | ☐ restricted |
|---|---|---|---|

| | | |
|---|---|---|
| **Project Details** | ENEA<br>AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE,<br>L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE | |
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| **Abstract** | *This Interface Sheet defines the interface data of a specific interface between Control Room and HYRMAN.* | |

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# Control Room to HYRMAN Interface Sheet

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| Distribution List | Involved design teams | |
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RHCR-REF-007: [CR_7] ControlRoom-IS-004-CMM
RHCR-REF-008: [CR_8] Management and Quality Specification

# 1 Scope

The scope of this document is to identify the interface points between:

- **Control Room**

  and

- **HYRMAN**

for the following aspects:

- Operative Commands, from the High-Level Control System (HLCS) to HYRMAN controller
- Operative Telemetries, from HYRMAN Controller to HLCS
- Hardware network connection to HLCS
- Safety commands from HLCS
- Safety telemetries from HYRMAN Controller

In this document HLCS is used as synonym of the Control Room

# 2 Interfaces requirement data

## 2.1 Description of HYRMAN

The HYRMAN robot is a serial manipulator made of 5 planar joints and 6 dexterous joints and it is conceptually divided into two different parts:

1. The **planar part** consists of a carrier and a series of planar joints that enable the robot to move within a plane orthogonal to the carrier.
2. The **dexterous part** represents the second section of HYRMAN and is capable of performing movements in Cartesian space.

The HYRMAN has an electromechanical interface, called Tool Exchange Mechanism (TEM), installed at the dexterous part tip, allowing automatic connection/disconnection of external tools.

## 2.2 Description of the Interface for commands and telemetries

Commands sent by the HLCS, and telemetries received from HYRMAN can be either operational or related to safety management. The handling of safety-related commands shall be executed and managed by dedicated hardware. Finally, the HLCS will have the capability to receive video streams produced by the cameras situated at various positions within the HYRMAN system, including those associated with the foreseen tools, through the network.

All messages between HLSC and HYRMAN have the following header fields (followed by the message content)

- Time stamp (day, hour, minute, s, ms)
- Message Type
- Progressive Number (message unique ID)

Operative Commands from HLCS and HYRMAN control system include:

- Enable/Disable motor drivers.
- Enable/Disable teleoperation mode.
- Enable or disable any operational states provided by HYRMAN
- Teleoperation input command for HYRMAN
  - Joint Mode (1 or more joints at a time)
  - Cartesian Mode
- Set teleoperation reference frame.
- Robotic job Load/Unload
- Robotic job Start/Pause/Abort
- Set one of the operating modes provided by HYRMAN:
  - Arm joint motion for planar arm, dexterous arm, or full arm
  - Planar arm cartesian motion: the dexterous arm is kept still, while the planar arm is moved to the desired position.
  - Dexterous arm cartesian motion: the planar arm is kept still, while the dexterous arm is moved to the desired position.
  - Base reconfiguration: the planar arm is moved to the desired position (it is the base of the dexterous arm), while the dexterous arm end effector is kept still. This mode exploits the full arm self-motion granted by its redundancy.
- Go To Operational/Safe
- Controlled/Emergency Stop
- System Shutdown/Reboot
- Set Tool:
  - Multipurpose Gripper Tool
  - INW Tool
- Tool Teleoperation input command
- Alarm/Warning overrides
- Clear Alarm/Warning
- Planar arm redundancy resolution strategy
- Tool Exchange Mechanism (TEM) commands
- Diagnostic commands
- Configuration parameters

Operative Telemetries from HYRMAN control system and HLCS include:

- Cartesian positions/speeds (tool frame w.r.t. world frame; dexterous arm base frame w.r.t. world frame)
- Joint positions/speeds
- TEM feedback measurements

- Tools feedback measurements
- Tools camera video stream
- Arm Camera video stream
- Instrumentation feedback
- Cabinet status
- Alarms/warnings status
- Motor current, speed, temperature & status
- Motor running time (duty time)
- Diagnostic telemetries

Operative commands and telemetries shall use the underlying communication framework.
Video transmission will be done using the available video network using the RTSP protocol which is supported by each IP camera (located at tools, arm or other locations)

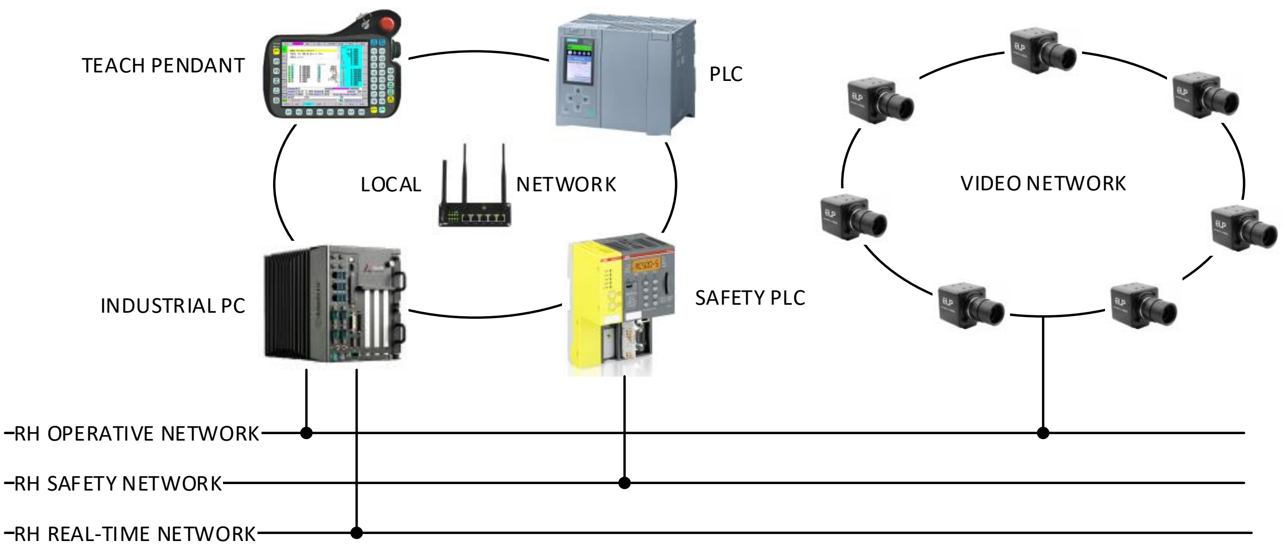
Safety Telemetries include:

- Measurements of instrumentation related to safety.
- Status of the Safety PLC

Safety commands and telemetries shall use the underlying communication framework.

## 2.3 Network Interface Description

The following picture show the HYRMAN network architecture:




A local network interfaces all the control cabinet components (like controller, safety PLC, etc.). The same network is also used to connect to the external teach pendant. A segregated network is used to connect all the IP cameras installed on the arm and on the tools.

The connection between the HYRMAN control cabinet and the Control Room will utilize the following three networks, which are routed to the HLCS as described below:

1. **The Real-Time network:** is used to transmit primarily force information from the robot force sensors to be utilized for haptic. Moreover, the real-time network can be used to transmit high-frequency or hard real-time set points for the manipulator to implement advanced control algorithms. This aspect has currently not been considered for HYRMAN but must be considered for the development of the HLCS for further improvements in the control architecture.
2. **The Operative network:** is used for all data which can be considered at low frequency and not real-time. This includes robot set points, diagnostics, and video. video information can be routed to the internal **visualization network** to avoid congestions on the operative network whether the number of video streams inside the S/S increases.
3. **The Safety Network:** is used to manage all safety aspects related to the robot. It interfaces directly with the digital hardwired network and with the real-time safety network of the HLCS

## 2.4 Identification of the HLCS / HYRMAN interfaces

| | HLCS | HYRMAN |
|---|---|---|
| **IP n.** | **IP designation** | **IP designation** |
| IP1 | Commands for HYRMAN LLCS | Commands to the HYRMAN LLCS |
| IP2 | Telemetries from HYRMAN LLCS | Telemetries from HYRMAN LLCS |
| IP3 | Safety Commands for HYRMAN LLCS | Safety Commands for the LLCS |
| IP4 | Safety Telemetries from HYRMAN LLCS | Safety Telemetries from HYRMAN LLCS |
| IP5 | Network addresses | Network addresses |
| IP6 | Video Streams | Video Streams |

**Table 1.List of the geometrical and functional interfaces between HYRMAN and HLCS**

### 2.4.1 IP1 Commands for HYRMAN

Operative commands are initiated by HLCS (automatically or by an operator), to ask services/data to the HYRMAN LLCS. Commands can be sporadic or synchronous (teleoperation commands). The latter are sent at the rate required for the correct execution of the service.

Commands can be divided in two categories depending on their execution time:

- Short execution time: these commands are immediately executed (if possible) when received and an acknowledge is sent after their execution. The acknowledge contains also the data requested by the command, if any. Examples are: Get Joints Values, Set Teleoperation Reference Frame, etc. No other commands can be sent until the acknowledge of the command is received
- Long execution time: the command execution (if possible) is started when the command is received. Two acknowledges are sent for these commands:
    - Reception acknowledges when the command execution starts
    - Completion acknowledges when the command execution completes (or is aborted).

  The completion ack, of course, is sent only if the command execution is started. Examples are: Start robotic job, etc. Other commands can be sent after the reception acknowledge of the command is received.

All commands acknowledge contains the unique ID of the command they acknowledge.
These commands can be grouped into functional sets. In some cases, commands could require an answer from HYRMAN controller (e.g., sporadic measure requests). This answer is not considered as “Telemetry”, but it is a part of the acknowledge to the command. Any command shall be correctly formatted at HLCS level and HYRMAN control system will interpret them to carry out the consequent services.

The list of potential commands, along with their frequencies, is defined but not restricted solely to Table 2

| COMMAND | RATE | NOTES |
|---|---|---|
| CONTROLLER | | |
| System shutdown/Reboot | sporadic | |
| Controlled/Emergency stop | sporadic | |
| Enable/Disable any operational states provided by HYRMAN | sporadic | |
| Go To Operational/Safe | sporadic | |
| Alarm/Warning overrides | sporadic | |
| Clear Alarm/Warning | sporadic | |
| ROBOT | | |
| Set Operating Mode | sporadic | • Arm joint motion for planar arm, dexterous arm or full arm<br>• Planar arm cartesian motion<br>• Dexterous arm cartesian motion<br>• Base reconfiguration |
| Enable/Disable motor drivers | sporadic | Drivers are enabled/disabled accordingly to the current operating mode |
| Enable/Disable teleoperation mode | sporadic | |
| Teleoperation input command<br>• Joint Mode | High | (1 or more joints at a time) |
| Teleoperation input command<br>• Cartesian Mode | high | |
| Set teleoperation reference frame | sporadic | |
| Set Tool | Sporadic | Multipurpose Gripper Tool, Inboard first wall tool, User defined tool, etc. |
| Set Planar arm redundancy resolution strategy | Sporadic | |
| Tool Teleoperation setpoint | High | This is a placeholder for a set of tool teleoperation input command (e.g. gripper current, gripper position, screw driver current, etc.).<br>Tools are out of the scope of the supply |
| Set brake status | Sporadic | Brakes are disengaged accordingly to the current operating mode |
| Get Specific measurements | Sporadic | Specific request commands |
| Calibrate device | Sporadic | e.g. FTS, end strokes, etc. |
| TEM | | |
| TEM lock/unlock | Sporadic | |
| ROBOTIC JOBS | | |
| Load Program | Sporadic | Program is prepared by HLCS |
| Start/Stop/Pause/resume Program | sporadic | Management of the Robotic programs |
| Step/Continuous mode | sporadic | Automatic Pause after each program line |
| CONFIGURATION | | |

| | | |
|---|---|---|
| Read/Write configuration | sporadic | |
| Set specific parameter | sporadic | |
| DIAGNOSTICS | | |
| Set Log info level | Sporadic | Type of info collected during operations |
| Upload Log | Sporadic | Only desired info types |
| Execute diagnostic check | Sporadic | Sporadic request to check a specific device (e.g. actuators, cabinet, instruments, electronics, etc). Periodic checks are executed autonomously by the controller |

**Table 2. List of possible commands and its rate**

### 2.4.2 IP2 Telemetries from HYRMAN

Operative telemetries are sent by HYRMAN (automatically) to HLCS, to transmit HYRMAN status.
Telemetries are normally sent as a data flow, at specific rates, without retransmission in case of corrupted packets.
These telemetries can be grouped into homogeneous sets. Syntax and relevant functionalities can depend on the used framework (existing or created from scratch).

The list of potential telemetries, along with their frequencies, is defined but not restricted solely to Table 3

| TELEMETRY | RATE | NOTES |
|---|---|---|
| ROBOT | | |
| Joint values | High | |
| Joint speed | High | |
| Current tool frame | High | |
| Current reference frame | High | |
| Cartesian position/speed Dextrous | High | Position in Homogeneous Matrix |
| Cartesian position/speed Planar | High | Position in Homogeneous Matrix |
| Tools related values | High | Fields according to the used tool and relevant sensors (e.g., gripper position, gripper position, speed, current, etc. Tools are not in the scope of the supply |
| INSTRUMENTATION | | |
| Force torque sensor | High | 3 axes force + 3 axes moment<br>Real time network shall be used to transmit these data |
| Accelerometers | High | Located onboard joint electronics |
| Inclinometers | High | Located onboard joint electronics |
| End stroke sensors | High | Located onboard joint electronics |
| CONTROL SYSTEM | | |
| Alarms codes | low | |
| Warning codes | low | |
| Current/Voltage values | High | |
| Axes setpoints | High | |
| TEM | | |
| TEM values | low | |

| | | |
|---|---|---|
| AXES | | |
| Axes encoder (fast shaft) | High | |
| Axes encoder (slow shaft) | High | |
| Driver data (for each redounded motor) | High | Temperature, currents, etc. |
| Drivers status | low | Enabled/disabled |
| Axes usage time | low | |
| Brakes status | low | Engaged/disengaged |
| CABINET | | |
| Current/Voltage values | low | |
| Insulation values | low | |
| PLC Status | low | Many values can be considered |

**Table 3. List of possible telemetries and its rate**

### 2.4.3 IP3 Safety Commands for HYRMAN

Safety signals are initiated by HLCS safety system (automatically or by an operator) to ask services/data after detection of some alarm/critical situation, possibly coming from Plant. Signals could be sporadic.
The list of potential safety commands, along with their frequencies, is defined but not restricted solely to Table 4

| SAFETY SIGNALS | RATE | NOTES |
|---|---|---|
| SAFETY | | |
| Immediate shutdown | sporadic | |
| Return to cask | sporadic | For instance, due to power down |
| Immediate power cut off | sporadic | |

**Table 4. List of possible safety signals and its rate**

Any command, when received, will be decomposed into several elementary actions aiming at the achievement of the command objective. Command decomposition is in charge of Safety PLC included into the HYRMAN cabinet, that knows the HYRMAN status, and can pass relevant actions to the HYRMAN controller.

### 2.4.4 IP4 Safety Telemetries from HYRMAN

Safety telemetries are sent by HYRMAN controller (automatically) to HLCS through the Safety PLC, to transmit HYRMAN status in case of detected possible safety problems.
The list of potential safety telemetries, along with their frequencies, is defined but not restricted solely to Table 5

| SAFETY TELEMETRY | RATE | NOTES |
|---|---|---|
| SAFETY | | |
| Controller safety Alarm | low | Collision, … |
| Cabinet safety Alarm | low | |

**Table 5. List of possible safety telemetries and its rate**

### 2.4.5 IP5 Network Addresses

HYRMAN system is based on a local network (visible by HYRMAN devices only) and different RH plant networks that connect HYRMAN control system to HLCS. In order to reach devices, the IP addresses shall be known. Preliminary, network addresses defined in the HYRMAN Interface Sheet (IS) are as in table 6

| Equipment | Local Network IP address (**) | Operative Network IP address | Real-time Network IP address |
|---|---|---|---|
| HYRMAN Controller (PC) | 192.168.1.10 | DHCP (*) | DHCP (*) |
| PLC | 192.168.1.20 | - | - |
| Safety PLC | 192.168.1.30 | - | - |
| Tech pendant | 192.168.1.40 | - | - |
| Any other equipment | 192.168.1.xxx | - | - |
| IP Cameras | - | DHCP (*) | - |

**Table 6. Network IP defined by HYRMAN IS**

(*) it is supposed that each RH plant network has a dedicated DHCP server.
(**) local network will have a dedicated DHCP server with some fixed IPs

### 2.4.6 IP6 Video Streams

HYRMAN system includes some IP cameras that produce video streams, located on the arm or on the tools. Such video streams shall be read and shown at the Control Room, and the relevant visualizer shall be compatible with the used protocol. Video transmission will be done using the available video network using the RTSP protocol which is supported by each IP camera.

# Control Room to CMM Interface Sheets

| Access: | ☐ contractual | ☐ open | ☐ restricted |
|---|---|---|---|

| | | |
|---|---|---|
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# Control Room to CMM Interface Sheet

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RHCR-REF-008: [CR_8] Management and Quality Specification

# 1 Scope

The scope of this document is to identify the interface points between:

- **Control Room**

  and

- **CMM**

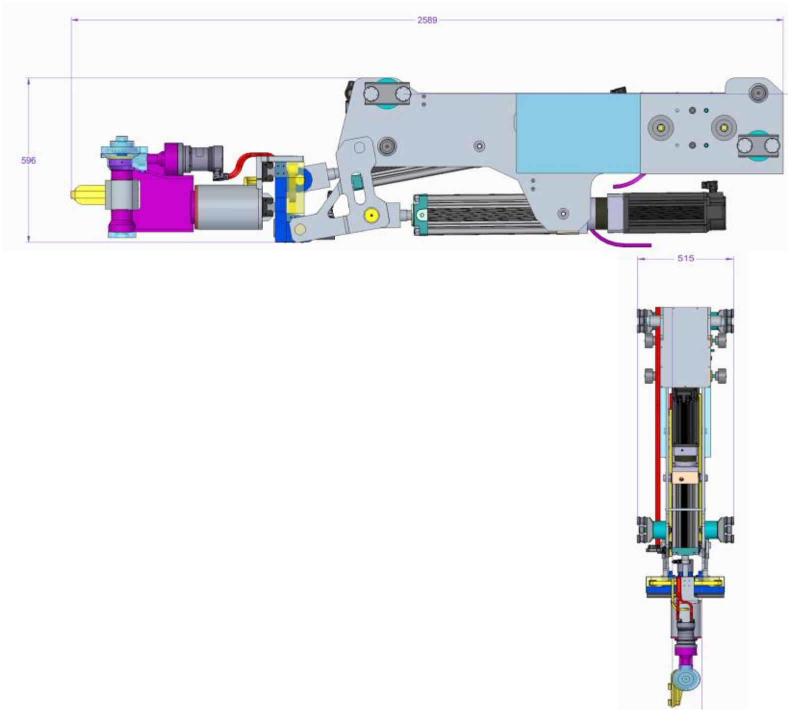
for the following aspects:

- Operative Commands, from the HLCS to CMM controller
- Operative Telemetries, from CMM Controller to HLCS
- Hardware network connection to HLCS
- Safety commands from HLCS
- Safety telemetries from CMM Controller

In this document HLCS is used as synonym of the Control Room

# 2 Interfaces requirement data

## 2.1 Description of CMM




The CMM is a robotic device with a main body and a two-link articulated mechanism for various motions. It travels along maintenance tunnel rails, driven by two electrical servomotors connected to rack-and-pinion systems. The articulated mechanism enables lifting and tilting movements for the divertor cassette in the vertical plane.

## 2.2 Description of the Interface for commands and telemetries

Commands sent by the HLCS, and telemetries received from CMM can be either operational or related to safety management. The handling of safety-related commands shall be executed and managed by dedicated hardware. Finally, the HLCS will have the capability to receive video streams produced by the cameras situated at various positions within the CMM system, including those associated with the foreseen end effectors, through the network.

All messages between HLSC and CMM have the following header fields (followed by the message content)

- Time stamp (day, hour, minute, s, ms)
- Message Type
- Progressive Number (message unique ID)

Operative Commands from HLCS and CMM control system include:

- Enable/Disable motor drivers.
- Enable/Disable teleoperation mode.
- Enable or disable any operational states provided by CMM
- Teleoperation input command for CMM
    - Joint Mode (1 or more joints at a time)
    - Cartesian Mode
- Set teleoperation reference frame.
- Robotic job Load/Unload
- Robotic job Start/Pause/Abort
- Set one of the operating modes provided by CMM:
    - Robot joint motion: robot joints (1 or more at a time) are directly controlled
    - Robot cartesian motion: the CMM end effector is moved to the desired position position in operative space
- Go To Operational/Safe
- Controlled/Emergency Stop
- System Shutdown/Reboot
- Set End effector
    - Central Cassette (CC) end effector
    - Left Cassette (LC) end effector
    - Right Cassette (RC) end effector
    - Lock/unlock end effector
- End effector Teleoperation input command
- Alarm/Warning overrides
- Clear Alarm/Warning
- Diagnostic commands
- Configuration parameters

Operative Telemetries from CMM control system and HLCS include:

- Cartesian positions/speeds (end effector frame respect to the world frame)
- Joint positions/speeds
- End effector feedback measurements
- End effector camera video stream
- CMM Camera video stream

- Instrumentation feedback
- Cabinet status
- Alarms/warnings status
- Motor current, speed, temperature & status
- Motor running time (duty time)
- Diagnostic telemetries

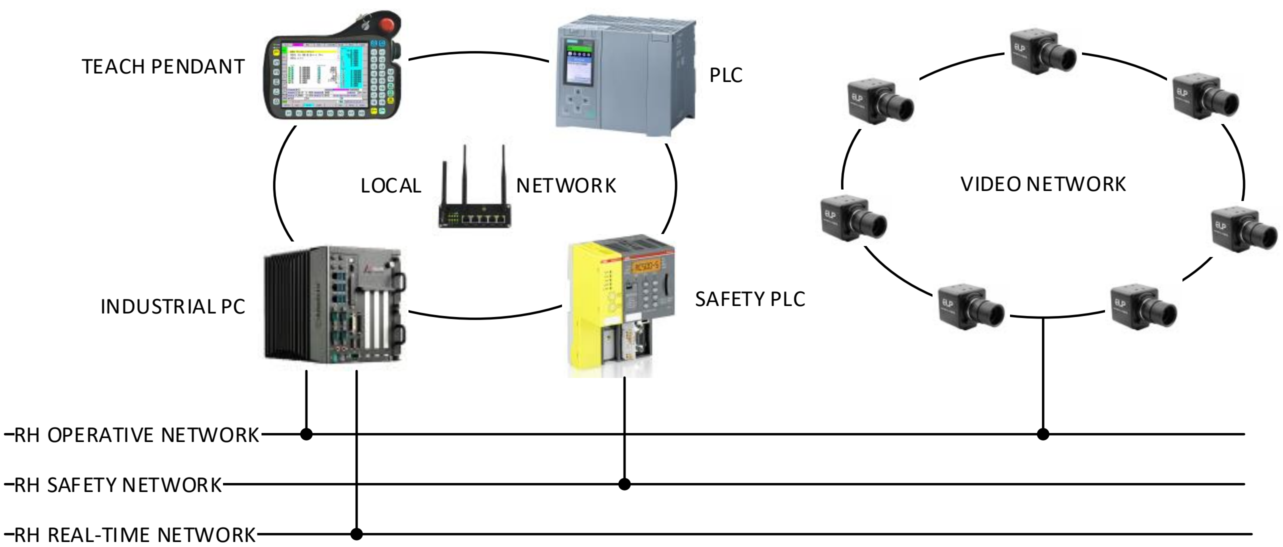
Operative commands and telemetries shall use the underlying communication framework.
Video transmission will be done using the available video network using the RTSP protocol which is supported by each IP camera (located at end effector, arm or other locations)

Safety Telemetries include:
- Measurements of instrumentation related to safety.
- Status of the Safety PLC

Safety commands and telemetries shall use the underlying communication framework.

## 2.3 Network Interface Description

The following picture show the CMM network architecture:




A local network interfaces all the control cabinet components (like controller, safety PLC, etc.). The same network is also used to connect to the external teach pendant. A segregated network is used to connect all the IP cameras installed on the arm and on the end effector.

The connection between the CMM control cabinet and the Control Room will utilize the following three networks, which are routed to the HLCS as described below:

1. **The Real-Time network:** is used to transmit primarily force information from the robot force sensors to be utilized for haptic.

2. **The Operative network:** is used for all data which can be considered at low frequency and not real-time. This includes robot set points, diagnostics, and video. video information can be routed to the

internal **visualization network** to avoid congestions on the operative network whether the number of video streams inside the S/S increases.

3. **The Safety Network:** is used to manage all safety aspects related to the robot. It interfaces directly with the digital hardwired network and with the real-time safety network of the HLCS

## 2.4 Identification of the HLCS / CMM interfaces

| | HLCS | CMM |
|---|---|---|
| **IP n.** | **IP designation** | **IP designation** |
| IP1 | Commands for CMM LLCS | Commands to the CMM LLCS |
| IP2 | Telemetries from CMM LLCS | Telemetries from CMM LLCS |
| IP3 | Safety Commands for CMM LLCS | Safety Commands for the LLCS |
| IP4 | Safety Telemetries from CMM LLCS | Safety Telemetries from CMM LLCS |
| IP5 | Network addresses | Network addresses |
| IP6 | Video Streams | Video Streams |

**Table 1.List of the geometrical and functional interfaces between CMM and HLCS**

### 2.4.1 IP1 Commands for CMM

Operative commands are initiated by HLCS (automatically or by an operator), to ask services/data to the CMM Control system. Commands can be sporadic or synchronous (teleoperation commands). The last ones are sent at the rate required for the correct execution of the service.

Commands can be divided in two categories depending on their execution time:

- Short execution time: these commands are immediately executed (if possible) when received and an acknowledge is sent after their execution. The acknowledge contains also the data requested by the command, if any. Examples are: Get Joints Values, Set Teleoperation Reference Frame, etc. No other commands can be sent until the acknowledge of the command is received
- Long execution time: the command execution (if possible) is started when the command is received. Two acknowledges are sent for these commands:
  - Reception acknowledges when the command execution starts
  - Completion acknowledges when the command execution completes (or is aborted).

  The completion ack, of course, is sent only if the command execution is started. Examples are: Start robotic job, etc. Other commands can be sent after the reception acknowledge of the command is received.

All commands acknowledge contains the unique ID of the command they acknowledge.
These commands can be grouped into functional sets. In some cases, commands could require an answer from CMM controller (e.g., sporadic measure requests). This answer is not considered as “Telemetry”, but it is a part of the acknowledge to the command. Any command shall be correctly formatted at HLCS level and CMM control system will interpret them to carry out the consequent services.

The list of potential commands, along with their frequencies, is defined but not restricted solely to Table 2

| COMMAND | RATE | NOTES |
|---|---|---|
| CONTROLLER | | |
| System shutdown/Reboot | sporadic | |
| Controlled/Emergency stop | sporadic | |
| Enable/Disable any operational states provided by CMM | sporadic | |
| Go To Operational/Safe | sporadic | |
| Alarm/Warning overrides | sporadic | |
| Clear Alarm/Warning | sporadic | |
| ROBOT | | |
| Set Operating Mode | sporadic | • Arm joint motion<br>• arm cartesian motion |
| Enable/Disable motor drivers | sporadic | Drivers are enabled/disabled accordingly to the current operating mode |
| Enable/Disable teleoperation mode | sporadic | |
| Teleoperation input command<br>• Joint Mode | High | (1 or more joints at a time) |
| Teleoperation input command<br>• Cartesian Mode | high | |
| Set teleoperation reference frame | sporadic | |
| Set End effector | Sporadic | Central Cassette, Left Cassette, Right Cassette, Lock/Unlock, etc. |
| End effector Teleoperation setpoint | High | This is a placeholder for a set of end effector teleoperation input command |
| Set brake status | Sporadic | Brakes are disengaged accordingly to the current operating mode |
| Get Specific measurements | Sporadic | Specific request commands |
| Calibrate device | Sporadic | e.g. FTS, end strokes, etc. |
| ROBOTIC JOBS | | |
| Load Jobs | sporadic | Program is prepared by HLCS |
| Start/Stop/Pause/resume Jobs | sporadic | Management of the Robotic Jobs |
| Step/Continuous mode | sporadic | Automatic Pause after each Job line |
| CONFIGURATION | | |
| Read/Write configuration | sporadic | |
| Set specific parameter | sporadic | |
| DIAGNOSTICS | | |
| Set Log info level | Sporadic | Type of info collected during operations |
| Upload Log | Sporadic | Only desired info types |
| Execute diagnostic check | Sporadic | Sporadic request to check a specific device (e.g. actuators, cabinet, instruments, electronics, etc). Periodic checks are executed autonomously by the controller |

**Table 2. List of possible commands and its rate**

### 2.4.2 IP2 Telemetries from CMM

Operative telemetries are sent by CMM (automatically) to HLCS, to transmit CMM status. Telemetries are normally sent as a data flow, at specific rates, without retransmission in case of corrupted packets.
These telemetries can be grouped into homogeneous sets. Syntax and relevant functionalities can depend on the used framework (existing or created from scratch).

The list of potential telemetries, along with their frequencies, is defined but not restricted solely to Table 3

| TELEMETRY | RATE | NOTES |
|---|---|---|
| ROBOT | | |
| Joint values | High | |
| Joint speed | High | |
| Current end effector frame | High | |
| Current reference frame | High | |
| Cartesian position/speed | High | Position in Homogeneous Matrix |
| End effector related values | High | Fields according to the used end effector and relevant sensors |
| INSTRUMENTATION | | |
| Accelerometers | High | Located onboard joint electronics |
| Inclinometers | High | Located onboard joint electronics |
| End stroke sensors | High | Located onboard joint electronics |
| CONTROL SYSTEM | | |
| Alarms codes | low | |
| Warning codes | low | |
| Current/Voltage values | High | |
| Axes setpoints | High | |
| AXES | | |
| Axes encoder (fast shaft) | High | |
| Axes encoder (slow shaft) | High | |
| Driver data (for each redounded motor) | High | Temperature, currents, etc. |
| Drivers status | low | Enabled/disabled |
| Axes usage time | low | |
| Brakes status | low | Engaged/disengaged |
| CABINET | | |
| Current/Voltage values | low | |
| Insulation values | low | |
| PLC Status | low | Many values can be considered |

**Table 3. List of possible telemetries and its rate**

### 2.4.3 IP3 Safety Commands for CMM

Safety signals are initiated by HLCS safety system (automatically or by an operator) to ask services/data after detection of some alarm/critical situation, possibly coming from Plant. Signals could be sporadic.
The list of potential safety commands, along with their frequencies, is defined but not restricted solely to Table 4

| SAFETY SIGNALS | RATE | NOTES |
|---|---|---|
| SAFETY | | |
| Immediate shutdown | sporadic | |
| Return to cask | sporadic | For instance, due to power down |
| Immediate power cut off | sporadic | |

**Table 4. List of possible safety signals and its rate**

Any command, when received, will be decomposed into several elementary actions aiming at the achievement of the command objective. Command decomposition is in charge of Safety PLC, that knows the CMM status, and can pass relevant actions to the CMM controller.

### 2.4.4 IP4 Safety Telemetries from CMM

Safety telemetries are sent by CMM controller (automatically) to HLCS through the Safety PLC, to transmit CMM status in case of detected possible safety problems.
The list of potential safety telemetries, along with their frequencies, is defined but not restricted solely to Table 5

| SAFETY TELEMETRY | RATE | NOTES |
|---|---|---|
| SAFETY | | |
| Controller safety Alarm | low | Collision, … |
| Cabinet safety Alarm | low | |

**Table 5. List of possible safety telemetries and its rate**

### 2.4.5 IP5 Network Addresses

CMM system is based on a local network (visible by CMM devices only) and different RH plant networks that connect CMM control system to HLCS. In order to reach devices, the IP addresses shall be known. Preliminary, network addresses defined in the CMM Interface Sheet (IS) are as in table 6

| Equipment | Local Network IP address (**) | Operative Network IP address | Real-time Network IP address |
|---|---|---|---|
| CMM Controller (PC) | 192.168.1.10 | DHCP (*) | DHCP (*) |
| PLC | 192.168.1.20 | - | - |
| Safety PLC | 192.168.1.30 | - | - |
| Tech pendant | 192.168.1.40 | - | - |
| Any other equipment | 192.168.1.xxx | - | - |
| IP Cameras | - | DHCP (*) | - |

**Table 6. Network IP defined by CMM IS**

(*) it is supposed that each RH plant network has a dedicated DHCP server.
(**) local network will have a dedicated DHCP server with some fixed IPs

#### 2.4.6 IP6 Video Streams

CMM system includes some IP cameras that produce video streams, located on the arm or on the end effector.

Such video streams shall be read and shown at the Control Room, and the relevant visualizer shall be compatible with the used protocol. Video transmission will be done using the available video network using the RTSP protocol which is supported by each IP camera.

| Access: | ☐ **contractual** | ☒ **open** | ☐ **restricted** |
|---|---|---|---|

# HYRMAN to High level Control System Interface Sheets

| | | |
|---|---|---|
| **Project Details** | DTT S.c.a r.l. *This document is issued for the execution of the DTT project* | |
| | DTT ID Number | Annex to RHS-SPT-76402 |
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| **Authors & Contributors** | PL of the involved design team | |
| **Distribution List** | Involved design teams | |
| **Abstract** | *This Interface Sheet defines the interface data of a specific interface between HYRMAN and High Level Control System (managed in Control Room)* | |

# Index

# 1 Scope

The scope of this document is to identify the interface points between:

- **HYRMAN system**

  and

- **High level Control System**

for the following aspects

  - Operative Commands, from HLCS to HYRMAN controller
  - Operative Telemetries, from HYRMAN Controller to HLCS
  - Hardware network connection to HLCS
  - Safety commands from HLCS
  - Safety telemetries from HYRMAN Controller

# 2 Interfaces requirement data

## 2.1 Description of the Interface Points

HLCS is an ensemble of HW and SW able to generate commands to the HYRMAN using devices allowing simple commanding to the robot, to receive telemetries from it and to display them in a suitable and "ergonomic" way, also exploiting 3D and immersive tools.
Commands and Telemetries can be operative or related to safety management. The latter shall be implemented and managed by dedicated HW.
Finally, HLCS will be able, through the network, to receive the video streams produced by the ethernet cameras available on the HYRMAN system at various positions, included the foreseen tools.

All messages between HYRMAN and HLSC have the following header fields (followed by the message content)

- Time stamp (day, hour, minute, s, ms)
- Message Type
- Progressive Number (message unique ID)

Operative Commands from HLCS and HYRMAN control system include:

- Enable/Disable motor drivers
- Enable/Disable teleoperation mode
- Arm Teleoperation setpoints
  - Joint Mode (1 or more joints at a time)
  - Cartesian Mode
- Set teleoperation reference frame
- Robotic job Load/Unload
- Robotic job Start/Pause/Abort
- Set Operating Mode
  - Arm joint motion for planar arm, dexterous arm or full arm
  - Planar arm cartesian motion
  - Dexterous arm cartesian motion

  - Base reconfiguration
- Go To Operational/Safe
- Enable/Disable contingency mode
- Controlled/Emergency Stop
- System Shutdown/Reboot
- Set Tool
  - Multipurpose Gripper Tool
  - INW Tool
- Tool Teleoperation setpoint
- Alarm/Warning overrides
- Clear Alarm/Warning
- Planar arm redundancy resolution strategy
- TEM commands
- Diagnostic commands
- Configuration parameters

Operative Telemetries from HYRMAN control system and HLCS include:
- Cartesian positions/speeds (tool frame w.r.t. world frame; dexterous arm base frame w.r.t. world frame)
- Joint positions/speeds
- TEM feedback measurements
- Tools feedback measurements
- Tools camera video stream
- Arm Camera video stream
- Instrumentation feedback
- Cabinet status
- Alarms/warnings status
- Motor current, speed, temperature & status
- Motor running time (duty time)
- Diagnostic telemetries

Operative commands and telemetries shall use the underlying communication framework (ROS2/DDS). Video transmission will be done using the available video network using the RTSP protocol which is supported by each IP camera (located at tools, arm or other locations)

Safety Signals may include:
- Hyrman immediate recovery on cask
- Stop operations
- Hyrman immediate shutdown

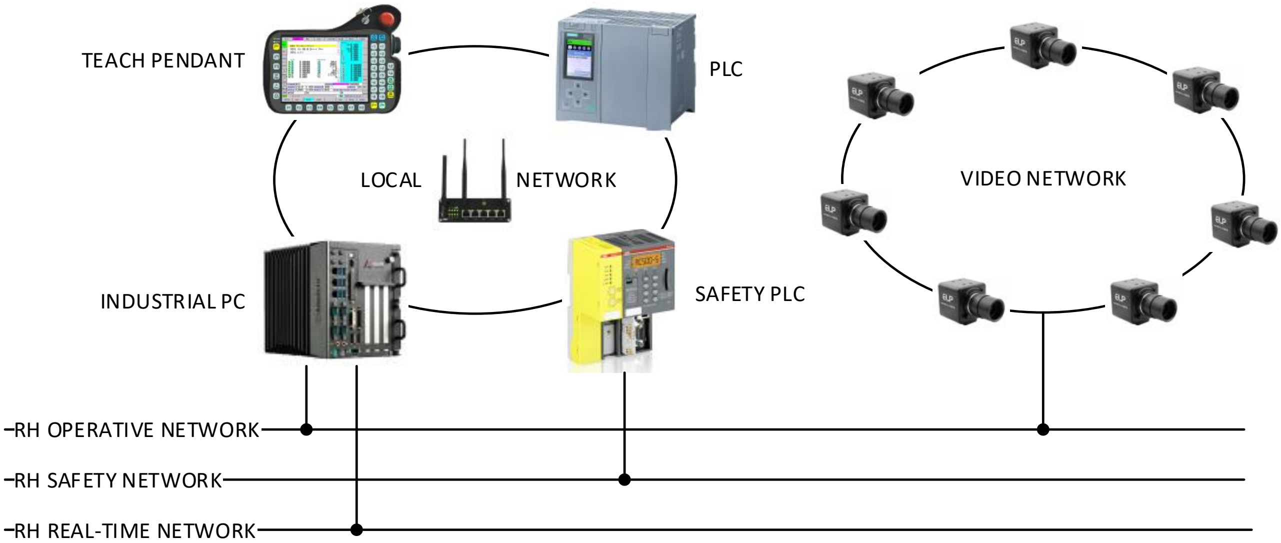
To be finalized

Safety Telemetries include:
- Measurements of instrumentation related to safety
- Status of the Safety PLC

Safety commands and telemetries shall use the underlying communication framework (ROS2/DDS)

Network address philosophy and assignment

The following picture show the HYRMAN network architecture:




A local network interfaces all the control cabinet components (like controller, safety PLC, etc.). The same network is also used to connect to the external teach pendant.
A segregated network is used to connect all the IP cameras installed on the arm and on the tools.
The HYRMAN control cabinet is connected to the RH plant network infrastructure by means of the following interfaces:

- **Operative network:** ethernet 1-10 Gb/s, used to transfer non-critical data (e.g. non critical telemetries, cameras outputs, etc.)
- **Safety network:** Hardwired type TBC, used to receive and send safety alarms requiring fast actions.
- **Real-Time network:** ethernet 1-10 Gb/s used to transfer real time critical data (e.g. force feedback)

The components that act as bridge between the local network and the RH plant network (PC and safety PLC) are provided with a double network interface card.

## 2.2 Identification of the HYRMAN / HLCS interfaces

| | **Hyrman** | **HLCS** |
|---|---|---|
| **IP n.** | **IP designation** | **IP designation** |
| IP1 | Operative Commands from HLCS | Commands |
| IP2 | Operative Telemetries from HYRMAN | Telemetries from HYRMAN |
| IP3 | Safety Signals from HLCS | Safety Commands |
| IP4 | Safety Telemetries from HYRMAN | Safety Telemetries from HYRMAN |
| IP5 | Network addresses | Network addresses |
| IP6 | Video Streams | Video Streams |

Table 1 - List of the geometrical and functional interfaces between Hyrman and HLCS

### 2.2.1 IP1 Operative Commands from HLCS

Operative commands are initiated by HLCS (automatically or by an operator), to ask services/data to the HYRMAN Control system. Commands can be sporadic or synchronous (teleoperation commands). The last ones are sent at the rate required for the correct execution of the service.

Commands can be divided in two categories depending on their execution time:

- Short execution time: these commands are immediately executed (if possible) when received and an acknowledge is sent after their execution. The acknowledge contains also the data requested by the command, if any. Examples are: Get Joints Values, Set Teleoperation Reference Frame, etc. No other commands can be sent until the acknowledge of the command is received
- Long execution time: the command execution (if possible) is started when the command is received. Two acknowledges are sent for these commands:
  - Reception acknowledge when the command execution starts
  - Completion acknowledges when the command execution completes (or is aborted).

  The completion ack, of course, is sent only if the command execution is started. Examples are: Start robotic job, etc. Other commands can be sent after the reception acknowledge of the command is received.

All commands acknowledge contains the unique ID of the command they acknowledge.

These commands can be grouped into functional sets.

| COMMAND | RATE | NOTES |
|---|---|---|
| CONTROLLER | | |
| System shutdown/Reboot | sporadic | |
| Controlled/Emergency stop | sporadic | |
| Enable/Disable contingency mode | sporadic | |
| Go To Operational/Safe | sporadic | |
| Alarm/Warning overrides | sporadic | |
| Clear Alarm/Warning | sporadic | |
| ROBOT | | |
| Set Operating Mode | sporadic | • Arm joint motion for planar arm, dexterous arm or full arm<br>• Planar arm cartesian motion<br>• Dexterous arm cartesian motion<br>• Base reconfiguration |
| Enable/Disable motor drivers | sporadic | Drivers are enabled/disabled accordingly to the current operating mode |
| Enable/Disable teleoperation mode | sporadic | |
| Arm Teleoperation setpoints<br>o Joint Mode | High | (1 or more joints at a time) |
| Arm Teleoperation setpoints<br>o Cartesian Mode | high | |
| Set teleoperation reference frame | sporadic | |
| Set Tool | Sporadic | Multipurpose Gripper Tool, Inboard first wall tool, User defined tool, etc. |
| Set Planar arm redundancy resolution strategy | Sporadic | |
| Tool Teleoperation setpoint | High | This is a placeholder for a set of tool teleoperation setpoint (e.g. gripper current, gripper position, screw driver current, etc.).<br>Tools are out of the scope of the supply |
| Set brake status | Sporadic | Brakes are disengaged accordingly to the current operating mode |
| Get Specific measurements | Sporadic | Specific request commands |
| Calibrate device | Sporadic | e.g. FTS, end strokes, etc. |
| TEM | | |
| TEM lock/unlock | Sporadic | |

| | | |
|---|---|---|
| ROBOTIC JOBS | | |
| Load Program | Sporadic | Program is prepared by HLCS |
| Start/Stop/Pause/resume Program | sporadic | Management of the Robotic programs |
| Step/Continuous mode | sporadic | Automatic Pause after each program line |
| CONFIGURATION | | |
| Read/Write configuration | sporadic | |
| Set specific parameter | sporadic | |
| DIAGNOSTICS | | |
| Set Log info level | Sporadic | Type of info collected during operations |
| Upload Log | Sporadic | Only desired info types |
| Execute diagnostic check | Sporadic | Sporadic request to check a specific device (e.g. actuators, cabinet, instruments, electronics, etc). Periodic checks are executed autonomously by the controller |

Command list to be finalized

In some cases, commands could require an answer from HYRMAN controller (e.g., sporadic measure requests). This answer is not considered as "Telemetry", but it is a part of the acknowledge to the command

Any command shall be correctly formatted at HLCS level and HYRMAN control system will interpret them to carry out the consequent services.

### 2.2.2 IP2 Operative Telemetries from HYRMAN

Operative telemetries are sent by HYRMAN (automatically) to HLCS, to transmit HYRMAN status. Telemetries are normally sent as a data flow, at specific rates, without retransmission in case of corrupted packets. These telemetries can be grouped into homogeneous sets. Syntax and relevant functionalities can depend on the used framework (existing or created from scratch).

| TELEMETRY | RATE | NOTES |
|---|---|---|
| | ROBOT | |
| Joint values | High | |
| Joint speed | High | |
| Current tool frame | High | |
| Current reference frame | High | |
| Cartesian position/speed Dextrous | High | Position in Homogeneous Matrix |
| Cartesian position/speed Planar | High | Position in Homogeneous Matrix |
| Tools related values | High | Fields according to the used tool and relevant sensors (e.g., gripper position, gripper position, speed, current, etc. Tools are not in the scope of the supply |
| | INSTRUMENTATION | |
| Force torque sensor | High | 3 axes force + 3 axes moment Real time network shall be used to transmit these data |
| Accelerometers | High | Located onboard joint electronics |
| Inclinometers | High | Located onboard joint electronics |
| End stroke sensors | High | Located onboard joint electronics |
| | CONTROL SYSTEM | |
| Alarms codes | low | |
| Warning codes | low | |
| Current/Voltage values | High | |
| Axes setpoints | High | |
| | TEM | |
| TEM values | low | |
| | AXES | |
| Axes encoder (fast shaft) | High | |
| Axes encoder (slow shaft) | High | |
| Driver data (for each redounded motor) | High | Temperature, currents, etc. |
| Drivers status | low | Enabled/disabled |
| Axes usage time | low | |
| Brakes status | low | Engaged/disengaged |
| | CABINET | |
| Current/Voltage values | low | |
| Insulation values | low | |
| PLC Status | low | Many values can be considered |

Telemetry list to be finalized

### 2.2.3 IP3 Safety Signals from HLCS

Safety signals are initiated by HLCS safety system (automatically or by an operator) to ask services/data after detection of some alarm/critical situation, possibly coming from Plant. Signals could be sporadic.

| SAFETY SIGNALS | RATE | NOTES |
|---|---|---|
| SAFETY | | |
| Immediate shutdown | sporadic | |
| Return to cask | sporadic | For instance, due to power down |
| Immediate power cut off | sporadic | |

Signal list to be finalized

Any command, when received, will be decomposed into several elementary actions aiming at the achievement of the command objective. Command decomposition is in charge of Safety PLC, that knows the HYRMAN status, and can pass relevant actions to the HYRMAN controller.

### 2.2.4 IP4 Safety Telemetries from HYRMAN

Safety telemetries are sent by HYRMAN controller (automatically) to HLCS through the Safety PLC, to transmit HYRMAN status in case of detected possible safety problems.

| SAFETY TELEMETRY | RATE | NOTES |
|---|---|---|
| SAFETY | | |
| Controller safety Alarm | low | Collision, … |
| Cabinet safety Alarm | low | |

Safety Telemetry to be finalized

### 2.2.5 IP5 Network Addresses

HYRMAN system is based on a local network (visible by HYRMAN devices only) and different RH plant networks that connect HYRMAN control system to HLCS.
In order to reach devices, the IP addresses shall be known. Preliminary, network addresses are as in table below:

| Equipment | Local Network IP address (**) | Operative Network IP address | Real-time Network IP address |
|---|---|---|---|
| HYRMAN Controller (PC) | 192.168.1.10 | DHCP (*) | DHCP (*) |
| PLC | 192.168.1.20 | - | - |
| Safety PLC | 192.168.1.30 | - | - |
| Tech pendant | 192.168.1.40 | - | - |
| Any other equipment | 192.168.1.xxx | - | - |
| IP Cameras | - | DHCP (*) | - |

(*) it is supposed that each RH plant network has a dedicated DHCP server
(**) local network will have a dedicated DHCP server with some fixed IPs

#### 2.2.6 IP6 Video Streams

HYRMAN system includes some IP cameras that produce video streams, located on the arm or on the tools. Such video streams shall be read and shown at the Control Room, and the relevant visualizer shall be compatible with the used protocol.

Video transmission will be done using the available video network using the RTSP protocol which is supported by each IP camera.

| Access: | ☐ **contractual** | ☒ **open** | ☐ **restricted** |
|---|---|---|---|

# CMM to High level Control System Interface Sheets

| | | |
|---|---|---|
| **Project Details** | DTT S.c.a r.l. *This document is issued for the execution of the DTT project* | |
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| **Authors & Contributors** | PL of the involved design team | |
| **Distribution List** | Involved design teams | |
| **Abstract** | *This Interface Sheet defines the interface data of a specific interface between CMM and High Level Control System (managed in Control Room)* | |

# Index

# 1 Scope

The scope of this document is to identify the interface points between:

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  and

- **High level Control System**

for the following aspects

- Operative Commands, from HLCS to CMM controller
- Operative Telemetries, from CMM Controller to HLCS
- Hardware network connection to HLCS
- Safety commands from HLCS
- Safety telemetries from CMM Controller

# 2 Interfaces requirement data

## 2.1 Description of the Interface Points

HLCS is an ensemble of HW and SW able to generate commands to the CMM using devices allowing simple commanding to the robot, receive telemetries from it and display them in a suitable and "ergonomic" way, also exploiting 3D and immersive tools.
Commands and Telemetries can be operative or related to safety management. The last ones shall be implemented and managed by dedicated HW.
Finally, HLCS will be able, through the network, to receive the video streams produced by the ethernet cameras available on the CMM system at various positions, included the foreseen end effectors.

All messages between CMM and HLSC have the following header fields (followed by the message content)

- Time stamp (day, hour, minute, s, ms)
- Message Type
- Progressive Number (message unique ID)

Operative Commands from HLCS and CMM control system include:

- Enable/Disable motor drivers
- Enable/Disable teleoperation mode
- Arm Teleoperation setpoints
  - Joint Mode (1 or more joints at a time)
  - Cartesian Mode
- Set teleoperation reference frame
- Robotic job Load/Unload
- Robotic job Start/Pause/Abort
- Set Operating Mode
  - Arm joint motion
  - Arm cartesian motion
- Go To Operational/Safe

- Enable/Disable contingency mode
- Controlled/Emergency Stop
- System Shutdown/Reboot
- Set End effector
    - CC end effector
    - LC end effector
    - RC end effector
    - Lock/unlock end effector
- Alarm/Warning overrides
- Clear Alarm/Warning
- Diagnostic commands
- Configuration parameters

Operative Telemetries from CMM control system and HLCS include:

- Cartesian positions/speeds (end effector frame respect to the world frame)
- Joint positions/speeds
- End effector feedback measurements
- End effector camera video stream
- CMM Camera video stream
- Instrumentation feedback
- Cabinet status
- Alarms/warnings status
- Motor current, speed, temperature & status
- Motor running time (duty time)
- Diagnostic telemetries

Operative commands and telemetries shall use the underlying communication framework (for example ROS2/DDS)
Video transmission will be done using the available video network using the RTSP protocol which is supported by typical IP cameras (located at end effector, arm or other locations)

Safety Signals, managed by Safety PLC, can include:

- CMM immediate recovery on cask
- Stop operations
- CMM immediate shutdown

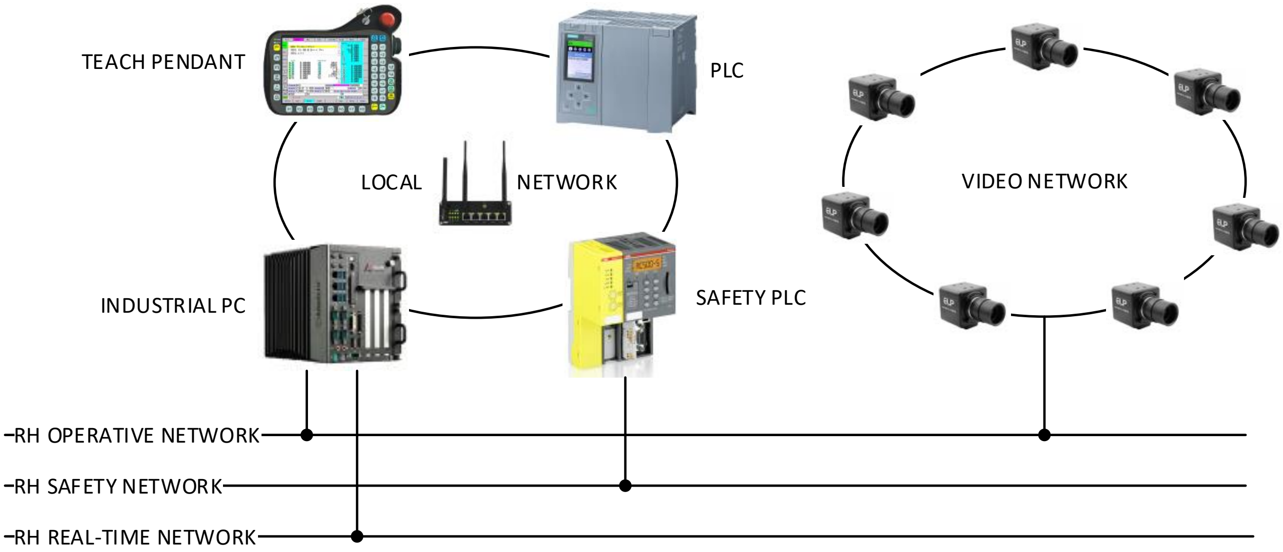
To be finalized

Safety Telemetries, managed by Safety PLC, include:

- Measurements of instrumentation related to safety
- Status of the Safety PLC

**Network address philosophy and assignment**

The following picture show the CMM network architecture:




A local network interfaces all the control cabinet components (like controller, safety PLC, etc.). The same network is also used to connect to the external teach pendant.
A segregated network is used to connect all the IP cameras installed on the arm and on the tools.
The CMM control cabinet is connected to the RH plant network infrastructure by means of three ethernet interfaces:

- **Operative network:** ethernet 1-10 Gb/s, used to transfer non-critical data (e.g. non critical telemetries, cameras outputs, etc.)
- **Safety network:** Hardwired type TBC, used to receive and send safety alarms requiring fast actions
- **Real-Time network:** ethernet 1-10 Gb/s used to transfer real time critical data (e.g. force feedback). Not used in the current design but retained for possible future developments.

The components that act as bridge between the local network and the RH plant network (PC and safety PLC) are provided with a double network interface card.

## 2.2 Identification of the CMM / HLCS interfaces

| | **CMM** | **HLCS** |
|---|---|---|
| **IP n.** | **IP designation** | **IP designation** |
| IP1 | Operative Commands from HLCS | Commands |
| IP2 | Operative Telemetries from CMM | Telemetries from CMM |
| IP3 | Safety Signals from HLCS | Safety Commands |
| IP4 | Safety Telemetries from CMM | Safety Telemetries from CMM |
| IP5 | Network addresses | Network addresses |
| IP6 | Video Streams | Video Streams |

Table 1 - List of the geometrical and functional interfaces between CMM and HLCS

### 2.2.1 IP1 Operative Commands from HLCS

Operative commands are initiated by HLCS (automatically or by an operator), to ask services/data to the CMM Control system. Commands can be sporadic or synchronous (teleoperation commands). The last ones are sent at a rate required for the correct execution of the service.

Commands can be divided in two categories depending on their execution time:

- Short execution time: these commands are immediately executed (if possible) when received and an acknowledge is sent after their execution. The acknowledge contains also the data requested by the command, if any. Examples are: Get Joints Values, Set Teleoperation Reference Frame, etc. No other commands can be sent until the acknowledge of the command is received
- Long execution time: the command execution (if possible) is started when the command is received. Two acknowledges are sent for these commands:
  - Reception acknowledge when the command execution starts
  - Completion acknowledge when the command execution completes (or is aborted).

  The completion ack, of course, is sent only if the command execution is started. Examples are: Start robotic job, etc. Other commands can be sent after the reception acknowledge of the command is received.

All commands acknowledge contains the unique ID of the command they acknowledge.

These commands can be grouped into functional sets.

| **COMMAND** | **RATE** | **NOTES** |
|---|---|---|
| CONTROLLER | | |
| System shutdown/Reboot | sporadic | |
| Controlled/Emergency stop | sporadic | |
| Enable/Disable contingency mode | sporadic | |
| Go To Operational/Safe | sporadic | |
| Alarm/Warning overrides | sporadic | |
| Clear Alarm/Warning | sporadic | |
| ROBOT | | |
| Enable/Disable motor drivers | sporadic | |

| | | |
|---|---|---|
| Set Operating Mode | sporadic | • Arm joint motion<br>• arm cartesian motion |
| Enable/Disable teleoperation mode | sporadic | |
| Arm Teleoperation setpoints<br>o Joint Mode | High | (1 or more joints at a time) |
| Arm Teleoperation setpoints<br>o Cartesian Mode | high | |
| Set teleoperation reference frame | sporadic | |
| Set Tool | sporadic | Central Cassette, Left Cassette, Right Cassette, Lock/Unlock, etc. |
| Tool Teleoperation setpoint | high | Only for active tools |
| Set brake status | sporadic | |
| Get Specific measurements | sporadic | Specific request commands |
| Calibrate device | sporadic | e.g. FTS, if any, end strokes, etc. |
| ROBOTIC JOBS | | |
| Load Jobs | sporadic | Program is prepared by HLCS |
| Start/Stop/Pause/resume Jobs | sporadic | Management of the Robotic Jobs |
| Step/Continuous mode | sporadic | Automatic Pause after each Job line |
| CONFIGURATION | | |
| Read/Write configuration | sporadic | |
| Set specific parameter | sporadic | |
| DIAGNOSTICS | | |
| Set Log info level | Sporadic | Type of info collected during operations |
| Upload Log | Sporadic | Only desired info types |
| Execute diagnostic check | Sporadic | Sporadic request to check a specific device (e.g. actuators, cabinet, instruments, electronics, etc). Periodic checks are executed autonomously by the controller |

Command list to be finalized

In some cases, commands could require an answer from CMM controller (eg. sporadic values). This answer is not considered as “Telemetry”, but it is a part of the acknowledge to the command

Any command shall be correctly formatted at HLCS level and CMM control system will interpret them to carry out the consequent services.

### 2.2.2 IP2 Operative Telemetries from CMM

Operative telemetries are sent by CMM (automatically) to HLCS, to transmit CMM status. Telemetries are normally sent as a data flow, at specific rates, without retransmission in case of corrupted packets.
These telemetries can be grouped into homogeneous sets. Syntax and relevant functionalities can depend on the used framework (existing or created from scratch).

| TELEMETRY | RATE | NOTES |
|---|---|---|
| | ROBOT | |
| Joint values | High | |
| Joint speed | High | |
| Current tool frame | High | |
| Current reference frame | High | |
| Cartesian position/speed | High | Position in Homogeneous Matrix |
| Tool values | High | Fields according to the used tool and relevant sensors |
| | INSTRUMENTATION | |
| Accelerometers | High | Located onboard joint electronics |
| Inclinometers | High | Located onboard joint electronics |
| End stroke sensors | High | Located onboard joint electronics |
| | CONTROL SYSTEM | |
| Alarms codes | low | |
| Warning codes | low | |
| Current/Voltage values | High | |
| Axes setpoints | High | |
| | AXES | |
| Axes encoder (fast shaft) | High | |
| Axes encoder (slow shaft) | High | |
| Driver data (for each redounded motor) | High | Temperature, currents, … |
| Drivers status | low | Enabled/disabled |
| Axes usage time | low | |
| Brakes status | low | |
| | CABINET | |
| Current/Voltage values | low | |
| Insulation values | low | |
| PLC Status | low | Many values can be considered |

Telemetry list to be finalized

### 2.2.3 IP3 Safety Signals from HLCS

Safety signals are initiated by HLCS (automatically or by an operator)., to ask services/data after detection of some alarm/critical situation, possibly coming from Plant. Signals could be sporadic.

| SAFETY COMMAND | RATE | NOTES |
|---|---|---|
| SAFETY | | |
| Immediate shutdown | sporadic | |
| Return to cask | sporadic | For instance due to power down (and exploiting UPS time) |
| Immediate power cut off | sporadic | |

Signal list to be finalized

Any command, when received, will be decomposed into a number of elementary actions aiming at the achievement of the command objective. Command decomposition is in charge of Safety PLC, that knows the CMM status, and can pass relevant actions to the CMM controller.

### 2.2.4 IP4 Safety Telemetries from CMM

Safety telemetries are sent by CMM (automatically) to HLCS through the Safety PLC, to transmit CMM status in case of detected possible safety problems.

| SAFETY TELEMETRY | RATE | NOTES |
|---|---|---|
| SAFETY | | |
| Controller safety Alarm | low | Collision, … |
| Cabinet safety Alarm | low | |

Safety Telemetry to be finalized

### 2.2.5 IP5 Network Addresses

CMM system is based on a local network (visible by CMM devices only) and different RH plant networks that connect CMM control system to HLCS.
In order to reach devices, the IP addresses shall be known. Preliminary, network addresses are as in table below:

| Equipment | Local Network IP address (**) | Operative Network IP address | Real-time Network IP address |
|---|---|---|---|
| CMM Controller (PC) | 192.168.1.10 | DHCP(*) | DHCP(*) |
| PLC | 192.168.1.20 | - | - |
| Safety PLC | 192.168.1.30 | - | - |
| Tech pendant | 192.168.1.40 | - | - |
| Any other equipment | 192.168.1.xxx | - | - |
| IP Cameras | - | DHCP(*) | - |

(*) it is supposed that each RH plant network has a dedicated DHCP server
(**) local network will have a dedicated DHCP server with some fixed IPs

### 2.2.6 IP6 Video Format

CMM system includes some IP cameras that produce video streams, located on the arm or on the end effectors.
Such video streams shall be read and shown at the Control Room, and the relevant visualizer shall be compatible with the used protocol.

Video transmission will be done using the available video network using the RTSP protocol which is supported by each IP camera.