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ON THE KINEMATICS OF A NEW PARALLEL ROBOT FOR BRACHYTHERAPY

Nicolae PLITEA, Doina PISLA, Calin VAIDA, Bogdan GHERMAN, Andras SZILAGHYI, Bogdan GALDAU, Dragos COCOREAN, Florin COVACIU

Research Center for Industrial Robots Simulation and Testing, Technical University of Cluj-Napoca, Romania
E-mail: Doina.Pisla@mep.utcluj.ro

An innovative approach in the treatment of cancer is brachytherapy, or local radiation therapy. This technique can deliver targeted doses in very specific body areas but the lack of a specialised device capable of placing the radiation source accurately inside the patient body is limiting the spread of this technique. The authors propose an innovative parallel robot working in cylindrical coordinates capable of reaching almost any point of interest in the thoracic-abdominal area of the human body. The geometrical model of the robot is computed along with the workspace generation emphasizing the importance of the relative position between the patient and the robot.

Key words: Parallel structure, Cylindrical modules, Kinematics, Brachytherapy, Workspace.

1. INTRODUCTION

One of the most rewarding fields in the development of innovative robotic devices is medicine. Medical robots are developed mainly to overcome the natural human limitations in terms of positioning accuracy, motion scaling, micro-motions and the manipulation of medical tools close to radiation sources that cannot be eliminated during therapy. Research centers around the world trying to provide solutions to medical requirements in an attempt to improve lives through the construction of robotic systems [1] or by studying and improving existing systems [2, 3, 4, 5].

One of the biggest challenges of the third millennium refers to the fight against cancer through the development of new techniques and solutions for the curative and palliative treatment of malignant tumors. Recently, a very effective solution for the local treatment of cancer tumors has been developed, namely brachytherapy. Brachytherapy is a form of radiotherapy where a radiation source is placed inside or next to the area requiring treatment. Brachytherapy is commonly used as an effective treatment for cervical, prostate, breast, and skin cancer and can also be used to treat tumors in many other body sites [6]. The current limitations in brachytherapy refer to the accuracy of the needle placement in the tumor area which, in an erroneous positioning situation can lead to disastrous situations: the puncturing of blood vessels, nerve damage, healthy tissue necrosis and so on. In [7] it is shown that a robotic device enhances the needle placement precision beyond the natural human capabilities, the positioning of the brachytherapy device becoming a challenging task where the use of a robotic device can extend the applications of this technique.

From the application definition point of view, one can say that the robotic structure must introduce, based on radiologic data, rigid needles with diameter between 1.6 up to 2 mm and length of 50 mm up to 200 mm inside the patient body, following linear, safe, trajectories.

The first step is to determine critical information about tumor: exact location, size, proximal organs. This is done by medical imaging devices such as US (ultrasound) probe, CT (computed tomography) or MRI (Magnetic Resonance Imaging). The next step is accomplished with robotic system that puts, in a minimally invasive way following the paths set in the first stage, specific brachytherapy devices in the tumor. The majority of these robotic systems are using the US probe for the imaging. EUCLIDIAN (Yu et al. [8] and Buzurovic et al. [9]) is a 16-DOF robot-assisted brachytherapy system. This robotic system is divided into

three subsystems: the cart, the supporting platform, and the surgery module, with 3, 6, and 7 DOF. The supporting platform connects the surgery module to the cart. The surgery module consists of a 2-DOF ultrasound probe driver and a 5-DOF needling module.

Another system is TRUS Guided Robotic Approach by Fichtinger et al. [10]. The robot consists of two 2D Cartesian motion platforms arranged in a parallel configuration.

BrachyGuide [11] developed by Salcudean et al, a two-axis wrist positioned by a translation platform. All these systems have the advantage of a real time imaging with low costs and easy to use but they are limited to prostate or inguinal zone. MrBot by Stoianovici et al. [12] is a fully actuated 5 DOF brachytherapy robot compatible with MRI. All components are constructed of nonmagnetic and dielectric materials. MAXIO from Perfint Healthcare (India) [13] is a 5DOF robotic arm for use in ablation, biopsy, drug delivery, drainage, robotic assistance for placing the probe. For the imaging is using CT because of the advantages like short-scan, best browsing acute hemoragic and bone lesions and lower costs compared to MRI examination for the standard investigations. To examine the abdomen and pelvis is necessary to drink a dye dissolved in water (made available by clinic staff), before starting the actual investigation, a disadvantage are the minor side effects for this pacients.

As a motivation for the researches in this paper, reference is made to a study [14], presented at the American Association of Physicists in Medicine meeting in 2010, where Podder and Fichtinger, presented the 13 robotic systems developed for prostate brachytherapy. The potential of robotic systems is clearly outlined but also is expressed a clear need for the development of a robotic system with a high degree of universality, capable of working in different cancer scenarios.

The paper presents an innovative parallel solution developed by the authors [15, 16] consisting in a 5-DOF structure working in cylindrical coordinates. The geometrical model of the robot will be presented with emphasis on the two operational modes of the structure. An analytic workspace generation will illustrate the positioning capabilities of the structure and thus, the range of applications and organs that can be targeted by this robot.

2. THE GEOMETRIC MODEL OF THE PARALLEL ROBOT BR3

Based on the kinematic scheme of the BR3 cylindrical parallel robot, presented in figure 1, it consists of two cylindrical modules (CYL-U), 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 number of moving elements is $N = 2 + 1 = 3$ (two exit elements (1 and 2) from the parallel modules working in cylindrical coordinates and the end-effector (the needle 3)). The number of class 4 joints is $C_4 = 2$ (universal joints), while the number of class 3 joints is $C_3 = 2$ (the two modules working in cylindrical coordinates). Using [16] and knowing that the parallel mechanism has the family $F = 1$ (the common restriction consists in the fact that the three moving elements do not execute a self-rotation motion, so $\varphi = 0$), the number of degrees of freedom of the robot can be computed:

$$M = 5 \cdot N - 3 \cdot C_4 - 2 \cdot C_3 = 5 . \tag{1}$$

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 axis of the two Cardan joints is connected and they guide the needle holder.

2.1. The inverse geometric model (IGM)

In order to develop the geometrical modeling of the structure several geometrical dimensions are introduced: $d_1, b_1, l_1, d_2, b_2, l_2, l_c, h$. For the IGM the needle tip (target point) coordinates, the needle orientation and the needle length inside the patient are known, namely:

– the coordinates of point $E(X_E, Y_E, Z_E)$;

– the needle orientation angles ψ (the angle between $C_1X' // OX$ and C_1x) and θ, $\varphi = 0$;

– the needle depth d_{ac}.

All the geometrical parameters of the cylindrical robot are known.

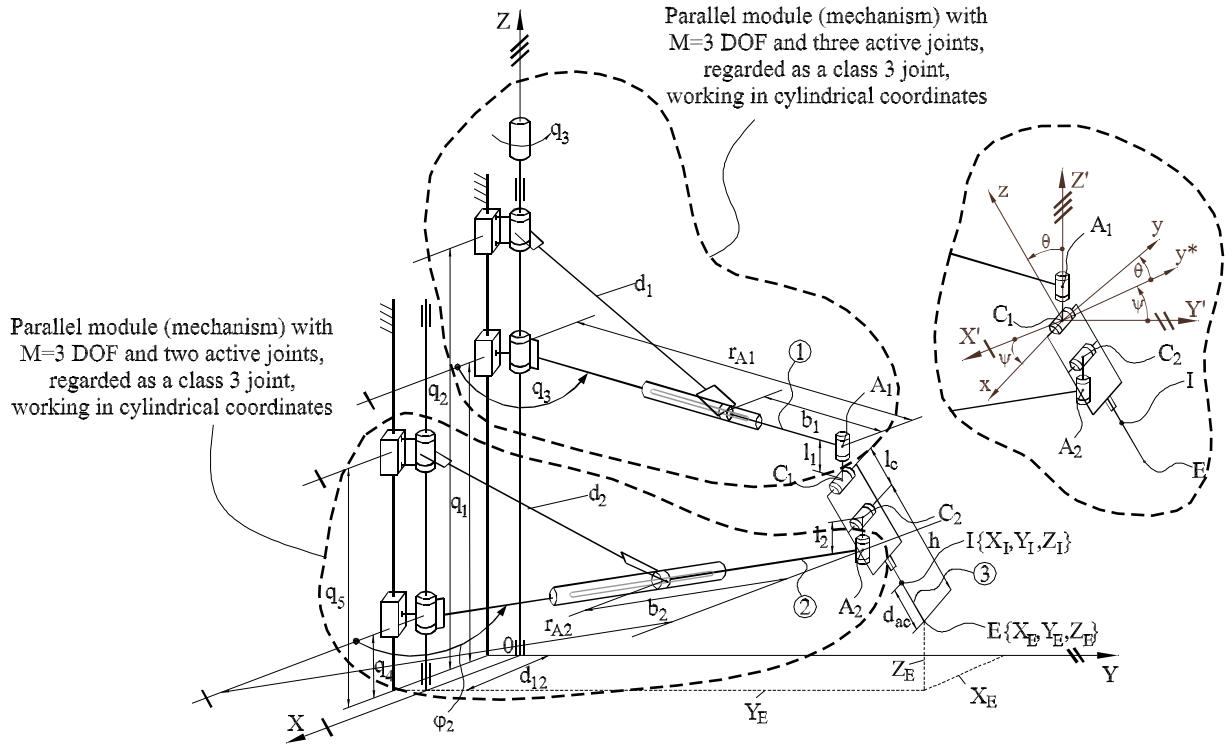

Fig. 1 – Kinematic scheme of the cylindrical parallel robot BR3.

Having the target point, the orientation and the targeted depth the insertion point can be calculated.

$$\begin{aligned} X_I &= X_E - d_{ac} \cdot \sin(\theta) \cdot \cos(\psi) \\ Y_I &= Y_E - d_{ac} \cdot \sin(\theta) \cdot \sin(\psi) \\ Z_I &= Z_E + d_{ac} \cdot \cos(\theta). \end{aligned} \tag{2}$$

The coordinates of the points C_1 and C_2 of the Cardan joints, can be determined, respectively:

$$\begin{aligned} X_{C1} &= X_E - (h + l_c) \cdot \sin(\theta) \cdot \cos(\psi) \\ Y_{C1} &= Y_E - (h + l_c) \cdot \sin(\theta) \cdot \sin(\psi) \\ Z_{C1} &= Z_E + (h + l_c) \cdot \cos(\theta) \end{aligned} \tag{3}$$

and

$$\begin{aligned} X_{C2} &= X_E - h \cdot \sin(\theta) \cdot \cos(\psi) \\ Y_{C2} &= Y_E - h \cdot \sin(\theta) \cdot \sin(\psi) \\ Z_{C2} &= Z_E + h \cdot \cos(\theta). \end{aligned} \tag{4}$$

The coordinates of points A_1 and A_2 are respectively:

$$\begin{aligned} X_{A1} &= X_{C1} \\ Y_{A1} &= Y_{C1} \\ Z_{A1} &= Z_{C1} + l_1, \end{aligned} \tag{5}$$

and

$$\begin{aligned} X_{A2} &= X_{C2} \\ Y_{A2} &= Y_{C2} \\ Z_{A2} &= Z_{C2} + l_2. \end{aligned} \tag{6}$$

A note can be made here, namely the lengths of the distances between the points C_i and A_i can be zero, meaning that the C and A points of each joint are superposed.

Knowing the coordinates of the points A_i the r_{Ai} lengths can be determined:

$$r_{A1} = \sqrt{X_{A1}^2 + Y_{A1}^2}, \tag{7}$$

$$r_{A2} = \sqrt{\left(X_{A2} - d_{12}\right)^2 + Y_{A2}^2}. \tag{8}$$

From the equations (2) to (8) the active coordinates of the robot can be determined:

$$q_1 = Z_{A1} \tag{9}$$

$$q_2 = q_1 + \sqrt{d_1^2 - \left(r_{A1} - b_1\right)^2} \tag{10}$$

$$q_3 = a\tan 2\left(Y_{A1}, X_{A1}\right) \tag{11}$$

$$q_4 = Z_{A2} \tag{12}$$

$$q_5 = q_4 + \sqrt{d_2^2 - \left(r_{A2} - b_2\right)^2}. \tag{13}$$

2.2. The direct geometric model (DGM)

For the DGM the coordinates of the active joints are known, namely, q_1, q_2, q_3, q_4, q_5, along with all the geometrical parameters of the robot. The unknowns are the end-effector (needle's tip) coordinates $E\left(X_E, Y_E, Z_E\right)$ and orientation (angles ψ and θ).

Knowing the coordinates of active joints q_1, q_2, q_4, q_5 the r_{Ai} lengths can be determined:

$$r_{A1} = b_1 + \sqrt{d_1^2 - \left(q_2 - q_1\right)^2} \tag{14}$$

$$r_{A2} = b_2 + \sqrt{d_2^2 - \left(q_5 - q_4\right)^2}. \tag{15}$$

The coordinates of the points A_1 (from Fig. 1) are:

$$\begin{aligned} X_{A1} &= r_{A1} \cdot \cos\left(q_3\right) \\ Y_{A1} &= r_{A1} \cdot \sin\left(q_3\right) \\ Z_{A1} &= q_1. \end{aligned} \tag{16}$$

The coordinates of the rotation joint C_1 (from Fig. 1) are:

$$\begin{aligned} X_{C1} &= X_{A1} \\ Y_{C1} &= Y_{A1} \\ Z_{C1} &= Z_{A1} - l_1. \end{aligned} \tag{17}$$

Due to the fact that both modules have cylindrical kinematic chains, there will be a double solution for the coordinates of point C_2 which determine the two working modes of the BR3 parallel robot. The equations of two circles can be written:

$$\begin{aligned} &(X_{C2} - X_{C1})^2 + (Y_{C2} - Y_{C1})^2 = a^2, \\ &(X_{C2} - d_{12})^2 + Y_{C2}{}^2 = r_{A2}^2, \end{aligned} \tag{18}$$

where

$$a = \sqrt{l_c^2 - \left(Z_{C2} - Z_{C1}\right)^2}. \tag{19}$$

Introducing the notations:

$$rr_1 = \sqrt{[\left(X_{C1} - d_{12}\right)^2 + Y_{C1}^2 - \left(a - r_{A2}\right)^2] \cdot [\left(a + r_{A2}\right)^2 - \left(X_{C1} - d_{12}\right)^2 - Y_{C1}^2]} \tag{20}$$

$$rr_2 = X_{C1}^2 + Y_{C1}^2 - a^2 - d_{12}^2 + r_{A2}^2 \tag{21}$$

$$rr_3 = Y_{C1} \cdot \left(\left(X_{C1} - d_{12}\right)^2 + Y_{C1}^2 - a^2 + r_{A2}^2\right). \tag{22}$$

The solutions of the equation are:

$$X_{C2\_1} = \frac{1}{2\left(X_{C1} - d_{12}\right)} \cdot \frac{1}{\left(X_{C1} - d_{12}\right)^2 + Y_{C1}^2} \cdot \left\{ rr_2 - Y_{C1} \cdot \left[rr_1 \cdot \left(d_{12} - X_{C1}\right) + rr_3 \right] \right\} \tag{23}$$

$$Y_{C2\_1} = \frac{1}{2} \frac{1}{\left(X_{C1} - d_{12}\right)^2 + Y_{C1}^2} \cdot \left[rr_1 \cdot \left(d_{12} - X_{C1}\right) + rr_3 \right] \tag{24}$$

$$X_{C2\_2} = \frac{1}{2\left(X_{C1} - d_{12}\right)} \cdot \frac{1}{\left(X_{C1} - d_{12}\right)^2 + Y_{C1}^2} \cdot \left\{ rr_2 - Y_{C1} \cdot \left[rr_1 \cdot \left(X_{C1} - d_{12}\right) + rr_3 \right] \right\} \tag{25}$$

$$Y_{C2\_2} = \frac{1}{2} \frac{1}{\left(X_{C1} - d_{12}\right)^2 + Y_{C1}^2} \cdot \left[rr_1 \cdot \left(X_{C1} - d_{12}\right) + rr_3 \right]. \tag{26}$$

For the θ angle a single value results based on the equation:

$$\theta = a\tan 2\left(\sqrt{l_c^2 - \left(Z_{C1} - Z_{C2}\right)^2}, \left(Z_{C1} - Z_{C2}\right)\right). \tag{27}$$

From (17), and (23–26) one can write the expressions of the ψ angle as:

$$\psi_1 = a\tan 2\left(\left(Y_{C2\_1} - Y_{C1}\right), \left(X_{C2\_1} - X_{C1}\right)\right), \tag{27}$$

$$\psi_2 = a\tan 2\left(\left(Y_{C2\_2} - Y_{C1}\right), \left(X_{C2\_2} - X_{C1}\right)\right). \tag{28}$$

The relative values of the rotation angles of the end-effector, θ and ψ could be checked using (29) and (30):

$$\cos(\theta) = \frac{q_1 - q_4 - l_1 - l_2}{l_c}, \tag{29}$$

$$\left[d_{12} - r_{A1} \cdot \cos(q_3) - l_c \cdot \sin(\theta) \cdot \cos(\psi)\right]^2 + \left[r_{A1} \cdot \sin(q_3) + l_c \cdot \sin(\theta) \cdot \sin(\psi)\right]^2 = (r_{A2})^2. \tag{30}$$

The final expressions for the coordinates of the needle tip are:

$$X_{E\_1,2} = X_{C1} + (h + l_c)\sin(\theta)\cos(\psi_{\_1,2}), \tag{31}$$

$$Y_{E\_1,2} = Y_{C1} + (h + l_c)\sin(\theta)\sin(\psi_{\_1,2}), \tag{32}$$

$$Z_E = Z_{C1} - (h + l_c)\cos(\theta). \tag{33}$$

The values of the ψ angle define the two operation modes of the BR3 cylindrical parallel robot, determines the two solutions for the coordinates of the needle tip. The borderline for these two operation modes is given by a plane parallel with the OYZ plane. Due to the fact that at the beginning of the procedure the final needle orientation is known the proper operation mode will be selected enabling the use of the proper solution for the DGM.

3. ANALYTICAL WORKSPACE GENERATION FOR THE BR3 PARALLEL ROBOT

A critical aspect in the development of a general purpose brachytherapy robot is its reach, or its workspace which will determine its capability to target different body areas and approaches under different inclination angles. The robot workspace has to be generated taking into account the coordinates of an insertion point $I(X_I, Y_I, Z_I)$ and then using the inverse geometrical model the geometrical loci of all the validated target points $E(X_E, Y_E, Z_E)$, can be obtained. All calculations have been made using the following set of geometrical parameters (figure 1): d_1 = 400mm, b_1 = 400mm, l_1 = 65mm, d_2 = 400mm, b_2 = 500mm, l_2 = 65mm, l_c = 200mm, h = 187mm, d_{12} = 500mm, For the active coordinates the following limits were defined: $q_{i\,min} = 0\text{mm}, q_{i\,max} = 950\text{mm}, i = 1,2,3,4,\ q_{3\,min} = 0, q_{3\,max} = 2\pi$. Figure 2 illustrates the maximum theoretical workspace of the BR3 robot, with point I selected in a set of coordinates $X_I = 250\,mm, Y_I = 340\,mm, Z_I = 200\,mm,$ where all the robot joints are positioned in the midway of their strokes. Figures 3a–f) illustrate the workspace volumes determined for different insertion points coordinates illustrating the importance of the proper definition of the robot positioning with respect to the patient and the targeted organ. For the workspace generation using the inverse geometrical model, a volume which integrates the robot workspace is initially defined. One considers that all the points in that volume are within the robot workspace, and for each point of the needle tip, the values of the active joints are determined. When a valid combination for the active joints is obtained the set of coordinates which defined the target point is saved. The matrix of the validated needle tip coordinates represents the robot workspace. For the validation, a set of conditions were imposed as follows: $q_{i_{\min}} < q_i < q_{i_{\max}}\, i = 1..5, q_1 < q_2, q_4 < q_5$, $q_1 > q_4 + l_1 + l_2, q_2 - q_1 < d_1$ and $q_5 - q_4 < d_2$.

Analyzing the robot workspace modifications based on the coordinates of the insertion point, one can conclude that for optimum performance the values for the coordinates of point I should not vary with more than ±150 mm on X axis, ± 50 mm on Y and Z axis with respect to the values obtained for the maximum robot workspace.

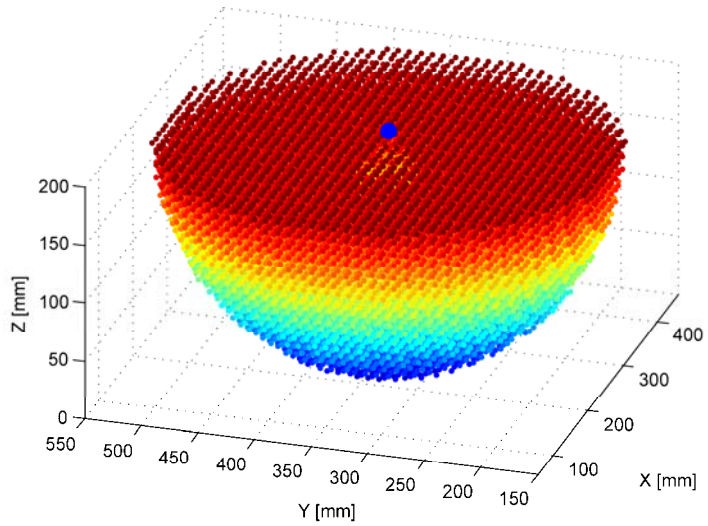

Fig. 2 – The maximum theoretical workspace of the cylindrical parallel robot BR3.

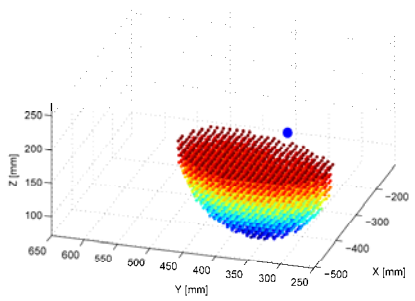

Fig. 3a) – The BR3 workspace for $X_I = -345\text{mm}, Y_I = 340\text{mm}, Z_I = 200\text{mm}$.

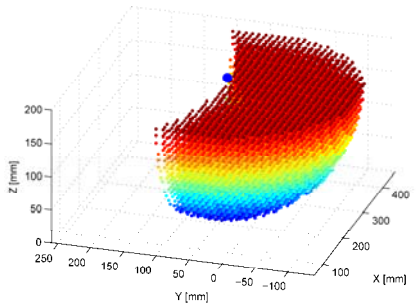

Fig. 3c) – The BR3 workspace for $X_I = 250\text{mm}, Y_I = 50\text{mm}, Z_I = 200\text{mm}$.

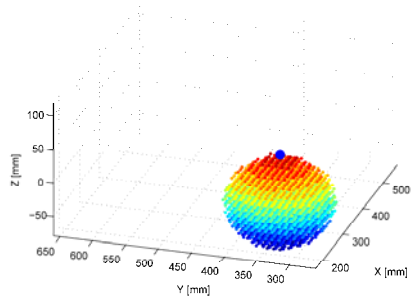

Fig. 3e) – The BR3 workspace for $X_I = 250\text{mm}, Y_I = 340\text{mm}, Z_I = 50\text{mm}$.

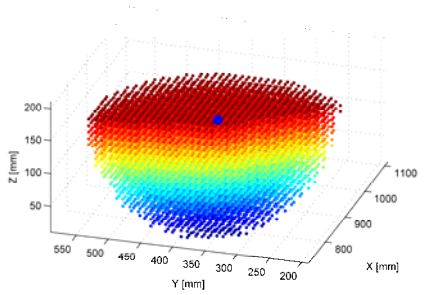

Fig. 3b) – The BR3 workspace for $X_I = 745\text{mm}, Y_I = 340\text{mm}, Z_I = 200\text{mm}$.

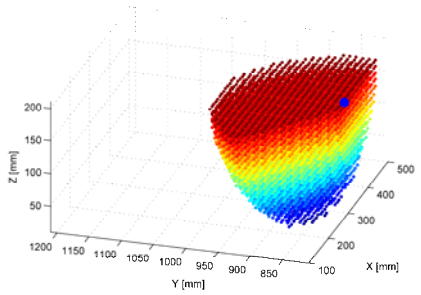

Fig. 3d) – The BR3 workspace for $X_I = 250\text{mm}, Y_I = 800\text{mm}, Z_I = 200\text{mm}$.

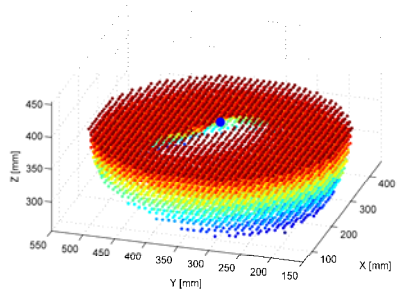

Fig. 3f) – The BR3 workspace for $X_I = 250\text{mm}, Y_I = 340\text{mm}, Z_I = 370\text{mm}$.

4. CONCLUSIONS

In this paper the geometric modeling and workspace analysis of an innovative parallel robot for brachytherapy was presented. The robot works in cylindrical coordinates using a set of 5 active joints for the insertion of the brachytherapy needles inside the patient body on linear trajectory. The geometrical modeling was achieved in analytical way and two operation modes were identified, separated by a plane parallel with the OYZ plane. The analysis of the workspace enabled the definition of relative position between the patient and the robotic structure that maximizes the working volume for a specified insertion point. This analysis leads to the conclusion that this structure can be used to target most of the tumors located in different body

areas making it a versatile, reliable tool for brachytherapy. Future work includes the modeling of velocities and accelerations in parallel with the singularities analysis followed by the inverse dynamic modeling of the BR3 robot.

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