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Robotic Arm Design and Simulation for Remote Maintenance in the DTT Fusion Reactor

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Abstract

The need for low-carbon, predictable, and reliable power has driven the European community to establish the EUROfusion project, aiming to provide grid electricity by the mid-21st century through nuclear fusion plants integrated with renewable energy sources. A key component of this initiative is the Divertor Tokamak Test facility (DTT) in Frascati, Italy, by ENEA, which will test reactor configurations and technologies for the future DEMOnstration (DEMO) reactor. Due to neutron-induced radioactivity, remote-controlled robots will perform maintenance on plasma-exposed components, operating during non-active periods. This paper proposes a robotic arm designed to perform pipe extraction and positioning in confined environments as part of the DTT's Divertor Handling subsystem. The robotic system described and its working environment are tested using a model of the system built in a multibody environment. Results allow to to evaluate joints motors specifications and the capability of the manipulator to achieve the task. The end effector trajectory is designed to avoid collision with the environment during the maneuver.

Keywords— nuclear fusion, robotics, mechatronics, multibody; remote maintenance

I. INTRODUCTION

The EUROfusion project, driven by the European Union's need for reliable, low-carbon electricity, aims to provide grid electricity by the middle of the 21st century through nuclear fusion plants integrated with renewable energy sources. The strategy of the EUROfusion program lies first in the implementation of a demonstration plant to validate the technology, the DEMOnstration (DEMO) reactor [1].

The construction of the DEMO plant is a large investment, requiring the use of the most efficient technologies in order to demonstrate to the community that nuclear fusion energy is a viable alternative to fossil fuels and nuclear fission. The Divertor Tokamak Test facility (DTT), has the task of experimenting and researching using knowledge, physics and theory, the reactor configurations and the technologies that will be adopted in the DEMO reactor [3]. The DTT plant will be built in Frascati, in Italy by ENEA.

As a consequence of neutron-induced radioactivity, the most part of maintenance operations inside the vacuum vessel will be performed by remotely operated robotics system [4]. Due the environmental conditions inside the vacuum vessel, many components will need periodic replacement during the lifespan of the plant [5]. In particular, the current design involves piping to connect the vacuum vessel with the rest of the plant, for cooling and energy transmission purpose[6]. Because of the wear induced by aggressive fluids, the pipes need periodic maintenance and substitution. The DEMO testing facility currently involves the using of a self-aligning system operated by an automated crane [7].

The current DTT design involves the usage of remote-controlled robots to perform maintenance on components in contact with plasma, which will access the vacuum vessel through a set of dedicated ducts [8].

The robot discussed in this work is a component of the Divertor Handling subsystem of the Remote Handling System envisaged for the DTT maintenance and serves the specific purpose of positioning, extracting, and welding cooling pipes of the DTT reactor during maintenance operations.

To access the duct, the robotic arm utilizes Cassette Multifunctional Mover (CMM) rails, a part of the Remote Handling (RH) maintenance and positioning system [9]. The robot needs to navigate freely within the duct while maintaining compact dimensions.

This work focuses on defining a robot architecture specifically designed to ensure full operability within the Port #4. The Port #4 is characterized by a length of 2906 mm and an inclination of 10° [8].

II. ROBOT REQUIREMENTS AND KINEMATIC DESIGN

The main operational objectives for the manipulator include the extraction of pipe modules 1400 mm long, with an outer diameter of 60 mm and a weight of approximately 11 kg. Additionally, the robot must be capable of introducing the pipe and positioning it with a high degree of precision, achieving positional accuracy evaluated to be within 1 mm, and angular accuracy within 1°. The manipulator must execute these tasks without encountering singular configurations, ensuring seamless operation within the specified environment.

Based on the defined requirements and constraints, a 6-degree-of-freedom anthropomorphic robot is selected for implementation.

To compute the kinematics of the system, the Denavit-Hartenberg (DH) convention is utilized. This approach systematically assigns coordinate frames to the robot's links, facilitating the derivation of the equations of motion and enabling a comprehensive analysis of the manipulator's performance [10]. The orientation between the joint axes, denoted by a_i, is set to 90°.

To assign the "d" parameters, the workspace is evaluated, defined as the three-dimensional volume within which the robot operates [5]. This workspace includes all points that the end-effector must be capable of reaching. For an accurate assessment of the workspace, it is essential to determine the cross-sectional area of the duct and the position of the manipulator base along the duct. The duct features a trapezoidal cross-section, characterized by a minor base of 306.9 mm, a major base of 500 mm, and a height of 650 mm. These geometric constraints informed the sizing of the manipulator links.

The parameters are refined through an iterative program that calculated the workspace and compared it to the duct section, aiming to ensure that the workspace encompasses the duct, allowing the end-effector to reach all points within it. The parameters obtained are shown in the Table 1.

TABLE I. DH PARAMETERS OF THE MANIPULATOR

Link	a_i [mm]	α_i [°]	d_i [mm]	ϑ_i
1	0	90	300	ϑ_1
2	0	90	0	ϑ_2
3	0	90	175	ϑ_3
4	0	90	0	ϑ_4
5	0	90	160	ϑ_5
6	75	0	0	ϑ_6

Figure 2 shows the workspace enclosed within the duct, calculated performing the inverse kinematics and setting a discrete angle variation of 10° at the joints to reduce computational cost.

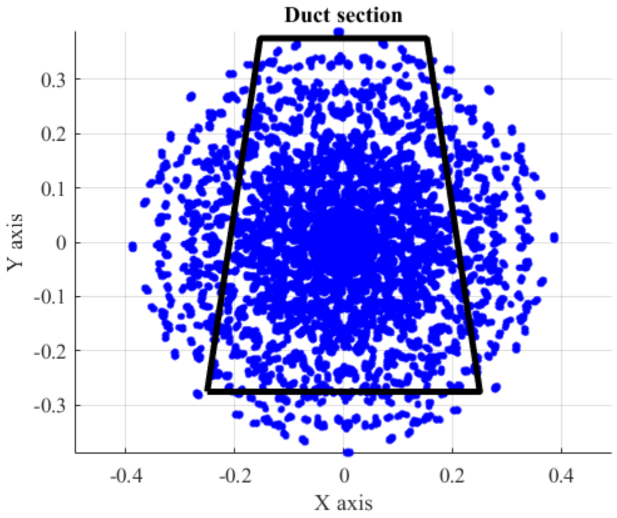


Fig. 1. Robot workspace compared with duct section

III. CAD MODEL

The manipulator operates in a confined environment. Its task is to extract and place pipes located on the base and sides of the duct, as shown in Fig. *2*.

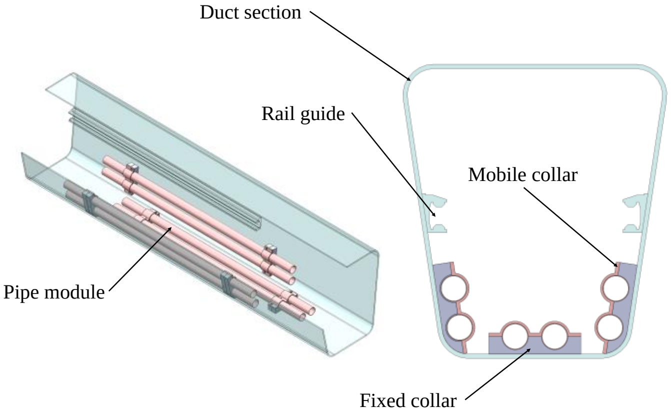


Fig. 2. Detail of the duct environment and of the pipe module layout

In the CAD modelling process, several critical aspects are considered to ensure the performance of the manipulator

Initially, the focus is on assessing the rigidity of the manipulator and its compatibility with the cross-section of the access door. For this purpose, the links are initially modelled as hollow bodies with gradually decreasing cross-sections, concentrating the masses at the base in order to increase the bending moment resistance, which largely depends on the outer radius. Smooth steel was chosen as the material.

A conceptual design proposal of the manipulator is shown in Fig. 3

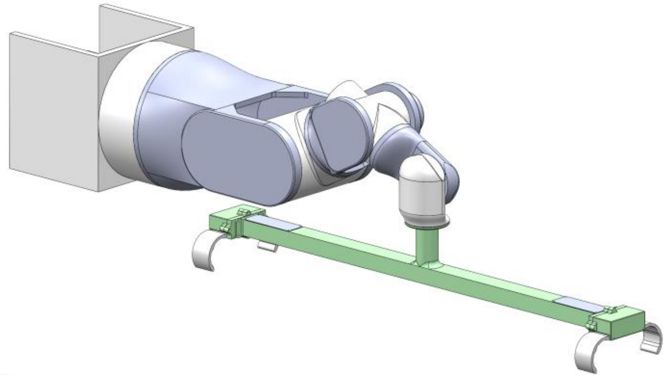


Fig. 3. CAD model of the robotic arm and its end effector

The end effector has to grip pipes 1.4 meters long, with a diameter of 60 mm and a weight of approximately 11 kg with extreme precision. The path required to the end effector to reach the pipe module grasping position is 250 mm.

In order to effectively meet these challenges, the solution incorporates an end effector equipped with two grippers, which enables a more controlled and stable handling of the pipe module. The end effector is provided with a specific designed gripper to maintain a 3 point contact during the whole maneuver. The synchronization in the gripper closing is ensured by a dedicated rack-pinion mechanism driven by a BLDC motor and its reducer.

The obtained design is shown in Fig. 4.

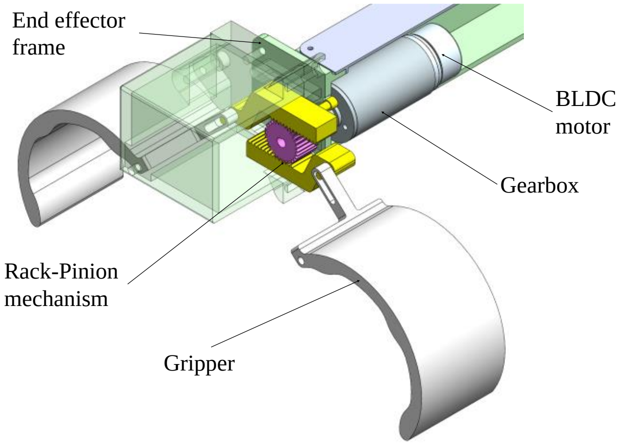


Fig. 4. Description of the end effector mechanism

IV. DEXTERITY ANALYSIS

One of the main disadvantage of nonredundant manipulators is that a large portion of their workspace is occupied by singularities regions [11]. Singularities can be interpreted physically as joint configurations in which one or more degrees of freedom are lost [12], and mathematically revealed by the Jacobian matrix losing its full rank.

In order to deal with these considerations, a dexterity analysis is conducted. This analysis aims to determine the optimal pose for performing the task of grasping the pipe. Initially, the focus will be on the pipes located at the base.

The manipulator and its working environment are shown in Fig. 5.

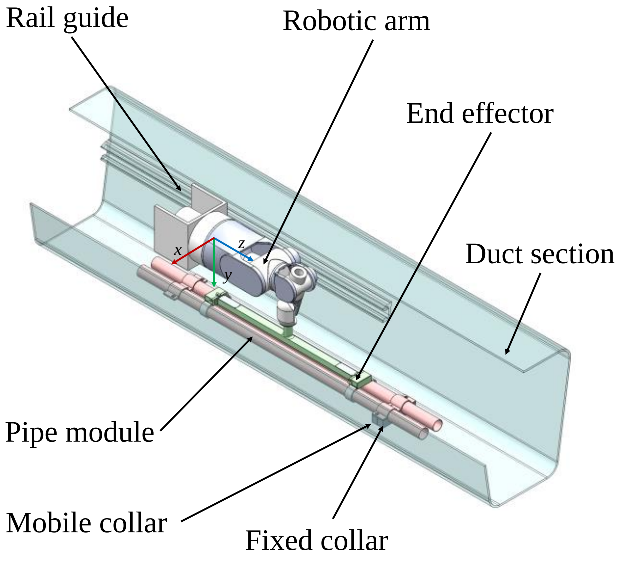


Fig. 5. Description of the workspace

The purpose of the study is to identify the configurations in which the manipulator can operate efficiently, minimizing the risk of encountering singularities and ensuring smoother and more reliable performance in the intended tasks.

The dexterity index used to describe the kinematic performance of the manipulator is the condition number k. It reflects the relationship between the amount of end motion and the active joint [13].

The condition number is defined a:

$$k(J^{-1}) = \|J^{-1}\| \, \|J\| \tag{1}$$

The inverse of the condition number , which ranges between 0 and 1, serves as a normalized dexterity index. A value close to 1 indicates high dexterity, meaning the manipulator can move and orient its end-effector efficiently in the workspace. Conversely, a value near 0 signifies low dexterity, where the manipulator may struggle with precise positioning and control [14].

The condition number and its inverse are calculated for each robot configuration. Then, the robot's workspace is calculated, assigning a color to each point in the workspace based on its dexterity value.

Results of the analysis are shown in Fig. 6. A more detailed view of the dexterity results is shown in Fig. 7

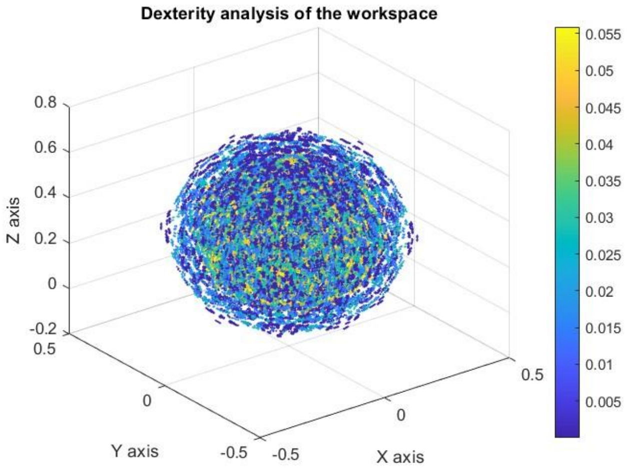


Fig. 6. Dexterity values in the workspace

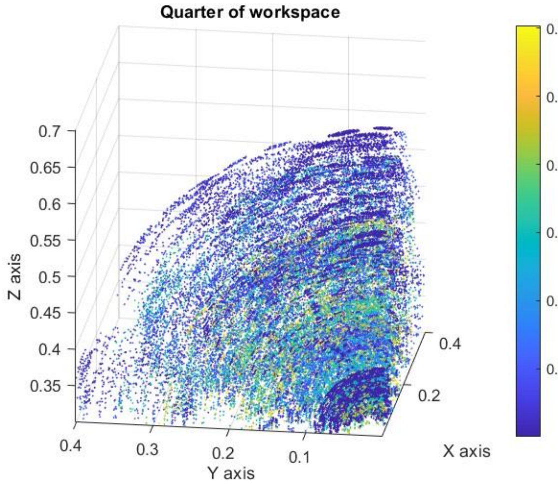


Fig. 7. Detail of the dexterity in a quarter of the workspace

From the data obtained, initial and final poses are selected for the task, ensuring them to be away from singularities.

V. PATH GENERATION

The task consists of extracting the pipeline avoiding collisions with duct walls, other ducts and avoiding singularities.

From the previously mentioned dexterity analysis, the initial and final positions of the manipulator are noted.

The current pose of the EE is calculated through the forward kinematics.

Defining the velocity set involves solving the position and orientation problem. Since this task does not require a change in the orientation of the end effector, it is implemented an algorithm that solves only the position problem.

$$e_p = \Delta p = p_s - p_{fb} \tag{2}$$

Where p_s is the position to be reached and p_{fb} is the current position of the end-effector. From the position error it is calculate the desired velocity of the end effector, choosing a trapezoidal profile. The velocity profile set $\dot{p}_s$ is defined as follow:

$$\dot{p}_s = \min\left(a_0 t, v_{0,}\sqrt{2a_0\|\Delta p\|}\right)\frac{\Delta p}{\|\Delta p\|} \tag{3}$$

Where

$$a_0 = 0.1\ m/s^2$$

is the maximum acceleration, while

$$v_0 = 0.1\ m/s$$

is the maximum velocity for the end-effector.

The typical velocity profile obtained with this method is shown in Fig. 8.

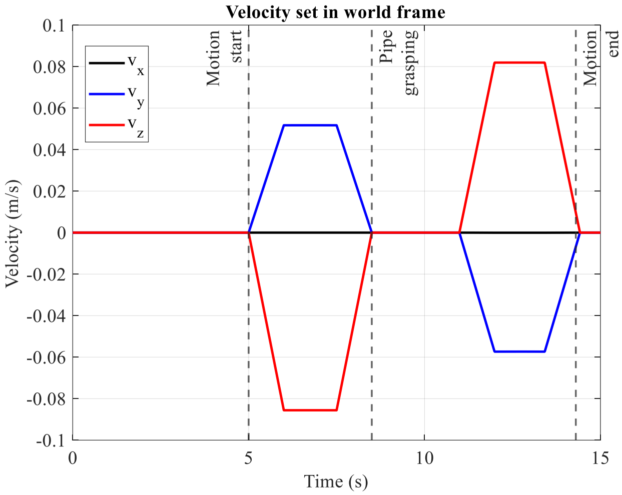


Fig. 8. Typical velocity set in world frame

Using the vector of desired velocity $v_s = [p_s, [0,0,0]]^T$, calculated from the error $e = [e_p, [0,0,0]]^T$, the set of joint velocities $\dot{q}_d$ are calculated by performing the inverse differential kinematics [15]:

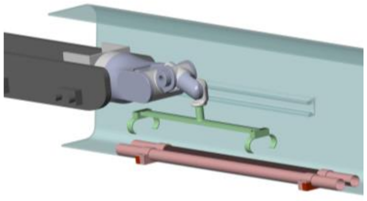
$$\dot{q}_d = J^{-1}\, v_d \tag{4}$$

VI. SIMULATION AND RESULTS

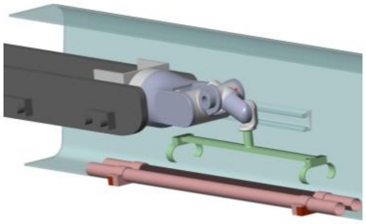
The effectiveness of the proposed control strategy is evaluated through task simulation using a multibody model build in Matlab/Simulink environment.

In the initial phase, the robotic manipulator has all joints locked and is introduced into the duct using the CMM's positioner. Once positioned in the initial position, it proceeds with the pipe extraction task. In particular, the end effector of the manipulator is programmed to move between the specified start and end positions. The end position is designated as the optimal gripping point for the tubes to be manipulated. Once the designated end position is reached, the manipulator grasps the tubes and subsequently returns to the initial position.

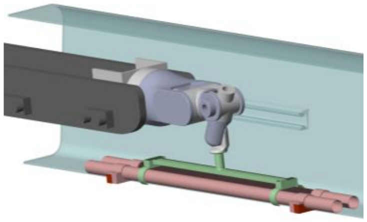
The main phases of task are detailed in Fig. 9



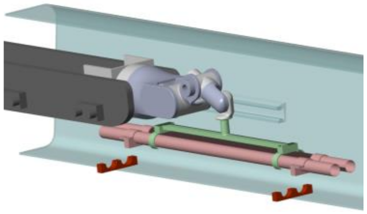
Duct entry



Initial grasping position



Grasping



Final grasping position

Fig. 9. Main phases of the task

It can be observed that the robotic arm and end-effector operate without collisions with the duct walls or the pipes. Additionally, singular configurations are not encountered during the operations performed.

The multibody analysis allow to evaluate the dynamics of the manipulator during the maneuver. In particular, are evaluated torques, Fig. 10, velocities, Fig. 11, and powers, Fig. 12, required by the joints to follow the trajectory.

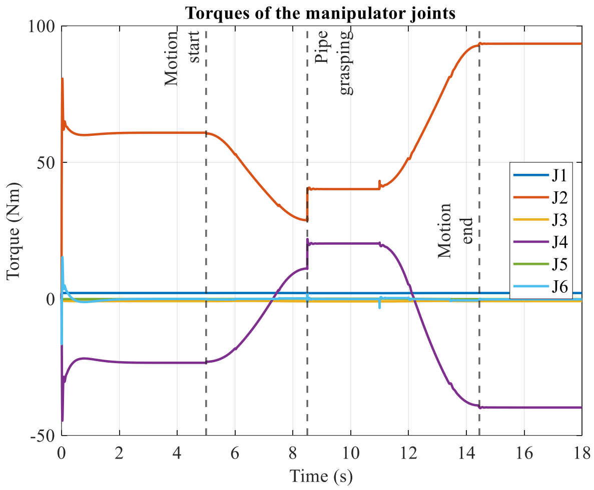


Fig. 10. Joint torques

Torque discontinuity shown in fig. 11 is computed when grasping is completed and the robot starts to stand its load.

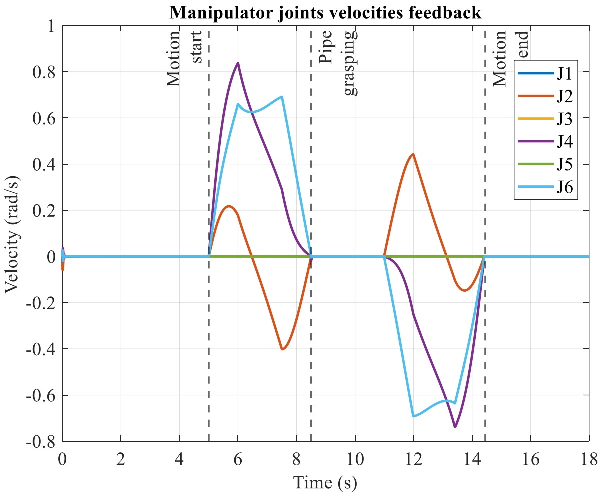


Fig. 11. Joint velocities feedback

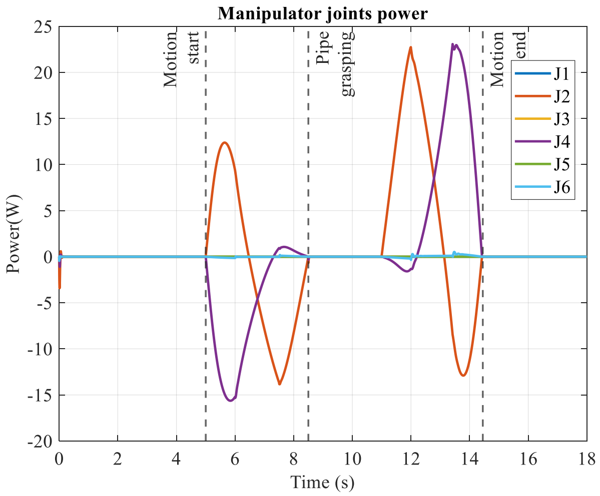


Fig. 12. Joint power requirements

As can be seen, although the torques are high, due to the limited speeds, the powers are relatively low.

Results shows that, even if the torques are high due the relatively large masses manipulated, the power required is maintained low by the low acceleration set by the law of motion.

Results give a requirement for the actuators and gearbox sizing, allowing to advance the design development.

VII. CONCLUSIONS

This paper presents a proposal for a robotic arm to perform pipe extraction and positioning operations in an extremely confined environment. A preliminary design of the robotic arm and its end effector consisting of two grippers is presented.

Particular attention is dedicated to the trajectory to be performed during the execution of the task in order to avoid singularity positions. A simulation tool is developed in a multi-body environment including the robotic arm, the duct and the pipes to test the control strategy developed.

The simulation results provide verification of the ability of the proposed robotic system to perform the required task. The analysis on the values for speeds, torques, and joint powers will then be used to select the actuation of the system.

The methodology adopted involved an iterative approach to meet stringent objectives and constraints, showing the value of a customized approach to meet specific requirements.

Future work will include the simulation of pipe placement and the executive design of the system.

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