The nordic man of the street

Preliminary configuration of a robotic arm for pipeline maintenance in the DTT reactor

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Abstract. The maintenance of the DTT nuclear fusion reactor will be operated by a remote handling system which includes a number of specifically designed manipulators and robotic arms. This work aims to disclose the preliminary consideration for the design of a robotic system intended to handle pipes that must be periodically substituted in port 4 of the vacuum vessel.
As the port appears as a narrow duct with a trapezoidal section, the arm must satisfy strict requirements in term of incumbrance and, at the same time, it must ensure the capability to remove and reposition the pipes which are displaced al around the perimeter of the section.
The configuration is analyzed considering the geometrical constraints and the requirements for the workspace.
The paper proposes a first design for the manipulator and shows the obtained workspace.

Keywords: nuclear fusion power plant; remote handling; maintenance

1 Introduction

Divertor Tokamak Testing (DTT) is a tokamak fusion power plant in construction at ENEA facility in Frascati, Italy[1]. It is a part of the European program in fusion research and its main objectives are to test different plasma solutions and divertor geometries for the DEMO power plant[2]. The in vessel environment is characterized by extremely high temperatures and high neutron fluxes [3] so that in vessel components are subjected to wear during the functioning of the plant. The most stressed components are the First Wall (FW) and the divertor, and they require to be substituted several time in the lifetime of the plant [1]. The in vessel environment is not suitable for direct maintenance provided by humans, so remote maintenance systems needs to be developed to perform in-vessel handling and maintenance. Furthermore, remote maintenance systems design is strictly correlated with the constraints given by the tokamak geometries, such as number of ports, orientation, dimensions, which have been defined taking care of the remote handling necessities [4]. Strategies to perform remote maintenance operations in DEMO and DTT power plants have been assessed in [5] and [4]. The remote handling system to replace the FW module and the divertor module has been designed in previous works [6], it involves the use of a highly redundant robotic manipulator. When possible pipes for technical fluids are substituted in groups of 3 or 6 [7]. However, the current DTT design involves tubing to connect in vessel modules with the rest of the plant. These pipes modules need to be removed and replaced during remote maintenance operations. This work proposes a preliminary analysis for the configuration for a robotic arm to perform remote maintenance of the pipeline in the DTT reactor. The designed robotic arm serves the specific purpose of facilitating precise tasks such as positioning, extracting, and welding cooling pipes within Port #4 of the DTT reactor during the maintenance operations. In Fig 1 [3] a rendering image of a section of the DTT Vacuum Vessel (VV) is provided, with the red arrow that indicates the Port #4, through which the robotic arm will be deployed.

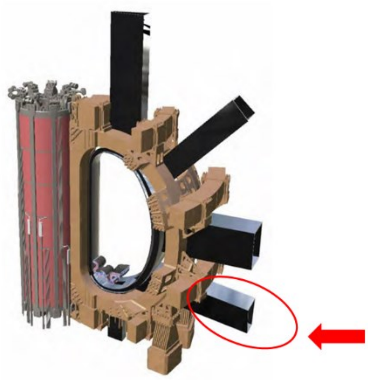

Fig 1 DTT Vacum Vessel section [3]

The robot needs to navigate freely within the duct while maintaining compact dimensions. High precision is crucial for aligning the pipes, considering the reactive forces on the robotic arm. Sufficient stiffness is required to hold the position during alignment operations, without the need for high movement speeds. This work focuses on defining a robot architecture suitable for ensuring full operability within the disposable room at Port #4, aiming to ensure that all pipes can be accessed and maintained with satisfactory dexterity.

A parametric model was created, and the parameters were defined through workspace analysis, ensuring that the robotic arm can reach all points within the conduit without encountering singularities, thus ensuring greater efficiency and safety in its operation. CAD models of the robotic manipulator and its end-effector were developed. The use of multibody environment allows flexibility of the bodies to be considered in subsequent phases of the design process [8].

2 Work environment

2.1 DTT Machine design

The Vacuum Vessel (VV) is located inside the magnet system. It provides an enclosed, vacuum environment for the plasma and also acts as a first confinement barrier. The VV shall provide several openings for the plasma diagnostic systems, the vacuum system, the auxiliary heating system, the in-vessel Remote Handling (RH) maintenance system, etc. Each 20° vessel standard module is equipped with 5 access ports conceived as single-walled structures welded to the main vessel [9].
The dimensions of access ports are shown in Fig 2.

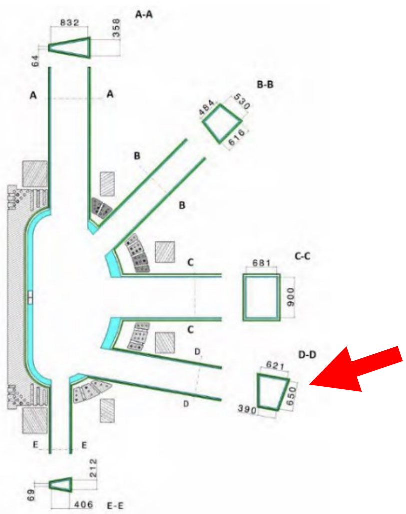

Fig 2 Dimension of access ports of a standard vessel module

The robot is required to operate within Port #4, marked with the red arrow in Fig. 2, which features a conduit with a length of 2906 mm and an inclination of 10°.

2.2 Definition of objectives and requirements

The main operational objectives of the manipulator robot are:

- To extract pipes approximately 2500 mm long, with an outer diameter of 60 mm and a mass of 3 kg.
- To introduce the pipe and position it with positional accuracy on the order of 0.1 mm and angular accuracy of 0.1° within the spatial domain.
- The manipulator robot must be capable of reaching all points within the duct without encountering singular configurations.

In accordance with the methodology outlined in [6], used for the sizing of the HyRMan ('Hyper Redundant Manipulator'), the RH equipment dedicated to FW modules handling, the manipulator has to be dimensioned on the basis of the assumptions and constrains imposed by task requirements and vessel geometry. Therefore, it is crucial to evaluate the operational space of the manipulator, i.e., the three-dimensional space accessible to the robot's end effector, and ensure that the volume of the duct falls within the reachable workspace

2.3 Model Assessment

The requirement for maneuverability imposes a robot with kinematic redundancy. Therefore, a manipulator robot with 7 degrees of freedom (DOF) is chosen.
To compute the kinematics and dynamics of the system, the Denavit-Hartenberg (DH) convention is followed [10], which defines the reference frames of the 7 joints.
The orientation between the joint axes, denoted by α_i, is set at 90°, while the distance d_i remains arbitrary. This approach allows for the parametric sizing of the robot.

Table 1 Denavit-Hartemberg parameters

Link	a_i ***[mm]***	α_i ***[°]***	d_i ***[mm]***	ϑ_i *[°]*
1	0	-90	d_1	ϑ_1
2	0	90	d_2	ϑ_2
3	0	-90	d_3	ϑ_3
4	0	90	d_4	ϑ_4
5	0	-90	d_5	ϑ_5
6	0	90	d_6	ϑ_6
7	0	0	d_{EE}	ϑ_7

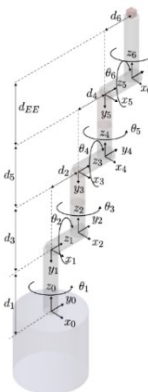

Fig 3 Parametric robot

The manipulator, as defined, is depicted in Fig 3, where dimensions and configuration are parametric.

For the workspace analysis and parameter definition, the robot model
is defined in Simulink through parametric dimensions and configuration. The reachable workspace is evaluated, Fig 4, representing the volume encompassing points accessible by the manipulator.
To assess the workspace, homogeneous transformations of the kinematic chain were calculated. Subsequently, these transformations were employed to determine the set of points in the reachable space by iteratively varying the joint angles. The last degree of freedom is disregarded since the rotation around the final axis does not provide any information to derive the workspace volume.

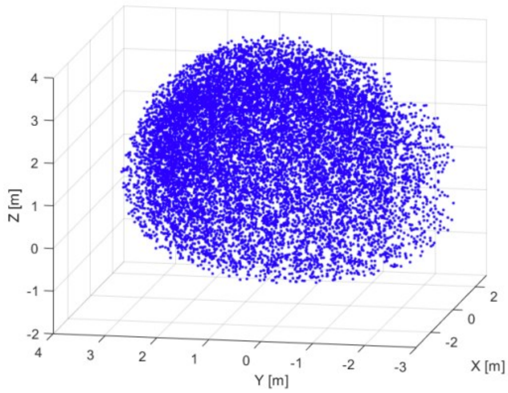

Fig 4 Reachable workspace of the manipulator

3 Preliminary robot design

The robot is axially positioned along the conduit by an additional axis, and the actual position is determined by the Coordinate Measuring Machine (CMM). The conduit is 2900 mm long, while the positioner measures 1800 mm in length. The robot is required to handle pipes which are parallel to the conduit. Axial motion of the pipes is not request to the robot, which is expected to pick up the pipe from its position and bring it in a central position of the conduit in order to make possible its removal, and make the opposite operation to put in place a new pipe.
The design parameters were obtained keeping in mind this goal and the constraints of the application.
The parameters were selected using the program employed to derive the workspace, iteratively adjusting them to ensure compliance with all constraints and requirements [11]. The optimal parameters obtained are listed in Table 2.

Table 2 Denavit-Hartenberg parameters

Link	a_i ***[mm]***	α_i ***[°]***	α_i ***[mm]***	α_i *[°]*
1	0	-90	400	ϑ_1
2	0	90	0	ϑ_2

Link	a_i *[mm]*	α_i *[°]*	α_i *[mm]*	α_i *[°]*
3	0	-90	175	ϑ_3
4	0	90	0	ϑ_4
5	0	-90	160	ϑ_5
6	0	90	0	ϑ_6
7	0	0	240	ϑ_7

As a result, the duct section is completely contained within the workspace of the robot, as shown in Fig 5.

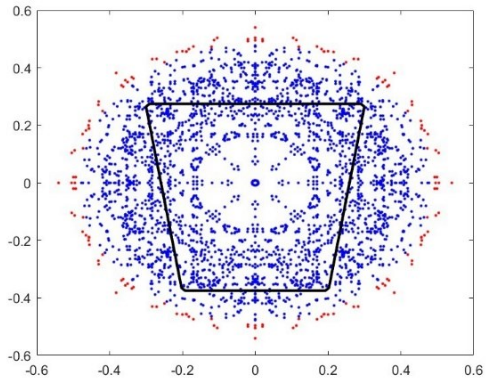

Fig 5 Reachable points and singular points of the manipulator compared with the duct section

In **Fig *4***Fig 5 the blue points represent the reachable points in Cartesian space, while the red ones indicate singular points. It is noteworthy that the reachable points are located within the duct, whereas the singular points are situated outside.

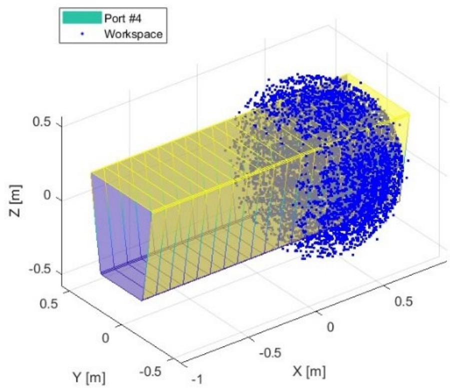

Fig 6 Isometric view of the duct and the manipulator workspace

In Fig. 6 it is shown the isometric view of the duct volume compared with the reachable points of the designed manipulator.

The initial joint configuration was set with $q_2 = 15°$, $q_4 = -15°$ and $q_6 = 90°$ to avoid singularity and reduce the end-effector volume. The manipulator model rendered in SolidWorks is illustrated in Fig 7, left side.

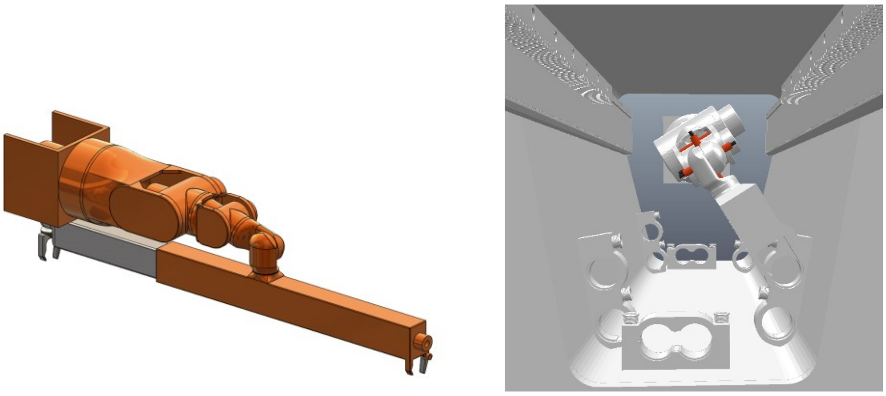

Fig 7 Manipulator model represented in SolidWorks (left) and a view in the duct (right)

The CoppeliaSim software was then used to simulate the gripping and positioning of pipes within the conduit, as shown in Fig. 7, right side, with the aim of evaluating the actual encumbrance of the robotic arm in the duct and the possibility to reach the areas where pipes to be removed will be located. The actual positioning of the pipes will be defined according to several technical considerations, within which the possibility to be handled by the remote maintenance system.

4 Conclusions

The aim of this study is to provide a preliminary configuration of a manipulator robot for pipeline maintenance in the DTT reactor. The results demonstrate that the approach adopted in this project has provided valuable insights into achieving a workspace with reachable points inside the conduit, as well as singularity points outside of it.

The methodology adopted involved an iterative approach to meet stringent objectives and constraints, with particular attention to the iterative verification of the robot model and its ability to operate effectively in the specific environment. To achieve a more compact section of the manipulator, the lengths of the links, d_2, d_4, and d_6, were set to zero, obtaining a manipulator with spherical shoulder and wrist.

The next development of the work includes the analysis of the dexterity of the robot and the execution of simulation to verify its effectiveness during maintenance operations.

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