The 5-DOF parallel cylindrical robot, PARA-BRACHYROB

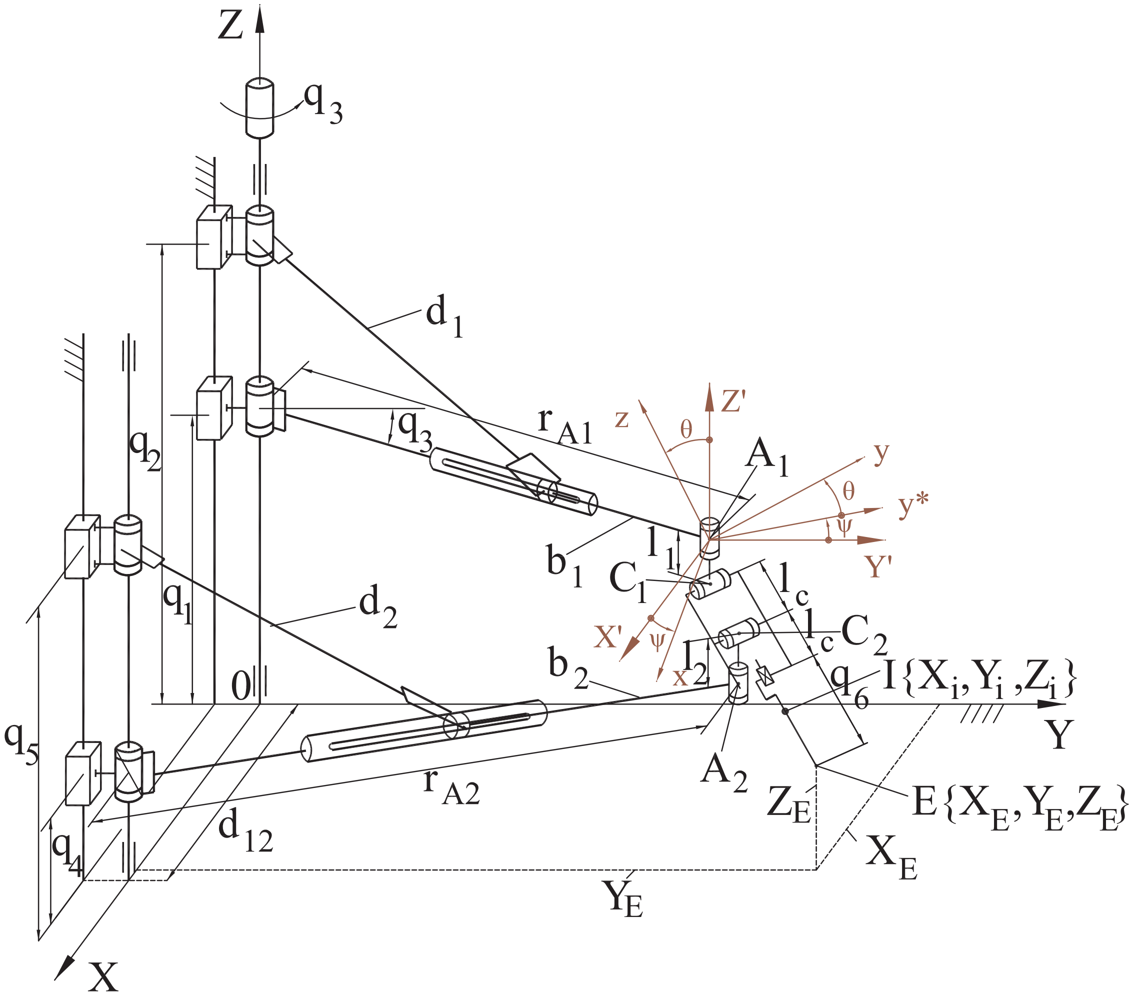

Figure 1. The kinematic scheme of PARA-BRACHYROB

Based on the kinematic scheme of the PARA-BRACHYROB cylindrical parallel robot, it consists of two modules, the first one having 3-DOF and 3 active joints, denoted with q_1, q_2, q_3 and a second module with 3-DOF and 2 active joints, q_4, q_5. The first two joints of each cylindrical module are translational joints, while the third motion is a rotational one around the axis of the first joints, whereas the first module has an active joint while the second one a passive joint. The modules end points are denoted with A_1 and A_2. At this point a fixed coordinate system is introduced, OXYZ, with the Z axis along the active rotational axis of the first module. The second module is positioned on the X axis, at a distance d_{12} from the origin. The two modules are interconnected with two Cardan joints having the first rotation axis around the Z axis and the second one perpendicular on it. The second rotational axes of the two Cardan joints are connected and they guide the needle holder. The needle holder integrates a translational actuator, q_6, which has a redundant motion (with respect to the robotic structure) enabling the needle insertion to the target point with all the other actuators fixed (blocked).

In order to develop the geometrical modeling of the structure several geometrical dimensions are introduced: $d_1, b_1, l_1, d_2, b_2, l_2, l_c$.

In order to study and validate the kinematic model presented in this paper, a kinematic simulation was performed, which has the following properties:

- It neglects gravity forces and the masses of the bodies in motion;
- The external and inertia forces do not affect the motion;
- The bodies and joints are considered to be perfectly rigid.

For the robot motion a real situation was defined as follows:

- The robot has a current arbitrary position which is known with respect to a fixed coordinates system;
- The robot will receive two sets of coordinates for the insertion point inside the patient and the target point inside the patient;
- The robot motion is decomposed into two parts: in the first, the robot will move from its current location to the insertion point, achieving, in the same time the final orientation for the needle; in the second part, the robot will drive the needle, along a linear path to the target point.

All the computations presented here are achieved using the geometrical dimensions of the experimental model of PARA-BRACHYROB, which are, as follows (see figure 1):

$$\begin{aligned} &d_1 = 400\,mm; b_1 = 395\,mm; l_1 = 67\,mm; \\ &d_2 = 400\,mm; b_2 = 495\,mm; l_2 = 67\,mm; \\ &l_c = 170\,mm; d_{ac} = -112.5\,mm; d_{12} = 615\,mm \end{aligned}$$

The negative value of d_{ac} is determined by the compact construction of the needle positioning module which sets the needle tip very close to the second Cardan joint, to enable the module to fit inside the CT gantry.

In the current (starting) position of the robot the coordinates of the needle tip are:

$$\text{Current position: } \begin{cases} X_c = 307.5\,mm; \\ Y_c = 800\,mm; \\ Z_c = 400\,mm; \\ \psi_c = 90^\circ \\ \theta_c = 60^\circ \end{cases}$$

The two sets of coordinates defining the insertion point and the target point inside the patient are:

$$\begin{cases} X_I = 360\,mm; \\ Y_I = 750\,mm; \\ Z_I = 350\,mm; \end{cases} \quad \begin{cases} X_T = 380\,mm; \\ Y_T = 810\,mm; \\ Z_T = 280\,mm; \end{cases}$$

Knowing the coordinates of the insertion and target points, the final orientation of the needle can be easily computed:

$$\psi_{IT} = \operatorname{atan2}\left(Y_T - Y_I, X_T - X_I\right);$$
$$\theta_{IT} = \operatorname{atan2}\left(\sqrt{\left(Y_I - Y_T\right)^2 + \left(X_I - X_T\right)^2}, Z_I - Z_T\right);$$

As motion parameters the following maximum speed and acceleration were imposed for the needle tip:

$$v_{\max} = 20\,mm/s; a_{\max} = 10\,mm/s^2$$

These values are higher than the actual ones (especially for the second part of the motion) but they enable the study of the robot motion is smaller time intervals without compromising the accuracy of the results.

The needle trajectory in terms of position and orientation is illustrated in the figure 2. The two separate motions are visible especially in the variation of speeds and accelerations. During the reaching of the insertion point the robot achieves also the final orientation of the needle thus, during the insertion the values of the two angles ψ and θ remain unchanged.

Figure 3 illustrates the variation of the displacements, speeds and accelerations at the level of the active joints, there the two separate motions are clearly visible.

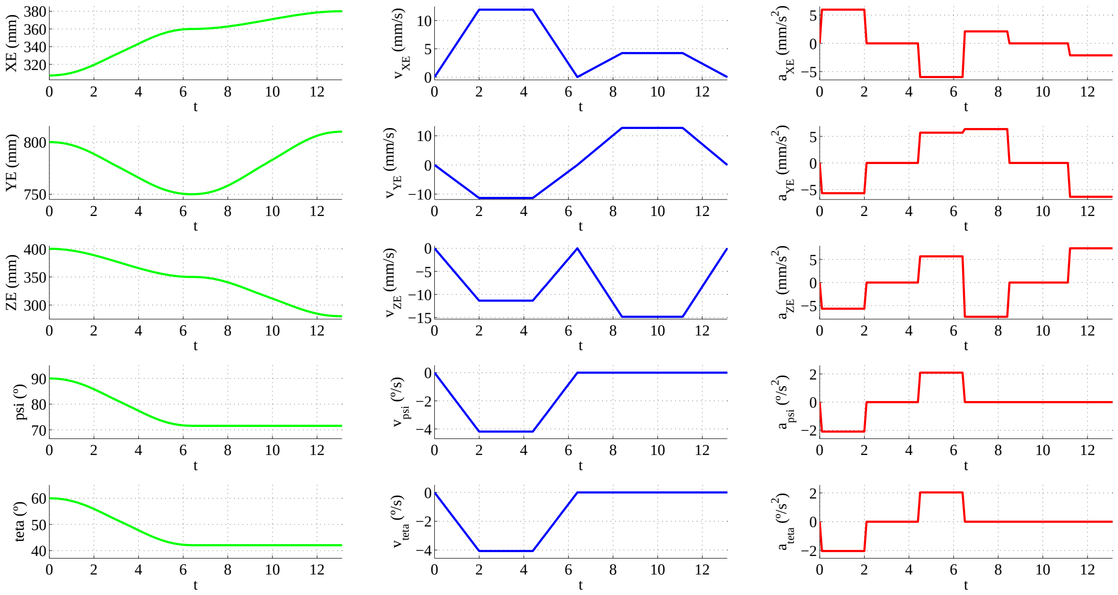

Figure 2. The needle tip trajectory (two steps motion)

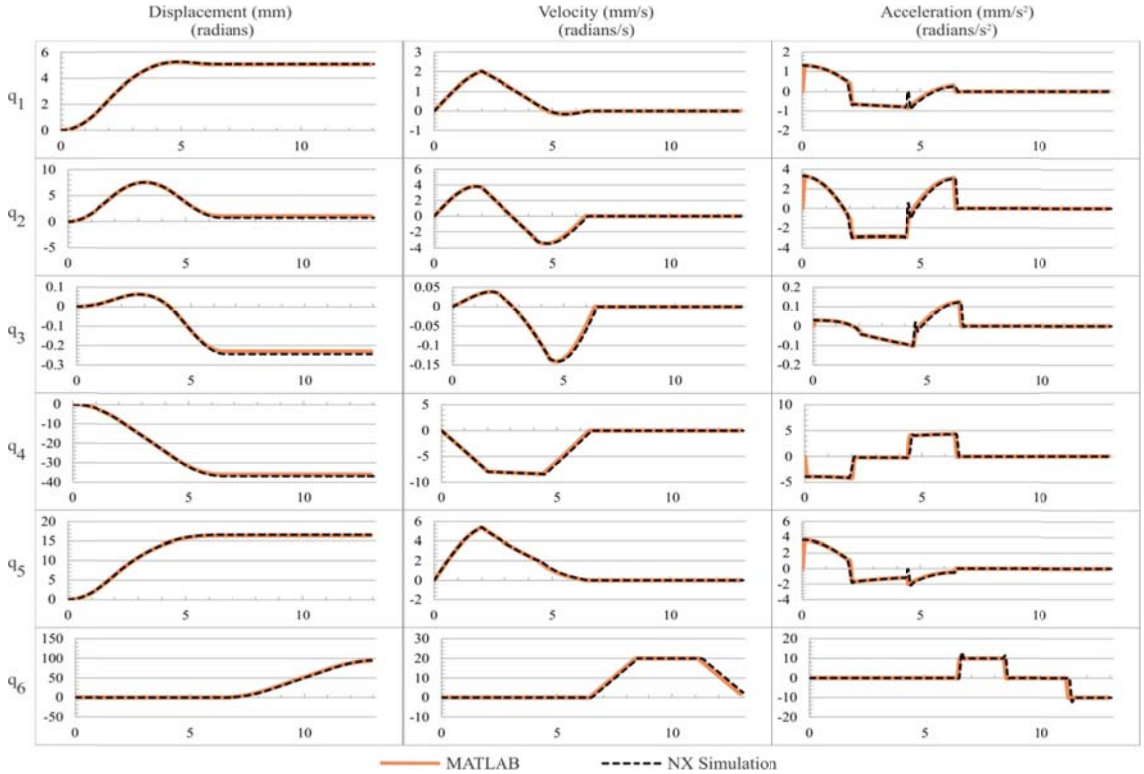

Figure 3. The variation of displacements, speeds and accelerations at the level of the active joints