Kinematic simulation activities of the CMM, CTM and Boom systems.

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DIV-IDTT.S.04-T015-D003
DTT-EUROfusion Midterm Meeting – June 23, 2022

DTT Consortium (DTT S.C.a r.l. Via E. Fermi 45 I-00044 Frascati (Roma) Italy)

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Introduction

Virtual simulations have a crucial role in the Design of the RH equipment.

Conducting virtual simulation RH equipment in the early stages of design allows to identify design errors or critical aspects that may be inspected.

For this reason, an iterative design process is the right way of optimizing the concept of the RH equipment.

OBJECTIVES OF THE SIMULATION

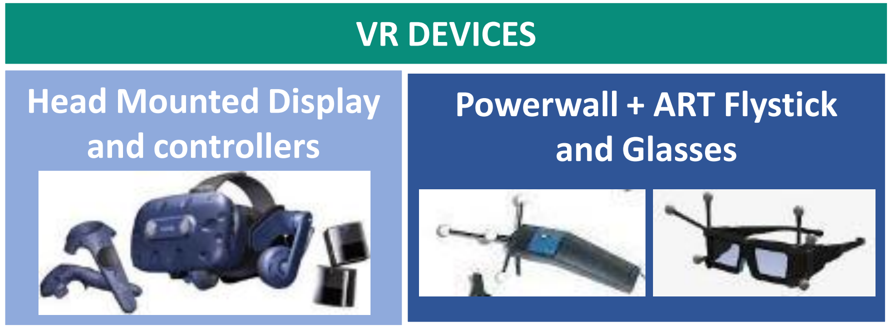
Virtual simulations have been carried out to verify if the design of RH equipment is consistent with functional requirements, in terms of:

- Reachability of the required zones
- Avoidance of unwanted **collisions** with the in-vessel components

THE ROLE OF VIRTUAL REALITY:

The possibility to visualize, navigate and interact within an immersive virtual environment allows to inspect such a complex system.

It is possible to view in-scale 3D models, inspect each subsystem from several point of view, further to test, evaluate and learn new RH procedures.



About the simulations

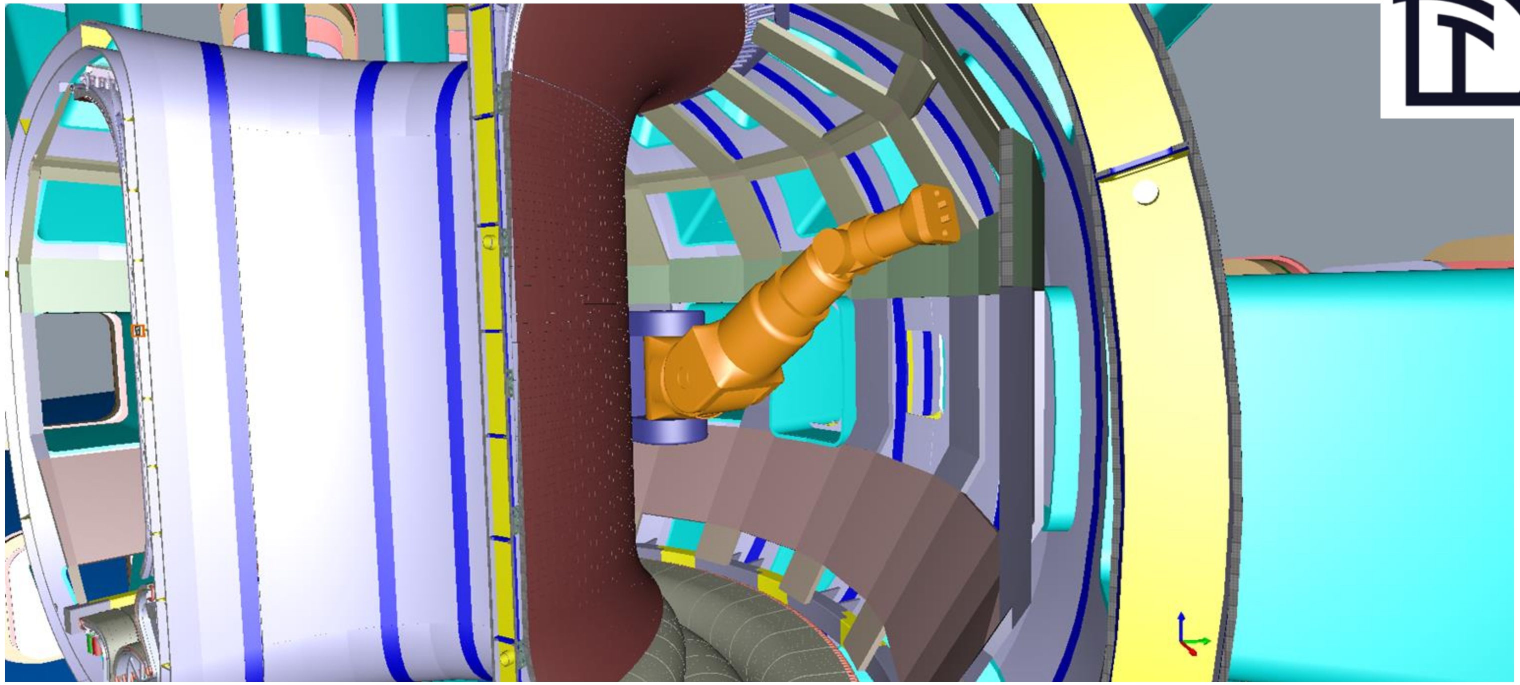
Outline:

- Applied **Methodology** for Forward and Inverse Kinematic approaches
- Implementation **workflow**
- **Results** and discussion

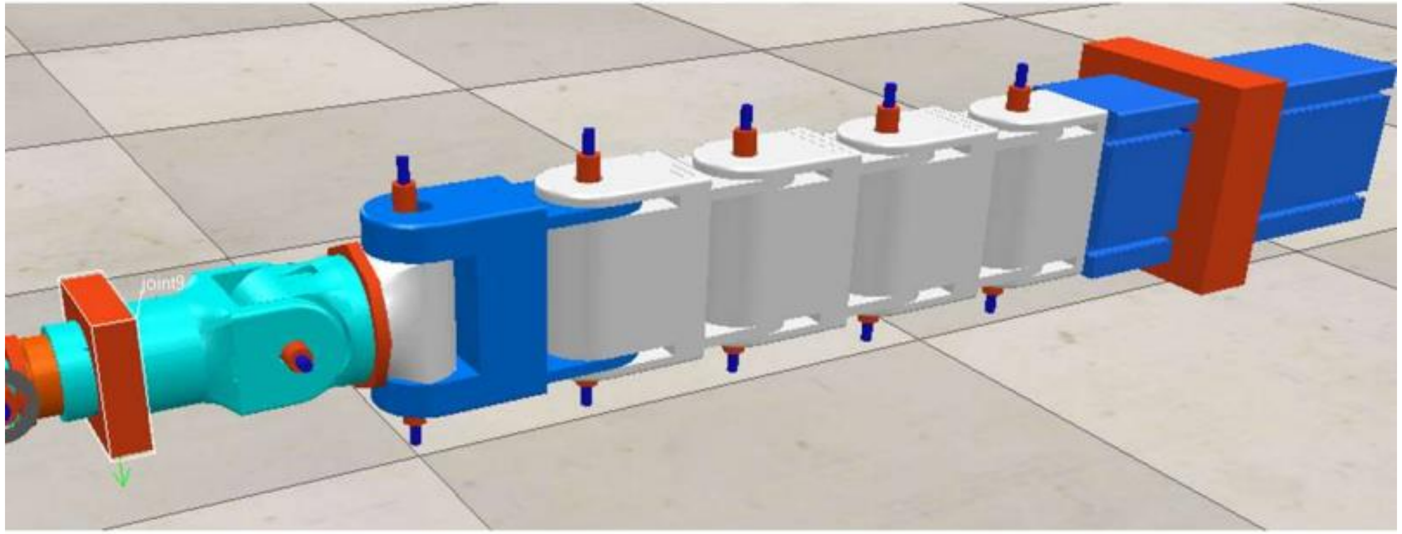
SELECTED PLATFORMS FOR VIRTUAL SIMULATIONS OF THE HYRMAN (Rigid Bodies Hypothesis):

- **DELMIA V5 (Forward Kinematics):** a platform for 3D CAD modeling that enables manufacturing organizations to design, simulate, optimize and program robotic workcells in a digital factory environment.
- **COPPELIASIM (Forward and Inverse Kinematics):** a robotic simulator for factory automation simulations, fast prototyping and verification, robotics related education, remote monitoring, safety double-checking, as digital twin, etc.

Hyrman



Direct and Inverse Kinematic Simulations within Virtual Immersive environment



The Hyrman Concept Design

- The Hyrman robot is a serial manipulator made of a sequence of 12 joints (10 revolute and 2 prismatic), divided into a planar and a dexterous arm:

- The **planar arm** must be moved in order to reach a convenient point in the VV. The idea is to position the base of the second segment of Hyrman, that is dexterous and capable to reach all the points in the poloidal section, in a suitable point along the equatorial line in order to allow reachability of the required points/trajectory.

- The **dexterous arm** of the Hyrman is commanded in cartesian space along the required trajectories.

Planar robot (D-H)

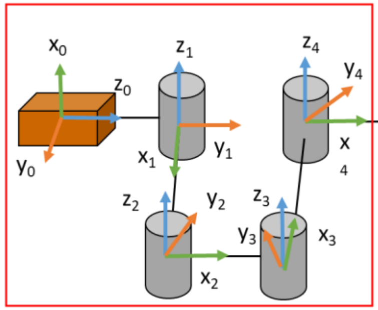
link	d	a	α	ϑ	Offset
1	q_1	0	90°	-90°	0
2	0	0.75 m	0	q_2	90°
3	0	0.75 m	0	q_3	0
4	0	0.75 m	0	q_4	0
5	0	0.75 m	0	q_5	0

Joint RoM

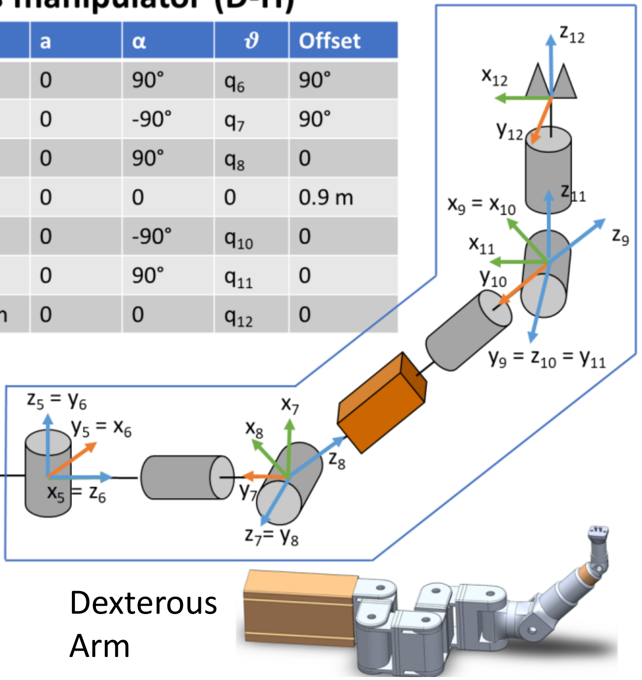
q_1 = [0 ; 6.7 m]
q_2 = [-100° ; 100°]
q_3 = [-100° ; 100°]
q_4 = [-100° ; 100°]
q_5 = [-100° ; 100°]
q_6 = [-100° ; 100°]
q_7 = [-180°; 180°]
q_8 = [-100° ; 100°]
q_9 = [0 ; 0.8 m]
q_{10} = [-180° ; 180°]
q_{11} = [-100° ; 100°]
q_{12} = [-180° ; 180°]

Dexterous manipulator (D-H)

link	d	a	α	ϑ	Offset
6	0	0	90°	q_6	90°
7	0.6 m	0	-90°	q_7	90°
8	0	0	90°	q_8	0
9	q_9	0	0	0	0.9 m
10	0	0	-90°	q_{10}	0
11	0	0	90°	q_{11}	0
12	0.526 m	0	0	q_{12}	0



Planar Arm



Dexterous Arm

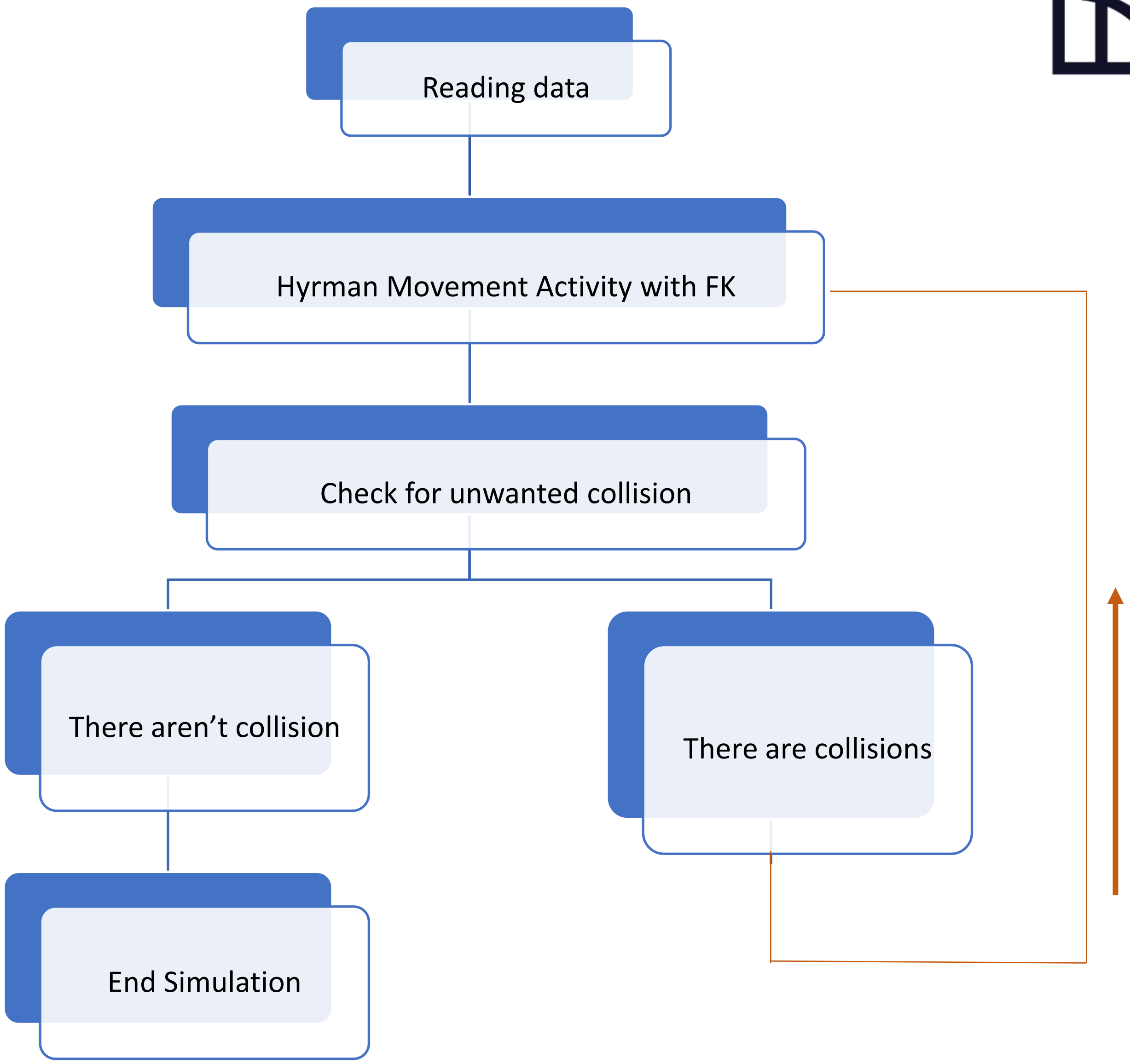
FK Simulations within DELMIA V5

THE ITERATIVE PROCESS:

Starting to apply a **Forward Kinematic algorithm**, the manipulator's output trajectory was obtained through an **iterative process**.

The robot is moved in the joints space and each movement is evaluated to avoid any collision with in-vessel components.

If a collision is detected, new joint values must be inserted, till a collision-free solution is found.



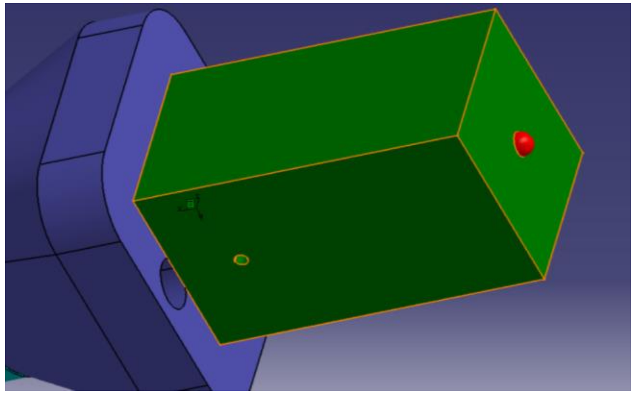
FK Simulations within DELMIA V5

WORKFLOW OF IMPLEMENTATION:

Three activities were implemented to complete the assigned tasks:

- “**Movement activity**” involves every kind of movement for an item. In case of Forward Kinematics, this consists in selecting the component and entering manually the values for each joint, paying attention to not exceed their limits.
- “**Capture activity**” allows to keep attached an item to the selected one. It was used in simulations that required to grab and move components with the Hyrman.
- “**Release activity**“ is the opposite of the previous one, allowing to leave the item that was attached. It was used to place a component in its slot.

In absence of the gripper’s 3D-model, a green prism with dimensions of **150x150x250mm** with a semi-sphere on it has been attached to the manipulator’s end effector to simulate the presence of the tool. (Fig.).



Test Cases - DELMIA V5

TC #1) Hyrman Left and Right Deploy Position ✓

TC #2) VV sectors Inspection in several sections, with tool distance of 100 and 200 mm: ✓

Sometimes a change of the specific section was necessary to carry out the inspection movements.

TC #3) Near IFW handling for removal (IFW-R-1 module: the most critical) ✓

TC #7) Far OFW module 2 removal ✓

The manipulator resulted to be not able to take the modules through the port

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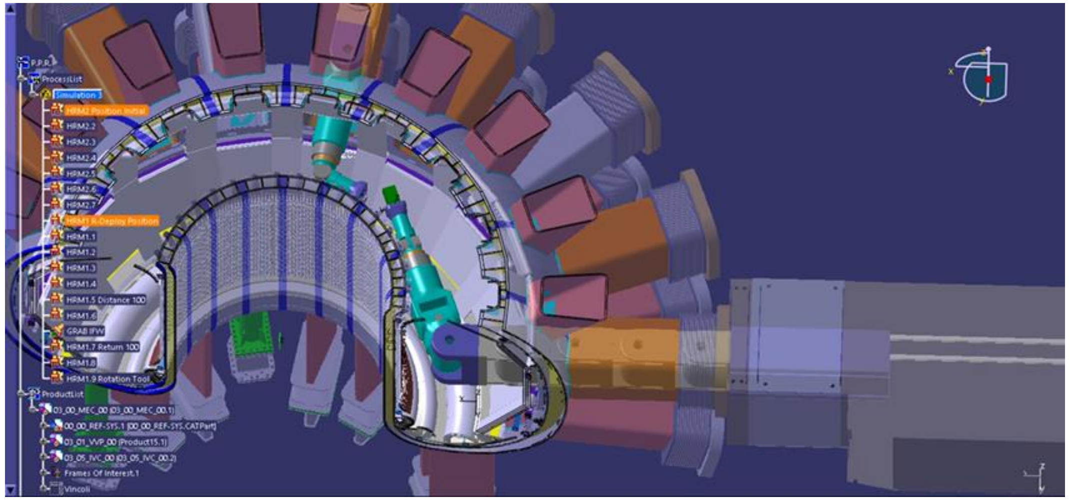
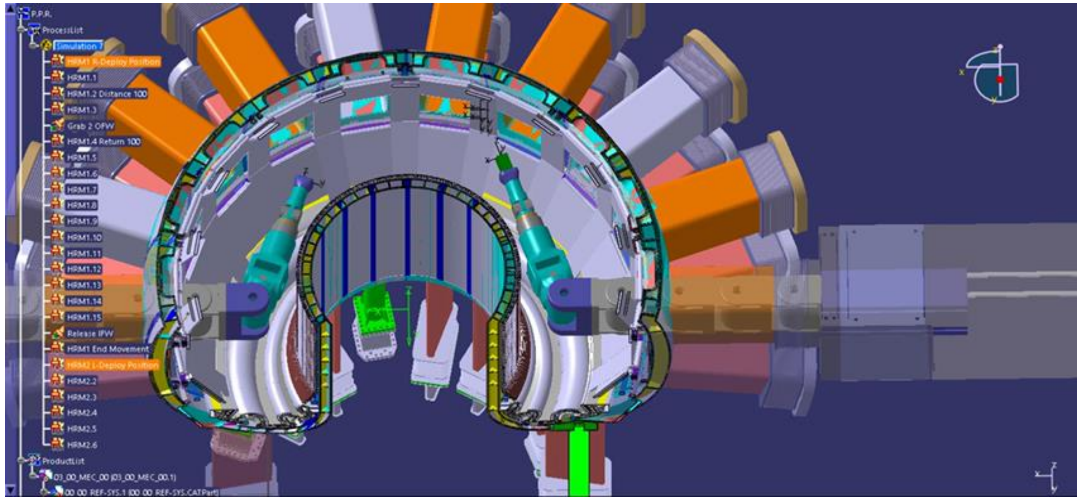
TC #3) Near IFW-R-1 module handling for removal



TC #7) Far OFW module 2 removal



What has resulted - DELMIA V5

- Simulations of Test Cases #3 and #7 outlined the necessity to deeply investigate manipulator's interfaces with IVC, since it was not able to conduct the required movements. For instance, the insertion of a 13° revolute joint around trasversal axis could be one of the alternative solutions to be evaluated and tested.

INVERSE KINEMATIC PROBLEM:

- Regarding the **Inverse Kinematic algorithm,** it was found that the IK solver programmed within DELMIA is not able to manage kinematic chains characterized by more than 6 joints. The reason is that this software was originally designed to simulate robotic cells and manufacturing contexts in which the robotics systems does not generally have more than 6 joints (or even 6 D.O.F.s).
- The main consequence of this discovery about DELMIA characteristic is a limited evaluations on the conducted simulations, since the fact that a solution was not found for a specific Test Case does not necessarily mean that the solution does not exist. This criticality has caused the necessity to subsequently move to another virtual platform.

FK and IK Simulations within CoppeliaSim

OBJECTIVES OF THE SIMULATION

- Virtual simulations were required to verify if the design of the serial manipulator Hyper Redundant Hyrman is consistent with functional requirements, with the need of overcome the DELMIA’s limit about IK.

Therefore, the simulation had to be conducted with both Direct and Forward Kinematic algorithms, to guarantee the reliability of the results and its independence by the team responsible of conducting the simulations.

FORWARD KINEMATICS FOR PLANAR ARM

FK has been applied to the planar arm: in line with the task specification, it was required that the planar arm should just translate into the port, without any rotation applied to the joint. For this reason, only if necessary, these joints were moved in FK.

INVERSE KINEMATICS ON : PATH PLANNING APPROACH

Due to the fact that the manipulator is redundant, the only application of the **Inverse Kinematic** algorithm, is insufficient to determine **univocally** if a task is feasible or not. Therefore, a **Path Planning** process can be the right instrument to search and verify the infinite set of possible trajectories, within a defined range of time.

FROM IK TO FK: An auxiliary script has been added to display in real-time the joints configuration, obtained by the application of IK algorithm. These values will be stored and may be useful for other analyses.

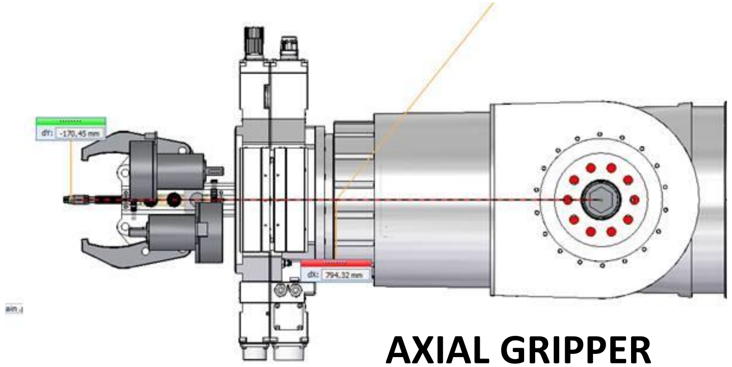
FK and IK Simulations within CoppeliaSim

WORKFLOW OF IMPLEMENTATION:

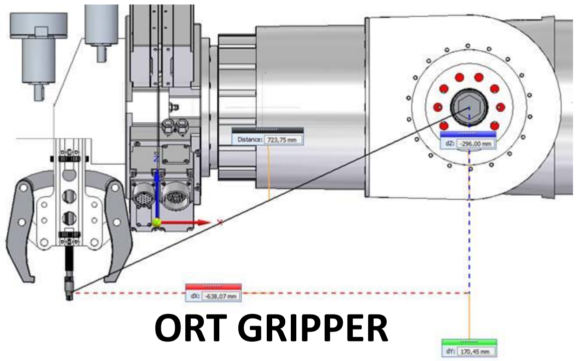
1. Schematize the Environment and the HyRMan with *Pure Simple Shapes*
2. Set the Position and the Orientation of the simulation's *Target*
3. Activate the IK algorithm and Program the main Path-Finding / Collision Avoidance *Script*

THE PROPOSED ALTERNATIVES TO THE INTRODUCTION OF THE 13° JOINT: THE AXIAL AND ORT GRIPPERS

- To avoid any modify to the designed kinematic chain of the Hyrman, a first alternative solution was proposed: the use of two different grippers: one axial (left side of the figure), and the other with the head rotated of 90° (on the right side). This solutions needed to be tested within the new virtual platform.



AXIAL GRIPPER

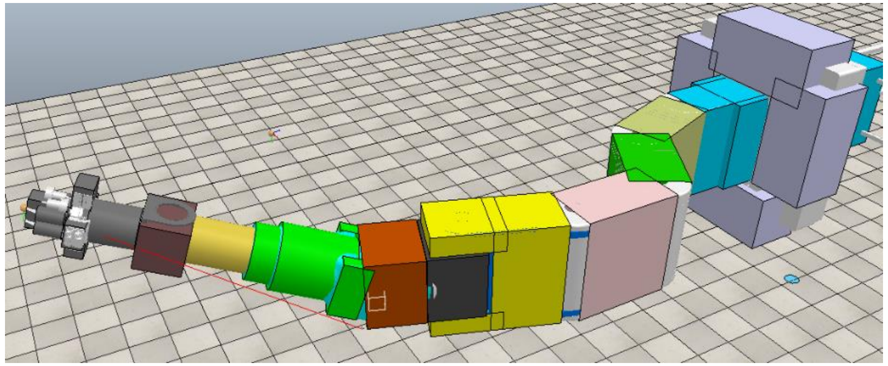


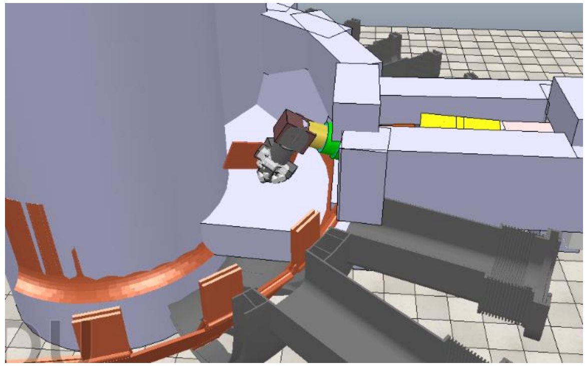
ORT GRIPPER

FK and IK Simulations within CoppeliaSim

1. Schematize the Environment and the HyRMan with Pure Simple Shapes

Since CoppeliaSim can properly manage the collision avoidance of only simple shapes, even better if only concave, a fundamental preliminary action is the attribution of the so-called *Pure Simple Shapes* to every component (which are mainly cuboids and parallelepipeds). These shapes were considered as rigid bodies, which will be not visible during the simulation.

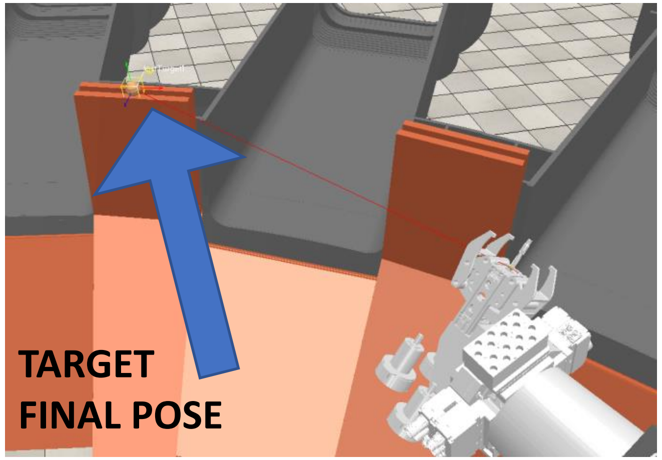




HyRMan and Tokamak environment simplified with *Pure Simple Shapes*

- 2. Set the Position and the Orientation of the simulation's Target

- A specific **path** (which is the succession of several points position and orientation) has been planned and a **Target** defined. The Target is the primitive object which must follow that path.
- When the simulation is turned on, the manipulator's end-effector follows the same trajectory of the Target to make perfectly match the two triads: one centered in the Target and the other inn the Hyrman's gripper.
- The movement of the end-effector was programmed via **script**.



The manipulator's end-effector follows the Target's path

FK and IK Simulations within CoppeliaSim

3. Activate the IK algorithm Program the main Path-Finding / Collision Avoidance Script

Once the Target Pose has been defined, the manipulator's end-effector should follow a certain path to reach it.

A **Path Planning** was employed: among different types available inside CoppeliaSim, the **RRT*** was applied. It is a trajectory planner that, with a more than 90% reliability (it arrives asymptotically to the solution), verifies all possible trajectories, taking a list of constraints into account.

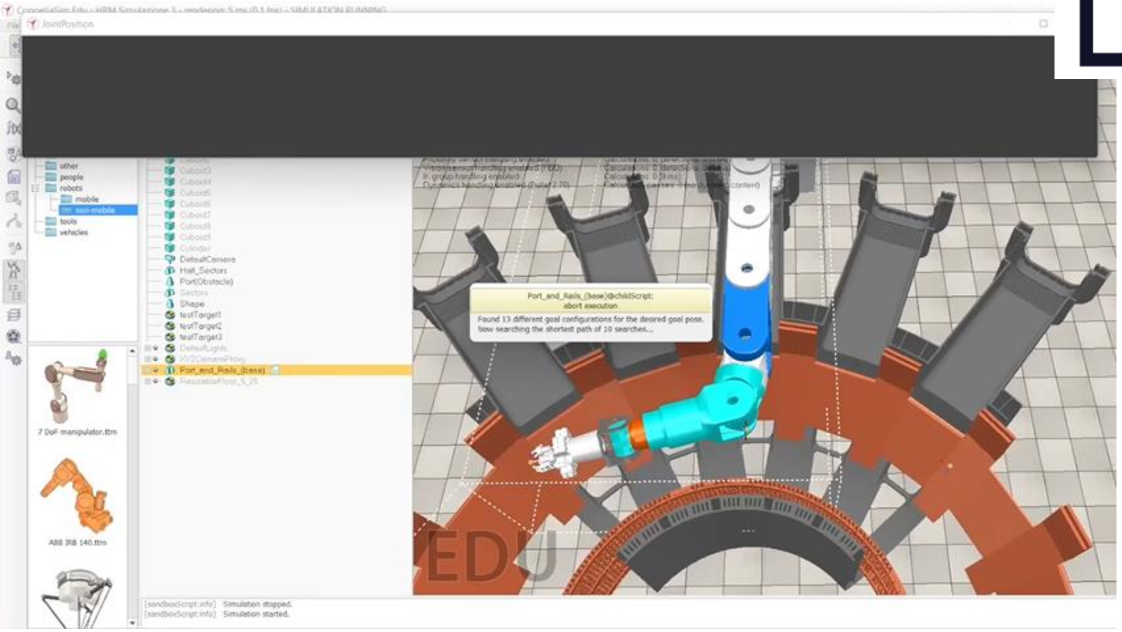
In this case, the first constraint was to avoid collisions with in-vessel components. In addition, also the minimum time required to complete the trajectory has been introduced as constraint. Therefore, the Path Planning script allows to find and select, if exists, the ***shortest collision-free trajectory***.

This allowed to affirm that, in case of no trajectory found, the disruption factor was not caused by the design team's choices, but possibly by an insufficient processing time set (we chose a maximum time of 8 hours). Otherwise, a collision-free path was not possible.

RRT* stands for: Rapidly exploring Random Tree (RRT). It is an algorithm used in Machine-Learning, designed to efficiently search nonconvex, high-dimensional spaces by randomly building a space-filling tree.

Test Cases – COPPELIASIM

TC #3) Near IFW-R-1 module handling for removal

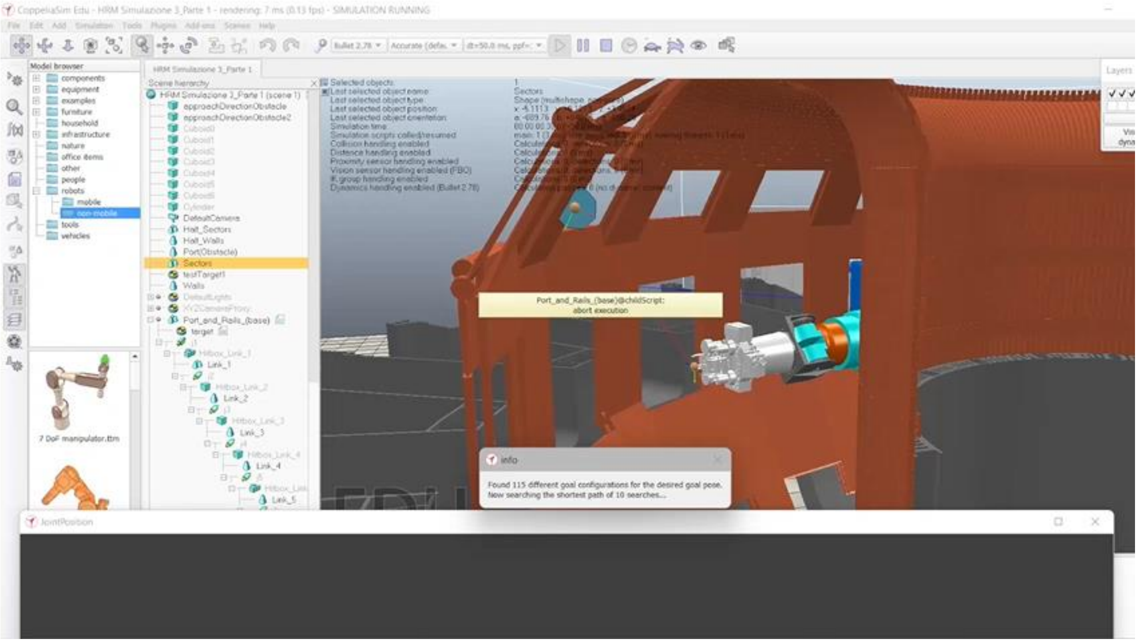


TC #1) Hyrman Left and Right Deploy Position ✓

TC #3) Near IFW handling for removal ✓

The simulation gave positive results with the **Axial Gripper**

TC #7) Far OFW modules 1 removal



TC #7-8-9) Far OFW module 1 ✓ **and module 2** ✓ **removal**

The simulation of removal of module 1 ended successfully, with the employment of the **Ort Gripper.**

The simulation of module 2 removal did not give positive results.

Conclusions on Hyrman's simulations

- The **Forward Kinematic** simulations conducted within DELMIA V5 offered a first **iterative** approach to the kinematic analysis of the designed Hyrman, outlining the criticalities that may occur.

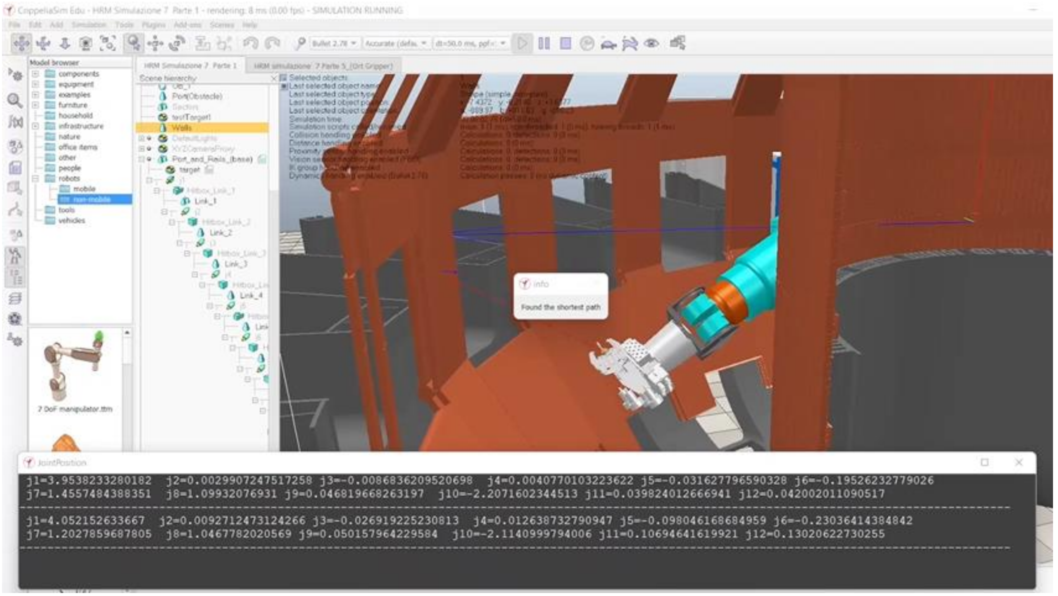
- A second platform as CoppeliaSim was necessary to apply the **Inverse Kinematic** algorithm (and **Motion planning script**) to be confident that the results were **reliable** and all the tasks were effectively feasible (or not).

THE MOTION PLANNING SCRIPT CAUSED HIGH COMPUTATIONAL TIME:

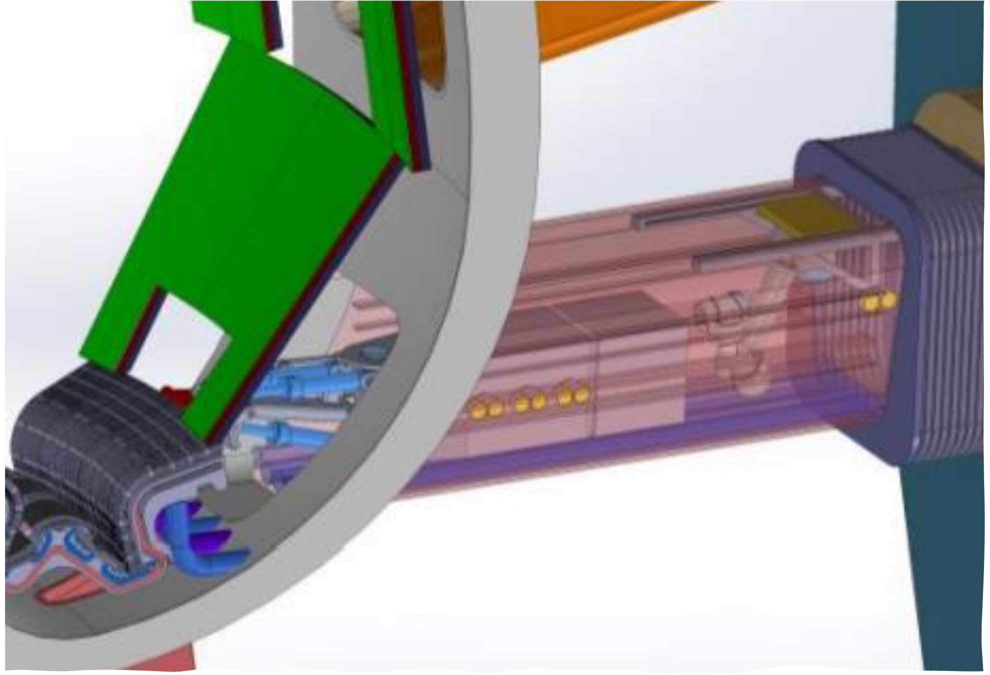
The employment of a robotic simulator such CoppeliaSim have outlined a new aspect about the high **computational time** required if an Inverse Kinematic algorithm is applied on a **hyper redundant kinematic chain** and the respective need of maintaining and optimizing the script.

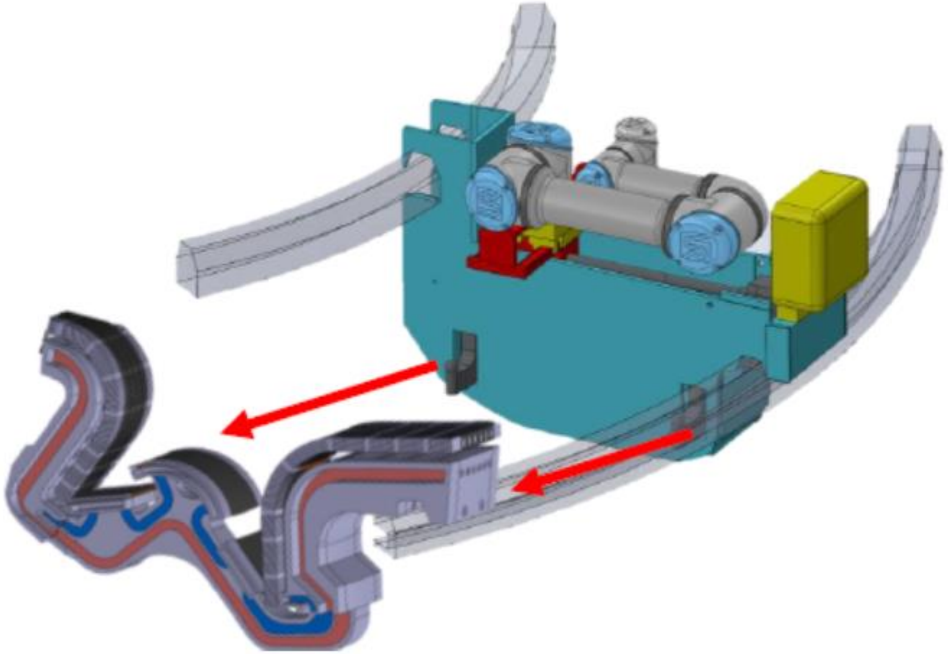
To reduce the computational time required*, the simulation of all the Test Cases was divided into **sub-simulations:** the end-effector's trajectory was divided into intermediate paths.

*Maximum computational time allowed was fixed to 8 hours for a first evaluation.



TC #7) Far OFW module 2 removal



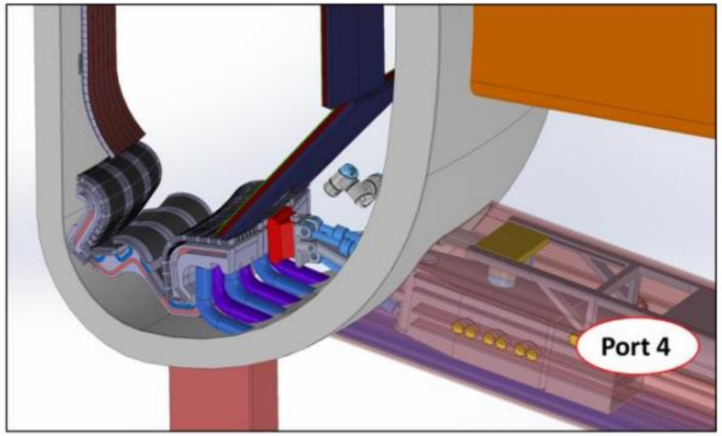


CMM and CTM

Preliminary simulations within Virtual Immersive environment

Preliminary simulations of cassette movers (CMM and CTM)

The Cassette Multifunctional Mover (CMM) and Cassette Toroidal Mover (CTM) are the main components of the RH equipment, together with Hyrman. These robotic systems are responsible for maintenance operations (mounting and substitution) on the divertor cassette.

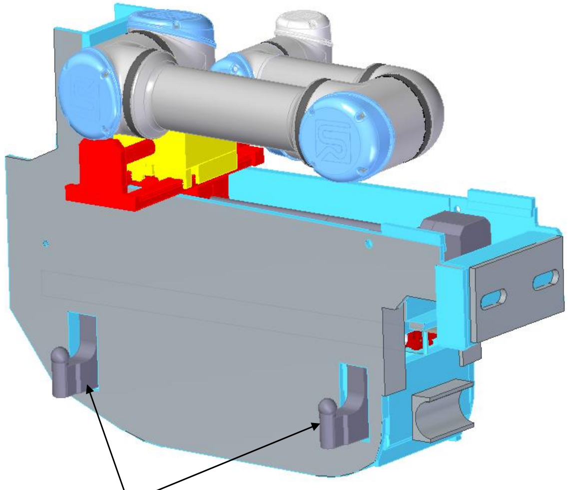


CMM

Preliminary simulations within Virtual immersive environment are already in progress, waiting for the definition of the fixation system and the cassette.

The adopted approach is based on **Forward Kinematic**, considering the low level of complexity of the robot’s kinematic chain.

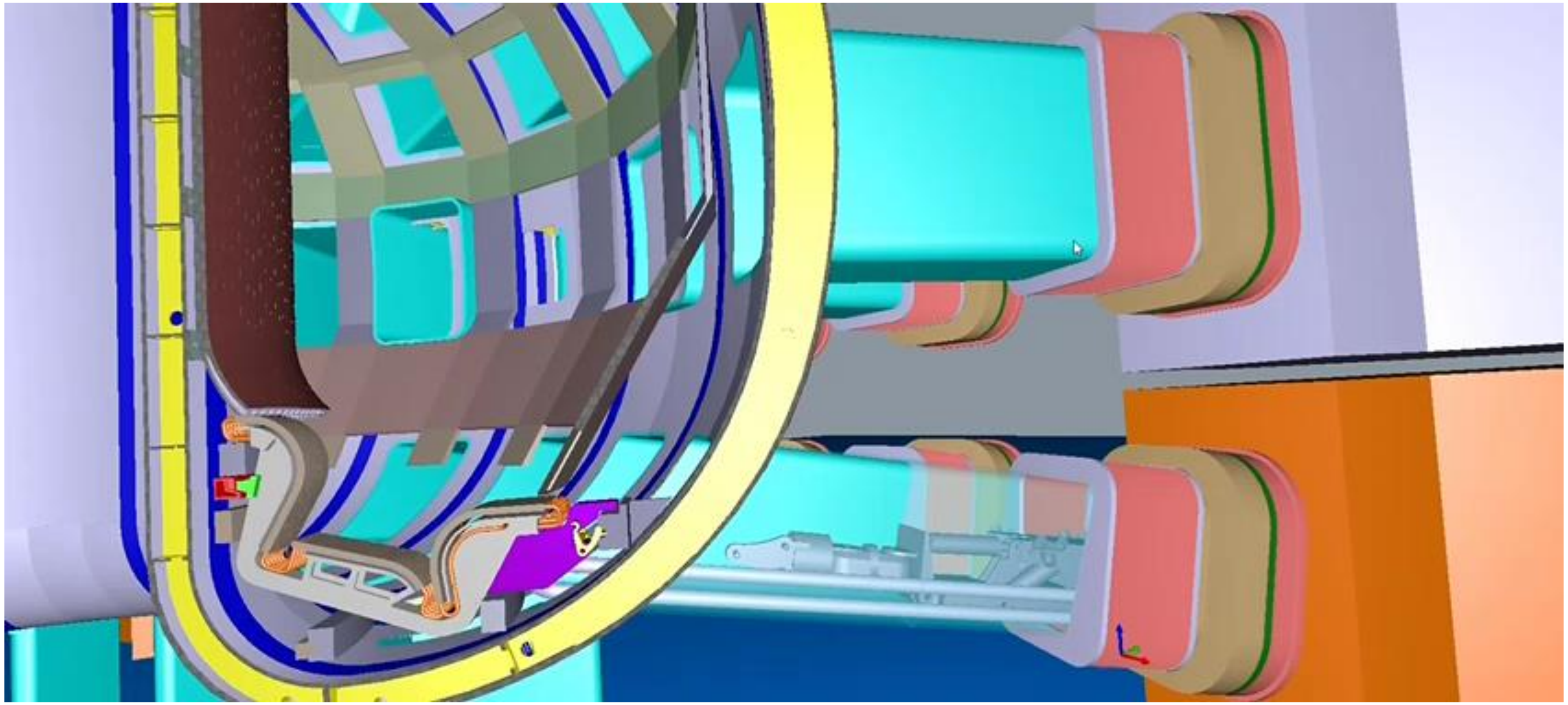
First simulations have allowed to visualize and discuss the RH strategy and start to evaluate the robotic system in terms of **encumbrance** and **collisions**.


CTM

Cassette Multifunctional Mover (CMM)

The Cassette Multifunctional Mover (CMM) is the robotic system depicted to handle divertor central and lateral cassettes of RH sectors. It is responsible for the following operations:

- Cassette gripping/releasing
- Cassette rotation about X axis for extracting/installing it from/to the toroidal rails
- Lateral Cassette moving
- Cassette transportation inside the port #4 duct



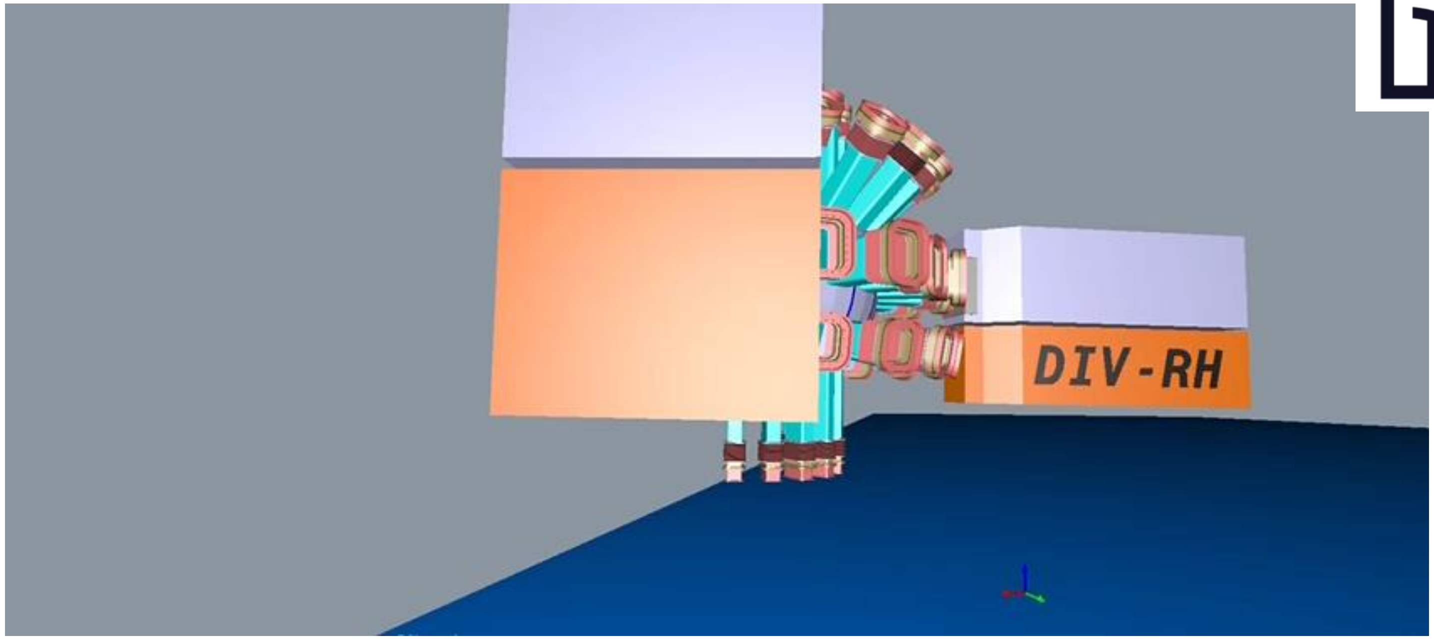
The Cassette Multifunctional Mover (CMM) with side grip resulted to be able to grab the divertor and take into through the port, without any collision occurring.

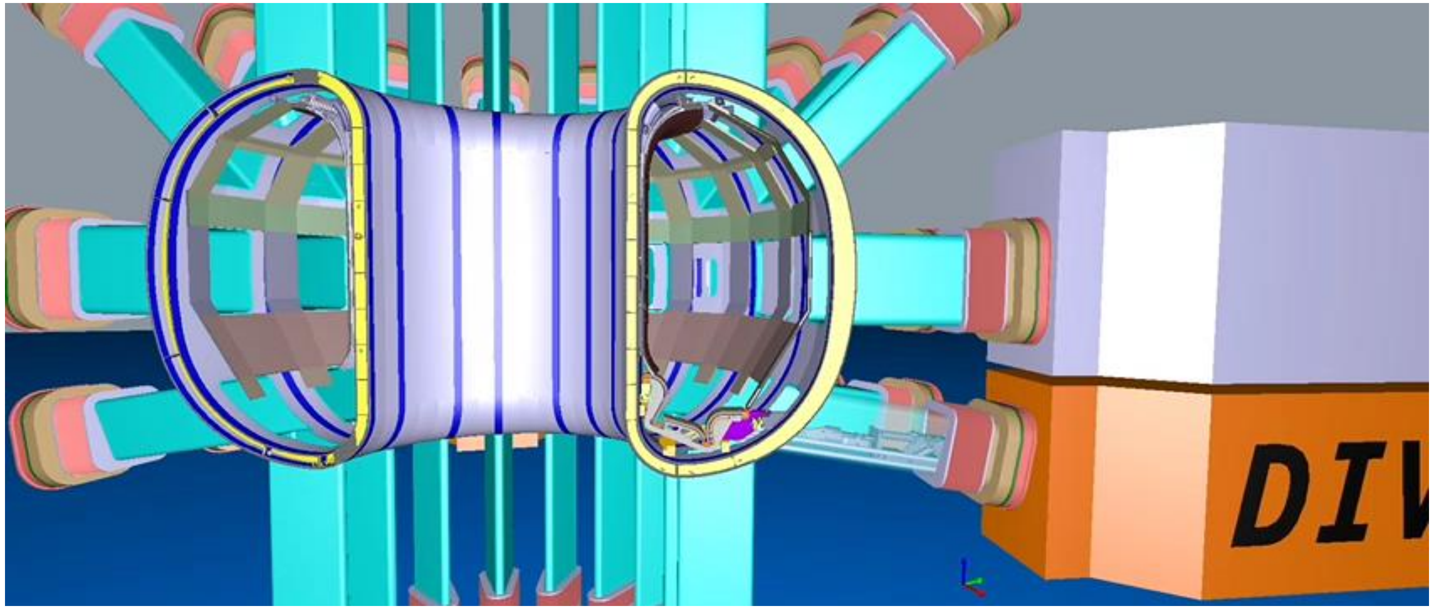
Cooperative Design Review Sessions

Since RH equipment is a strongly complex system, several modifies may be necessary.
Consequently, it is necessary to keep the simulated virtual environment constantly **updated** and easily **available** for **quick tests** about RH equipment and strategies.
For this reason, a **Cooperative Immersive** environment has been implemented. It offers the possibility to:

- Navigate inside and outside the VV, to access narrow points.
- Turn on/off the visibility of each subsystem (cryostat, VV, ports, coils, RH equipment) to inspect a specific part of the assembly.
- Interact with the components.
- Interact with other users, even connected remotely.

A Cooperation between different teams within the same virtual immersive environment is crucial to achieve an optimized concept of the RH equipment.

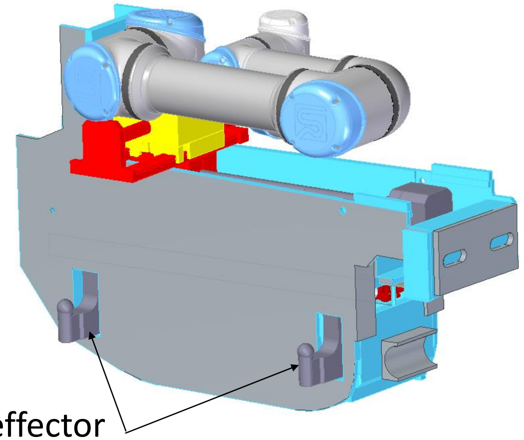




Cassette Toroidal Mover (CTM)

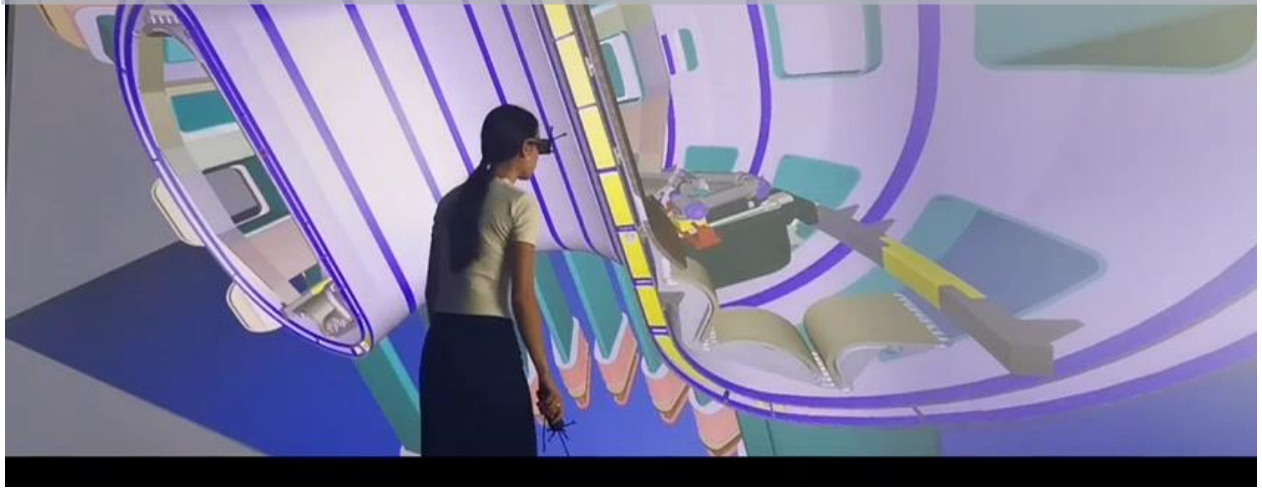
The Cassette Toroidal Mover (CTM) is the robotic device responsible for handling standard divertor cassettes inside the vessel. It moves along the toroidal rails to reach the standard cassettes and carry out the following operations:

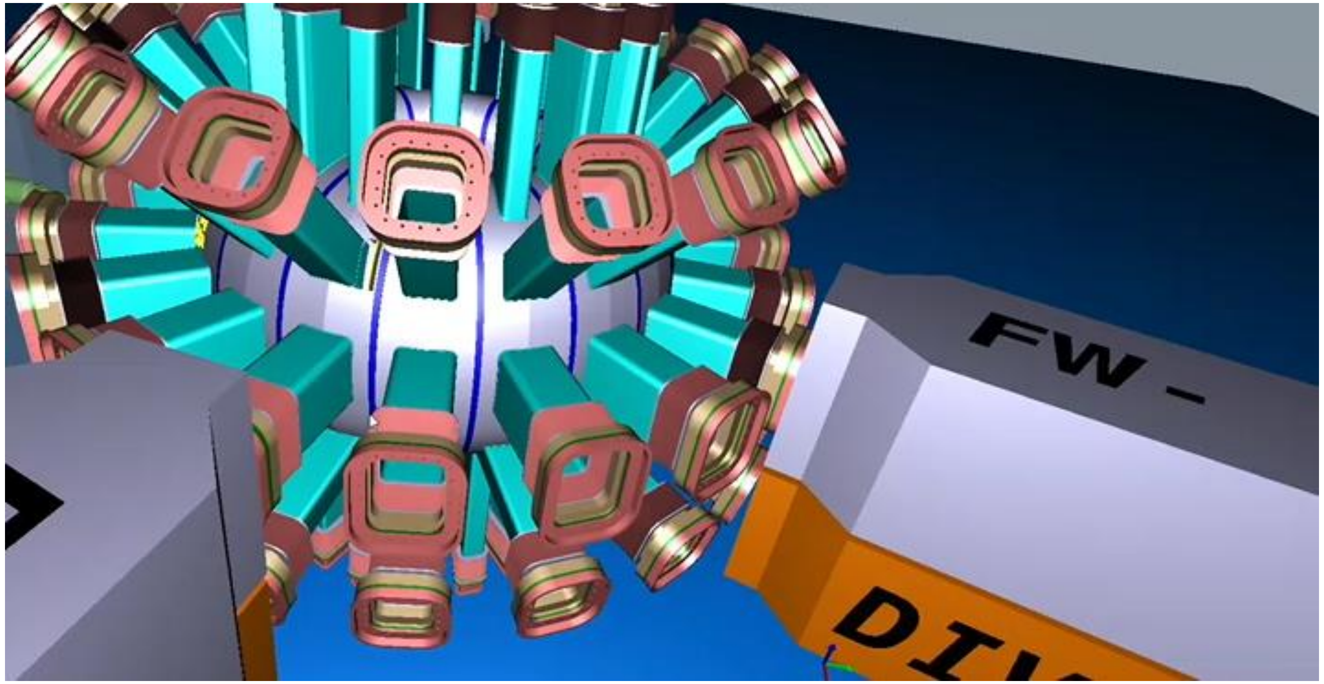
- Standard Cassette gripping/releasing
- Standard Cassette moving along toroidal rail
- Standard Cassette positioning in correspondence of the port #4 for transportation inside the duct by the CMM



Preliminary simulations gave positive results about the existence of a collision-free path for CTM movements needed to reach the divertors.

VR system: Powerwall and ART 3D glasses and flystick
CESMA's Virtual Reality Laboratory, University of Naples Federico II





Conclusions on CMM and CTM simulations

- Preliminary simulations within Virtual immersive environment allowed to have a first evaluation of the RH strategy about the feasibility of collision-free trajectories for the equipment dedicated to the divertor handling.

- The possibility of being immersed within Virtual simulated environment highlighted also the current critical aspects about the design of divertor cassettes and fixation system. In addition, the dedicated tools and interfaces for the divertor grabbing should be investigated, to introduce them in the simulations.

- Studies about the most suitable software for CMM and CTM's simulations are already ongoing. The decision is particularly influenced also by the choice/necessity of conducting analyses based on FK, IK or both.

Thanks for the attention

WP DIV-IDTT.S.11-T002 - D005
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This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.