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Preliminary architecture of the DTT Remote Handling Test and Training Facility

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Abstract

The realization of a specific REMote HAndling Test and Training Facility (REMHAT) is necessary for the development and optimization of the Remote Handling (RH) system, to demonstrate the fulfilment of all the design requirements, for testing and validation of the RH maintenance procedures, for the qualification and acceptance testing of RH equipment and tooling. Furthermore, it provides training and certification to the RH maintenance operators, by making available to operators the knowledge, instructions and experiencing of the Virtual Simulator platform, the control room devices, the robots and tooling to be used for RH tasks. In this work, the preliminary architecture of the DTT REMHAT facility is described, with a focus on the added value of the adoption of Virtual Reality technologies enabling real-time alignment of virtual robots' configuration with the real ones (Digital Twin). A first approach to the facility design is proposed, starting from the technical requirements: Environmental, Design, Physical, Functional, Operational, Human Factors and Product assurance and safety. The proposed logical architecture consists of four Sub-Systems (S/S): building and auxiliaries, mock-ups, robots and Control Room. In the present work, a particular attention is paid on the last one. The idea is to create a digital twin of the RH equipment mock-ups to have at disposition real-time additional information about the real environment. These data could be crucial for the operator's decision-making process about a sudden intervention on the RH system, further to their employment for future studies and optimization. Therefore, for each subsystem of the facility, the components identification and a description of the software and hardware aspects are provided. In conclusion, an overview of the criticalities of such complex system is presented, in order to prepare the ground for future research works.

Keywords: DTT, Test and Training Facility, Virtual Reality, Digital Twin, Remote Handling System

1. Introduction

This paper aims to introduce a preliminary architecture of the REMote HAndling Test and Training Facility (REMHAT), with reference to the European fusion research program DTT (Divertor Tokamak Test) [1]. It is commonly acknowledged that, during the lifetime of the Tokamak, the in-vessel components are constantly subjected to high temperatures, ultra-high vacuum conditions and a dangerous radiation level for the operators, with a subsequent contamination of the environment. This has caused the necessity of an efficient Remote Handling System (RHS) to enable several maintenance and components replacement operations inside the Tokamak, with the aim to guarantee two fundamental aspects:

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- the exposure of personnel to hazards within the facility kept within prescribed limits and minimised (ALARA) [2];
- the maximum availability of the fusion device for plasma operations (low shutdown time).

About the first point, due to the harsh environment, it is not possible for a human operator to conduct the required operations inside the Tokamak: every action must be performed remotely. With reference to the second point, a well-structured process of planning, testing and optimization of the RH operations is imperative to minimize any failure during the on-going procedures, as well as the time required for their completion.

1.1. The DTT Remote Handling System

DTT Remote Handling System (RHS), which is inspired by the well-known ITER RH system [3], is characterized by three main subsystems that enter the Vacuum Vessel (VV) through the ports #1, #3 and #4 of the dedicated RH sectors (#1, #5, #10 and #15):

- The HYper Redundant MANipulator (HYRMAN) is a 12 DoFs robotic system, composed by a planar arm and a dexterous arm, designed to enter the Tokamak through the equatorial ports (ports #3), to handle the Outboard and Top First Wall modules (OFW and TFW), as well as the Inboard First Wall modules with the aid of a dedicated lifting system. Further to maintenance operations, this manipulator may be used also for assistance to the other RH equipment, inspection of the VV environment, rescue purposes, tasks related to diagnostics and heatings [4]
- The IFW Lifting S/S is a robotic platform whose primary goal is to enable the In-board First Wall (IFW) modules transportation from the inside to the outside of the VV, through the upper ports (ports #1).
- The Divertor Handling (DH) System is conceived for the removal and installation of the lower divertor. The Cassette Multifunctional Mover (CMM) has the main function of grabbing/releasing cassettes that are located in central and second position, with reference to the RH lower lateral ports, and transporting them through the access port duct; the other cassettes, that are not directly visible from the access ports, are preliminary transported by the Cassette Toroidal Mover (CTM) along the toroidal direction to the closest sector dedicated to RH operations. Both CMM and CTM are equipped with a 6 DoF manipulator that performs service operations on the divertor cassettes [5].

A summary of DTT RHS is presented in Figure 1 [6].

1.2. The facility mission

The DTT REMHAT has three main missions that can be also identified with the stakeholders' requirements, where the users are the DTT facility and its operators:

- Training the operators about RH procedures and equipment: before gaining the required certification about the RH procedures, the human operator should receive a full training (theoretical and practical). The facility shall offer the possibility to the novel operators to get certified, by assisting to the procedures and subsequently conducting themselves in first person. The operator shall be able to navigate within the virtual simulation of the Tokamak machine, familiarize with the environment and interact with it, without any risk for his own safety or for damages to the real mock-ups.
- Validation of proof of concept for design solutions and control algorithms of equipment: since even a minor modify to the RH equipment design can have a significant impact on the entire Tokamak design and operation and can cause a strong time and money-consuming redesign process, the integration of the RH equipment into the design process of all the Tokamak machine is imperative [7]. Also, the design process of the components is itself an iterative process throughout the design phase, which involves several members from different departments. Thus, REMHAT shall offer a collaborative platform for testing and validating several alternatives for the RH equipment and its control algorithms, having the possibility to verify their compatibility with the design of the entire machine since the earliest stages of the design process.

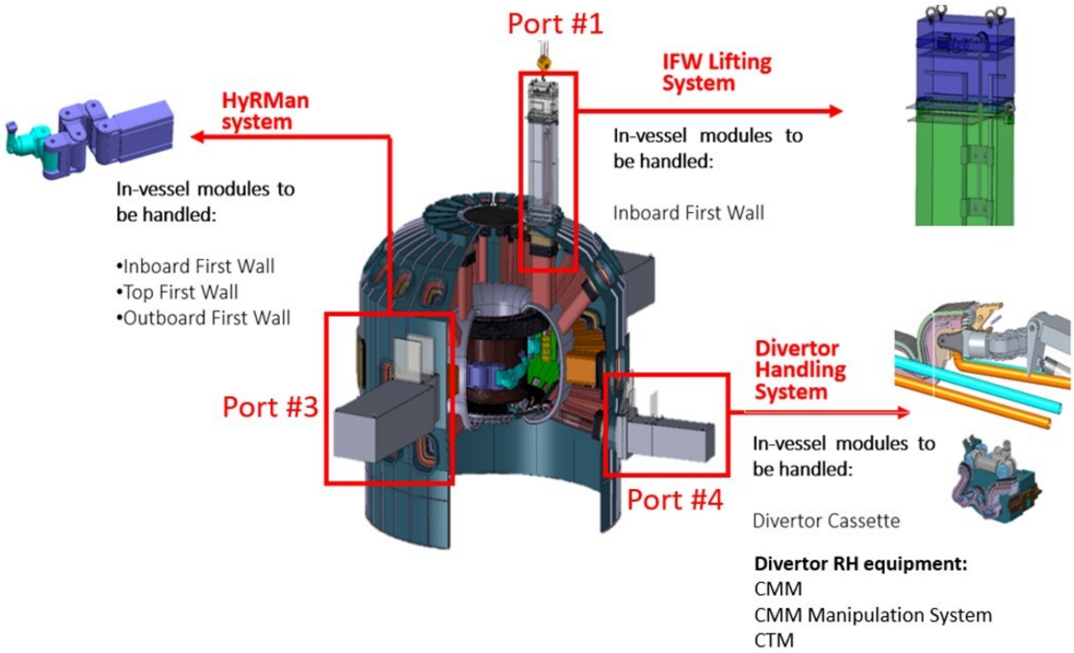

Figure 1. Overview of DTT RH equipment and dedicated ports

- Acceptance tests for new RH procedures, equipment and tooling: REMHAT shall be able to carry out acceptance tests also for new RH procedures, equipment and tooling that may be developed during the lifecycle of the machine to face unexpected issues.

With reference to the facility mission, the use of Virtual Reality (VR) technologies is crucial to overcome three main criticalities:

1. Since the internal environment of the Tokamak machine is narrow and characterized by poor light, it could make very difficult for the human operator to have a complete and clear overview, even placing several on-site cameras in the optimal positions. For both training and supervision purposes, the HO, who is in charge of controlling the RHS, can navigate and interact within the virtual environment that reproduces the real site, enriching the limited visual feedbacks received from on-site cameras. In this way, the operator's view is not dependant on the number and position of the on-site cameras, but can zoom into specific locations within the VR model to look at finer details and make a better judgment of control decisions [8].
2. Regarding the training purpose, the lack of a more interactive mode to train the future operators can negatively affect their consciousness of the environment and the procedures. The possibility to test several times the procedures without no consequence on the real environment could be decisive for their preparation, further to the need of avoiding accidents. The use of VR technology allows to reproduce in a realistic way the Tokamak machine and the RH equipment control, without no effect on the real system: this is a crucial instrument to let the operators several times the procedures until a proper confidence level is reached.
3. Furthermore, the possibility of testing and validating a new procedure or RH equipment through preliminary virtual simulations rather than physical mock-ups allows to identify earlier design mistakes, reducing significantly the required expenditure of resources. Furthermore, a virtual collaborative platform enables cooperative design sessions between different teams and overcomes the limit of the geographical distance between them.

In light of this, a brief overview of the adoption of VR technologies in such applications will be provided in the next section.

2. State of the art

Training Facilities for testing, assessment and validation of RH operations in nuclear fusion reactors, exploiting Virtual Reality (VR) and Augmented Reality (AR) techniques, have been already realized and are in operation. One of them is the Divertor Test Platform 2 (DTP2), constructed in 2009 at the laboratory hall of VTT Technical Research Centre of Finland in Tampere with the aim of superseding an earlier Divertor Test Platform (developed in the '90s at the ENEA Research Centre in Brasimone, Italy) and validating the ITER RH equipment and procedures. The DTP2 facility includes a reactor mock-up, the reactor component transporters, and several refurbishment tools. An operator control and command system with a combination of graphical user interface, visualisation system, and camera vision system is a critical component of the facility. During DTP2 operations, digital mock-ups are employed to improve, optimize and validate test procedures, assess the difficulty and fatigue experienced by the operators, gather technical specifications for designs and procurements of new RH equipment. The final goal is to produce a complete digital mock-up of the divertor region and its RH equipment, including operations and tasks procedures [9]. The Augmented Virtualised Reality (AVR) technologies that are used at DTP2 allow to overcome the limits of using cameras in a radioactive environment, represented by the limited position in which they are placeable, their reduced average life and the poor quality of the output images. AVR, in fact, uses data from other sensors so that, in case cameras either cannot be used or have degraded significantly, the real-time views of the work area required for RH operations may still be generated and used by the RH operators, by overlapping the virtual image on the real one. In this way, AVR also helps operators to manage problems related to optical effects, misleading perspectives, objects reduced visibility, scarce light, poor quality of images, objects with similar colours [10]. Virtual Reality has also been widely used for preparation and support of RH operations on JET, in the Remote Application in Challenging Environment (RACE) facility at Culham Science Centre near Oxford, UK. There, it is used in two different modes: in on-line mode the RH equipment electro-mechanical hardware is connected to the VR system and provides input for it to update a real time 3-D display of the equipment inside the torus; in off-line mode the operator manipulates the VR system model with no connections to the remote handling equipment, to experience the environment, prepare RH operational strategies and check operational feasibility and operations procedures [11]. Even if it is clear that huge steps have been made in the development of sites and methods aimed at improving the connection between the RH procedures and their operators, there is still absence of a test facility in which to convey all the different techniques for RH procedures' testing and updating and where to make different operators and systems collaborate, working on a unique digital-twin of the real environment in a multiuser platform, with the common aim of establishing and metabolizing procedures adaptable to the RH processes for every kind of tokamak or facility for nuclear fusion purposes. Moreover, a unique test facility where to test all the RH operations and equipment related to a fusion reactor is still to be realized, since, for instance, the DTP2 only features mock-ups of the divertor region, while the RACE facility only tests the operations carried out by robotic manipulators, like First Wall modules handling.

3. Methods of the activities: System Engineering (SE) approach

The System Engineering (SE) approach is applied to the design process of the DTT REMHAT, aiming to identify the main components of the innovative facility, in which the human operator will have a primary role. The human-centred design process has covered so far the following phases of the SE's V-model: "R-F-L-P" [12]. Starting from the requirements, the functions the facility and its sub-systems need to provide are defined in the present work, and a consequent logical architecture of the facility is established. The future activities will regard its physical design, together with the design of all the sub-components, which will conclude this first stream of the process and pave the way for the following stages of integration, verification and validation.

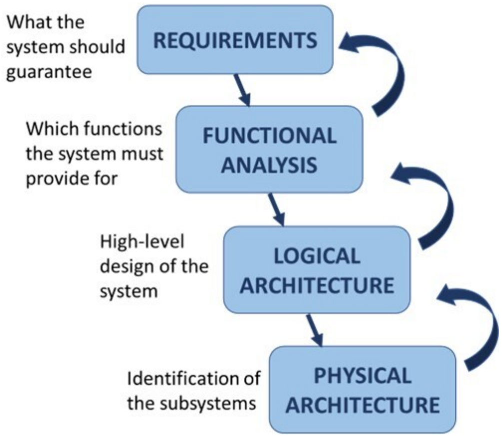

Figure 2. First four phases of System Engineering's V-model: Requirements, Functional analysis, Logical architecture, Physical architecture

4. Requirements analysis

The requirements of the REMHAT facility are elicited by the DTT facility and its operators and directly come from the ones highlighted in 1.2. The main ones have been organized in the categories showed in Table 1.

Table 1. Requirements of the REMote HAndling Test (REMHAT) facility

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

5. Functional analysis

Following the SE approach and moving to the next step in the V-model, a functional analysis has been conducted, highlighting the main functions the facility will need to provide for. They are directly derived from the just exposed facility's requirements, where possible, and are listed in Table 2.

Table 2. Functions to be provided by the REMHAT facility

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

6. Logical architecture

The REMHAT facility will be characterized by an in-scale replica of a section of the DTT machine, able to guarantee the correct execution of the RH procedures tests, taking also into account safety issues. During the conception of the logical architecture for the facility it is very important to identify those functions that need to be included and exactly replicated from the DTT machine, and the other ones that do not affect the RH procedures and therefore can be neglected. In this way, only part of the sub-systems the facility will include will need to be an exact reproduction of the real ones, while a large part of them can be a partial replica providing only the requirements affecting the RH procedures to be tested. As represented in 3, the facility will be divided in four main Sub-Systems (S/S):

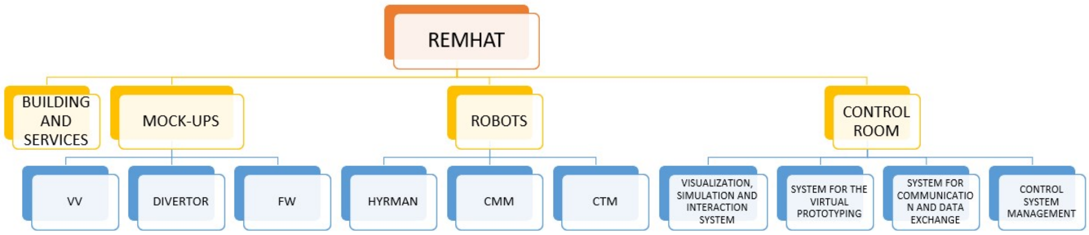

Figure 3. Logical architecture of the REMHAT facility

6.1. The building and auxiliaries S/S

This sub-system relates to the construction site where the facility will be realized and all the auxiliaries services that it will need to provide. Once the area to host the facility is defined, and the precise building identified, it is necessary to clarify all the auxiliaries services required by the facility and to develop a preliminary design of the tokamak replica, in order to estimate the exact space required. Eventually, building and civil works will be carried out to adapt the building to the facility's functions. Furthermore, other components will be necessary: an overhead crane and trolleys to transport the RH equipment within the main room of the REMHAT during the operations, as well as structures for the physical support of the RH equipment and casks.

6.2. The mock-ups S/S

This sub-system comprises those components that will need to be reproduced from the DTT machine's design, however without matching all the functions provided by the real equipment. This means that for these components a specific design for the REMHAT facility will be realized, only comprising those characteristics needed to fulfil the requirements relevant for the correct execution of the RH maintenance procedures. This approach allows to choose different solutions, cheaper compared to the real one adopted in the DTT machine, if they fulfil their requirements established by the REMHAT facility. For instance, since no burning plasma will be present in the facility, the components and materials will not face requirements related to radiation exposure. Instead, the correct reproduction of the real components' dimensions, weight and stiffness will be a key aspect in the mock-ups' design process. This Sub-System will be characterized by a 1:1 scale mock-up of 100° (5 sectors of 20°) of the DTT Tokamak, including:

- The VV with the following RH ports:
  - 1 Port #1, needed for testing, validation and training of IFW RH operations.
  - 2 Ports #3, needed for testing, validation and training of IFW, OFW, TFW and DIV RH operations.
  - 2 Ports #4, needed for testing, validation and training of DIV RH operation, from both left and right directions.
- The Divertor cassettes, whose removal and installation sequences need to be tested.
- The FW modules, whose removal and installation sequences need to be tested.

6.3. The robots S/S

The Robots S/S comprises the robotic equipment that will carry out the RH operations under the Human Operators (HOs) control. For these components, the same version designed for DTT shall be implemented in the REMHAT facility, or at least exact and fully functional replicas of the real DTT RH robots, featuring all the functionalities of the real versions except for rad-hard and vacuum-clean requirements. This S/S comprises

- 2 units of the HyRMan robot, for the test of the FW modules removal and installation sequences.

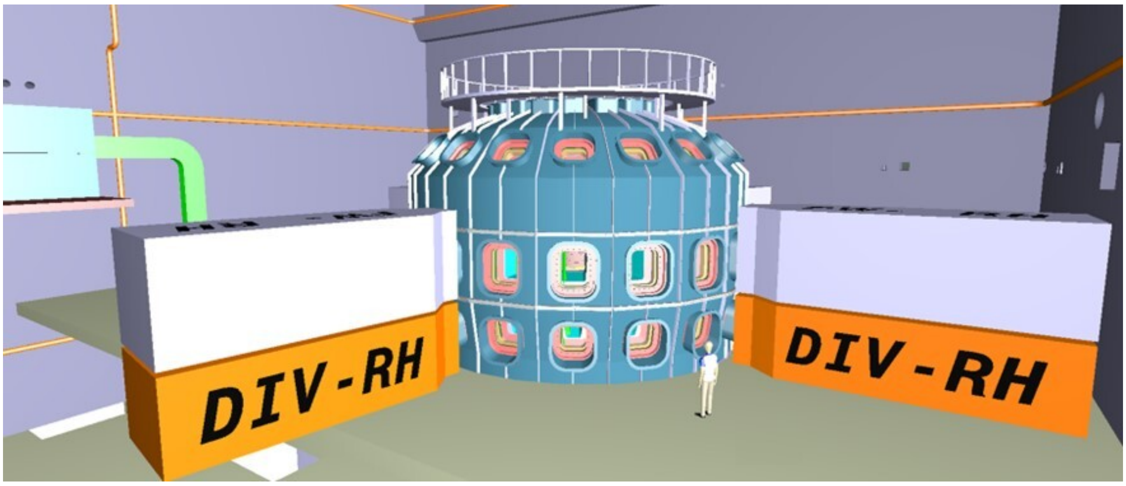

Figure 4. Pictorial view of the DTT mock-ups in the future facility

- 1 CMM for the test of the Divertor Cassettes removal and installation sequences through the ports #4.
- 1 CTM for the test of the Standard Divertor Cassettes removal, installation and toroidal transportation sequences.

6.4. The Control Room S/S

The new REMHAT facility will be centred on the Human Operator and on their training to control the RH robots and conduct the RH procedures in the most conscious way as possible. To achieve this goal, a comprehensive human-robot interaction system needs to be designed. The relevant feature of the REMHAT facility where this interaction will take place is the Control Room. It will have a key function during the facility operation, being able to connect the operators side to the machine side and allow the correct robots' manipulation throughout the procedures' execution. The importance of a well-structured Control Room in the REMHAT facility project also resides in the fact that it will pave the way for the RH Control Room of DTT, that will be equal to the REMHAT one. The proposed Control Room logical architecture is inspired by the currently operating RH facilities and is based on two control levels: the Machine and the Operator control levels 5. The first covers all the robotic machines, starting from the RH equipment to be remotely controlled, up to all the support machines involved in the tasks (i.e. control cabinets and tools); the second includes the numerous operators (with different roles and duties) that will interact within the Control Room.

The logical architecture of the Control Room is based on a Server/multi-Clients communication in both directions (Machine and Operator), in which the Control Room shall have one or more Server computer, that will be in charge of establishing a dedicated connection channel on which publish the data flux. Therefore, several clients from both the Machine and the Operator sides will connect to this communication channel, to publish or read the data flux. For the Machine side, the information to be published on the dedicated channel may be data collected from the sensors, robot current state, joint configurations, etc.; while Operator side publish input commands to the robotic machines.

In light of this, the Control Room shall provide three control modes, as different modalities and degrees of interaction between the two proposed control systems (machine and operator):

- **Offline mode**: This modality is designed for operators' training and testing of designed solutions. In these cases, it is necessary to switch off the connection between the real site and its digital twin, since the user will interact only with the latter. This modality will allow the user to conduct and test the tasks several times by interacting only with the virtual environment without no negative influence on the real site, especially in case of occurring malfunctions and errors [11].
- **Teleoperated mode**: This modality is design to enable the human operator to remotely control the RH equipment in first person, through a series of possible input commands provided in the interface. This control mode

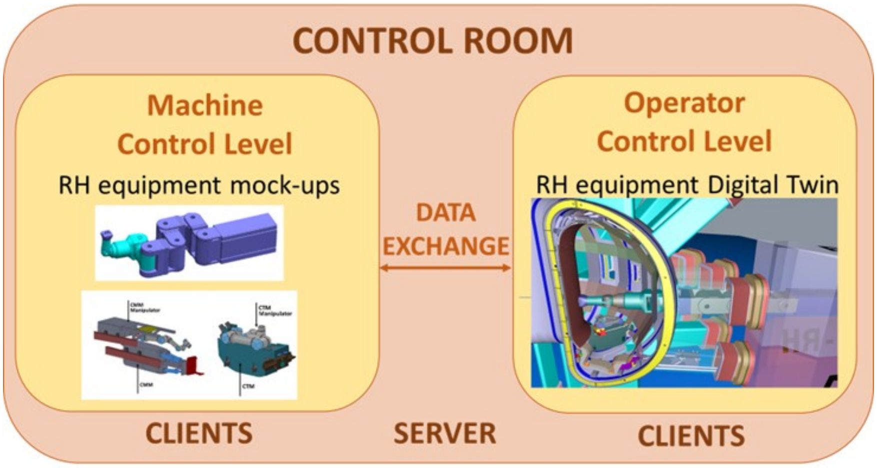

Figure 5. The Control Room Logical architecture, divided into two control levels: Machine and Operator

might have several applications, from the necessity to inspect the Tokamak internal environment, to test online a procedure that will be subsequently programmed offline, or a sudden intervention for the RH equipment from an undesired condition.

- **Supervisor mode**: the human operator should also be able to monitor the ongoing procedures. With this modality, the equipment executes the operations autonomously, while the operator supervises 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, the supervisor should switch to the "teleoperator mode" and intervene to bring the interested component to a correct configuration.

The Control Room shall provide to the operators the possibility to switch between the control modes, in order to select the correct one for the specific operation and the specific component of the RH equipment to be involved (Hyrman, CMM, CTM), under the coordination and supervision of a supervisor. This aspect will be detailed in section 7.4.

7. The preliminary physical architecture of the REMHAT Control Room and its sub-systems

As already mentioned, the Control Room plays a key role for the correct operation of the new REMHAT facility. In light of this, a major attention is paid on this S/S in this work, proposing a preliminary physical architecture for it and describing its three main subsystems: 1. "the Visualization, simulation and interaction system", 2. "the system for the virtual prototyping", 3. "the system for the communication and data exchange collected by the sensors". For each subsystem, the aspects that seem to be the most critical at the present stage of the design process will be highlighted.

7.1. The Visualization, simulation and interaction system

- **Visualization system**: the operator workstations shall be equipped with a Human Machine Interface (HMI) able to properly connect the Machine side to the Operator side. The HMI shall offer a general overview of the machines state, a panel to select the control mode and a section to focus on a specific robotic machine. From Machine to Operator side, it shall constantly keep the operator informed with the right and complete set of information collected by sensors and markers present in the machine environment to take the right decision; in the other direction (from Operator to Machine), it shall guarantee the HO to interact with and operate the robotic devices in the most direct and usable way as possible. The HMI shall be visualized on both 2D and 3D monitors, further to immersive visualization systems as Head Mounted Displays, with the possibility of easily switching between them.

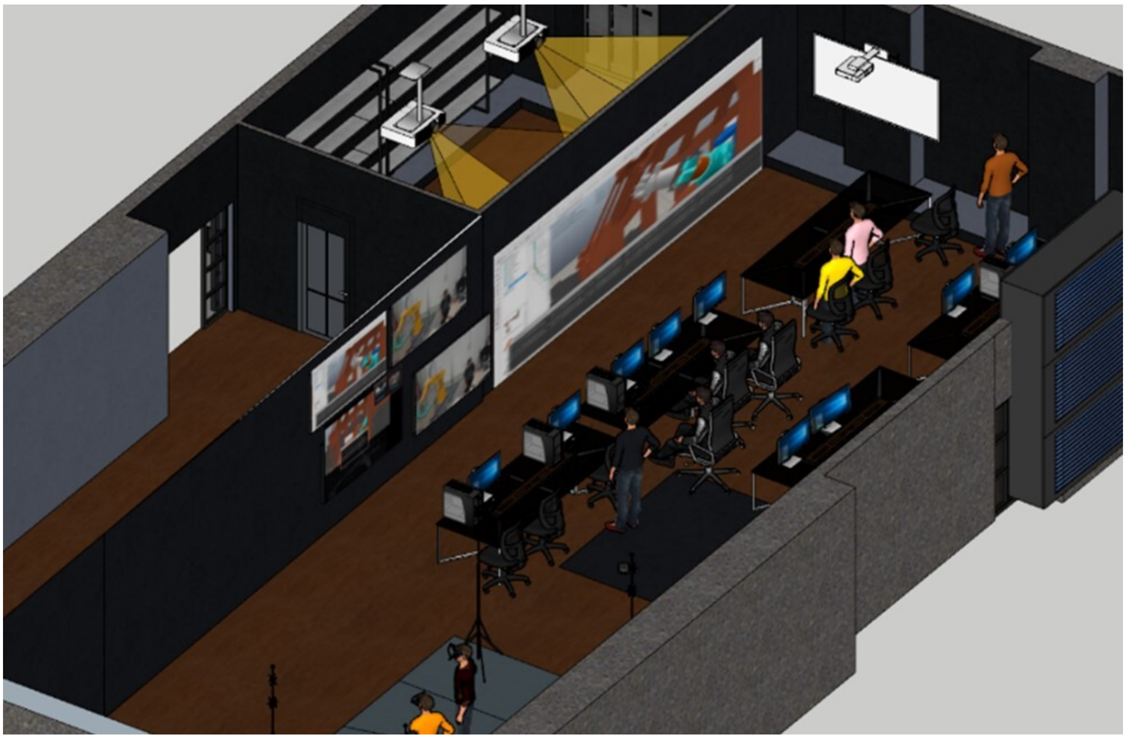

Figure 6. Pictorial view of the Control Room of the REMHAT facility

- **Simulation system**: each workstation shall include a dedicated software able to run kinematic, flexibility and structural analyses as quickly as possible (with a negligible delay), in order to predict the real trajectory and structural behaviour of the robotic devices and eventually detect upcoming impacts or hazards such to send to the operator information to avoid damages. The software shall support the coexistence and cooperation of multi-users simultaneously, working on different sections.

- **Interaction system**: the HMI will be not only a visualization, but also an interaction instrument for the operators. Starting from traditional interaction systems as keyboards and mouses, several VR devices will be employed to offer a more complete experience to the operators. Head Mounted Display will be equipped with hand controllers, with buttons to be pushed to activate a specific view of the internal Tokamak environment, or an input command on the robotic machines. Furthermore, haptic and force-feedback devices (such as sensorized gloves or other master-slave systems) will be included. In particular, the interaction with the haptic device is a two-way interaction by the operator: the operator moves the haptic device (master), this motion is sensed by the sensors and used to provide motion commands to the real robot (slave). The force/torque sensors installed on the real robot are responsible of detecting and record the applied forces: this information will be sent back to the master robotic arm to be regenerated by the actuators and be applied to the operator's hand.

One of the main criticalities of the whole REMHAT project resides in the current absence of methods and software able to simulate, in real-time, the flexibility and the structural behaviour of robotic and in general mechanical structures. Since the weight of the robotic devices and the components to be handled is considerable, their deflection can be not neglectable. A rigid 3D model may be not enough to simulate the real devices' behaviour and may show to the operator an incorrect reproduction of the real equipment. Therefore, a strong scientific effort will be paid to develop algorithms and platforms able to predict, in real-time, trajectories and structural behaviour of the robotic devices, and then represent these information in the VR environment experienced by the operator, taking into account also the flexibility effects on the machines and the possible collisions that these may cause.

Another hot topic is the design of the Human Machine Interface, considering that a proper design of the interface

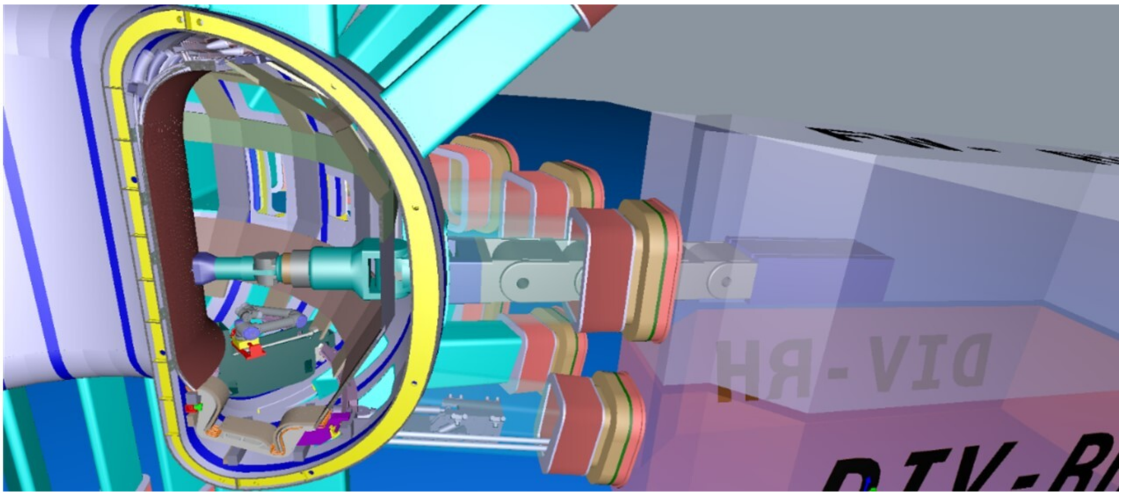

Figure 7. Example of in-scale virtual representation of DTT RH equipment (Hyrman, CMM and CTM), entering from the respective RH ports

significantly influences the usability of the whole Control Room and the human perception during the on-going procedures [13]. It will be necessary to find the optimal disposition of all the data flux in the interface, without inserting unnecessary or disturbing information that may overwhelm the operator. A modular interface shall be designed, in which different levels of detail for the information are showed, on the basis of the user's role.

7.2. *The system for the virtual prototyping*

A dedicated software for the Tokamak machine virtual prototyping shall be one of the main components of the Control Room. As showed in Fig.6, a virtual 3D model of the REMHAT, therefore a sector of the DTT Tokamak machine of about 100°, shall be reproduced inside the selected VR environment, together with precise collision surfaces and realistic textures. Particular attention shall be done for any part interacting with RH, such as rails inside ducts and VV, dock and latch interfaces of the modules, port plugs. All these equipment will be endowed of the same encumbrance of the real systems, with the possibility to conduct primary operations, as make a section of the 3D models, turn on/off the components' visibility and navigate inside the virtual environment.

Since the list of the involved in-vessel components is very long, 1:1 scale prototyping and demonstration for each RH operation becomes intensive in terms of cost and time. Moreover, the representation and motion of the virtual model in real-time with the real ones, combined with the great flux of data between the on-site sensors and the operators work-stations, cause the need of a wide storage space where to store and elaborate all these data. It will be necessary to have at disposition a considerable dedicated space to keep and elaborate all these data. In addition, it is a primary criticality to find a platform where to keep so many models, so frequently modified, always updated, considering the high number of 3D models to be managed and the amount of specialists from different departments working on the project related to nuclear fusion. Moreover, an even greater effort should be done to trace all the modifies made on the models, in order to organize and keep traceability of all their different versions and developments and also of their contributors.

7.3. *The system for the communication and data exchange collected by the sensors*

A proper synchronization between the virtual representation of the RH equipment and the real one is fundamental to obtain the effective digital twin of a real system. A well-designed calibration system disposed on the Machine site is crucial to collect all the information necessary to the human operator to make well-informed decision during maintenance interventions, while the presence of an appropriate data exchange system is mandatory to manage several information of a different nature about the RH equipment.

- **Calibration system**: it is made of sensors and cameras able to monitor the internal and external state of the robots.

- Internal state variables are collected for position control; these variables include joints configuration and robot's position-orientation and are obtained by means of position sensors (optical, potentiometric, magnetic, etc.);
- External state variables are collected to characterize the work environment; these variables can include the distance between the manipulator and other components, obtained, for instance, by means of visual 3D sensors or ultrasonic ones, or the external forces and torques needed to grab items, obtained by force and torque sensors.

Further to the sensors, a multi cameras system shall be properly installed in the Machine site, to provide for specific points of view of the on-going procedures.

- **Data exchange system**: the Machine and Operator Control Systems must exchange huge amount of data constantly, ensuring no interferences or unwanted stop. For this reason, a complex structure of dedicated internet-based channels shall be disposed, and a specific intelligent system for data collection and categorization shall be introduced. Taking into account that these data not only will require constant update, but will also have a significant role for reports and future investigations, distinguished channels shall be disposed for the data exchange, on the basis of the specific type of information required:
  - First of all, a separated internet communication channel shall be dedicated for the real-time streaming video from the on-site cameras system.
  - Since the RH equipment is comprehensive of several components characterized by different parameters, several separated channel shall be introduced for the exchange of the consistent amount of data collected by the on-site sensors and tracking devices, that will be stored and elaborated with reference to a session report, also to track possible errors or improvements for future studies and applications.

  A teleoperated process, in general, is always characterized by a latency between the command input from the remote site and its effective execution on-site, which increases in inverse proportion to the capability of the dedicated communication channel (which is generally Internet based). This criticality is also highlighted by the literature about the use of VR for teleoperation purposes, as it causes a divergence between what is happening on-site to the robotics system and what is simulated within the virtual environment at a specific instant [14]. The design and realization of a proper communication and data exchange structure between the Operator and Machine sites in such a complex system will be a demanding goal, requiring a particular attention also to the introduction of several safety protocols.

Another challenging line of research is related to the use of Artificial Intelligence and Machine Learning to collect, organize and reuse a certain flux of data. In this case, the employment of these innovative techniques may be determinant to prevent human errors during RH operations, by understanding which the most relevant and useful information are to be sent to the operators for the decision-making process. With reference to 7.2, the collected data shall be filtered and then showed to the operators in the most comprehensible way as possible within a Human Machine Interface.

7.4. Control System Management

The Control System will have a hierarchical management structure, with a RH Supervisory Control System and at least one Low Level Control System. The Supervisory Control System will be in charge of the coordination of the different robotic machines' operations and of the actions taken by the operators of the lower levels. Therefore, there will be a clear demarcation of roles in the Control Room of the REMHAT facility, with the operators of lower level who will teleoperate and control the robotic equipment under the supervision of the operators of the Supervisory Control System, i.e. the supervisors. The HMI and the information at disposal of the operator will be different on the basis of him/her role. Some actions shall only be in charge of the supervisors, or however allowed only after the acceptance by the supervisors, like, for instance, the switch to a different control mode. Once accepted, the operations shall be as simple and user-frinedly as possible, in respect of the principle of usability of the HMI. The Supervisory Control System shall also be provided with a Machine Protection Module and a Safety Module, to ensure the correct and safe execution of the procedures. Dedicated systems to predict, highlight and avoid possible imminent collisions shall be implemented. The supervisors shall also have the possibility to immediately stop the procedure if needed.

8. Conclusion and future works

In this work the project of a new REMote HAndling Test (REMHAT) facility for testing and validation of RH procedures has been introduced. The new facility aims to take a step further than the ones already realized for the same purposes:

- The Human Operator will be placed at the centre of the project, whose first goals will be to:
  - Assist the operators in the decision-making process, to increase their situational awareness and available information;
  - Enhance operators' comprehension of the RH activities, equipment and environment;
  - Increase operations' safety and reduce the risk of components' damage, preventing possible human mistakes.
- Virtual and Augmented Reality techniques will be developed and implemented in a unique multiuser platform able to make many operators and systems collaborate on the same digital twin of the real environment. Techniques for real-time prediction of robots' trajectories and structural behaviour will be studied in order to be also represented in the Virtual and Augmented Reality environments and give more accurate and realistic information to the operator, avoiding possible mistakes or accidents.
- An innovative Control Room, where this collaboration can take place, will be realized.
- REMHAT will be the first facility to feature several robotic machines, even capable of working together (as in case of rescue operations).

Following a System Engineering (SE) approach, the main requirements of the facility have firstly been defined and then translated in the respective functions to be provided. Subsequently, a logical architecture has been presented, dividing the facility in four main Sub-Systems (S/S): building and auxiliary services, mock-ups, robots and Control System. Focusing the attention on the role and the functionalities of the Control Room, its preliminary physical architecture has been proposed, with the description of its main sub-systems and their criticalities.

Future activities will regard the following stages of physical design, integration, validation and verification of the REMHAT. Particular attention will also be paid on study solutions to overcome the criticalities highlighted in the present work. Once the design process will be completed, the training of the Human Operators and the testing, validation and optimization of the RH operations and equipment will start, with the aim of making available important results and advances not only for DTT project but for each nuclear reactor and, more in general, for each application requiring Remote Handling in challenging environments.

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