TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 58, Issue II, June, 2015

MODULAR DESIGN OF A PARALLEL ROBOTIC STRUCTURE FOR BRACHYTHERAPY

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Abstract: *The paper presents design and constructive issues of a parallel robot used for brachytherapy. The medical procedure of brachytherapy implies the placement of radioactive capsules via needles inside the cancerous tissues and demands a high placement precision and several medical conditions, coming from procedural and safety necessities. Thus the robotic structure presented has been engineered for the given task through a set of design parameters and chosen mechanical joints.*

Key words: *Brachytherapy, Parallel robot, Structural design, Mechanical design,*

1. INTRODUCTION

Brachytherapy is a cancer treatment technique usable on most types of cancer which implies the local irradiation of cancerous tissue via the placement or passing of radioactive material. Thus brachytherapy can be achieved through surgical placement, through an incision or operation, or the placement of small capsules through needles, an option which is minimally invasive. The insertion of the brachytherapy needles necessitates the use of imaging techniques like an Ultrasound, CT or MRI scans, which implies complex operator control and lately recommends the use of robotic arms for handling the needles. The design of the robotic structures needs to follow certain medical conditions of space requirements modularity, ample workspace and safety.

From the current usable imaging techniques only the CT scan has been selected as suitable, as Ultrasound has limitations in visualizing air gaps or through bone and also being hard to interpret while the image generated is distorted by the field of view of the apparatus. MRI imaging imposes nonmagnetic materials for both the robotic structure and the working actuators a condition where most motors stepper motors and even conductors are susceptible for interference with the generated image and unsafe for general use. The CT scan uses X-rays which are affected by all materials in a somewhat linear fashion to their respective atomic weight and/or density. Thus any robotic arm or structure that will be used near or inside the CT scanner has material limitations aside from the structural ones. This paper addresses the solving of these limitations through design solutions and structural modularity.

Therefore the robotic structure needs a high precision and stability for accurate placement and a reliable imagistic feedback, while both being accessible for other medical procedures and targeting a wide area of the body.

2. STATE OF THE ART

Robotic brachytherapy as a cancer treatment technique has raised a high interest from the scientific community as can be seen in the following structures on parallel or serial robotic structures especially designed for the brachytherapy procedure studied in (1):

Of the brachytherapy designed structures several were analyzed for their structural solutions and workspace obtained. EUCLIDIAN in (2) for the modular design with several modules of various Degrees of Freedom (DoF) with an autonomous seed delivery and able of angled needle insertion and needle rotation.

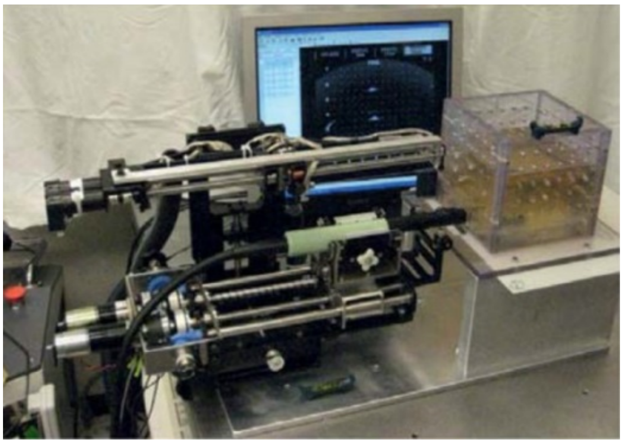

Fig 1. Setup of EUCLIDIAN

MIRAB (3) is of similar construction, yet offers the possibility of inserting multiple needles simultaneously into a somewhat smaller workspace.

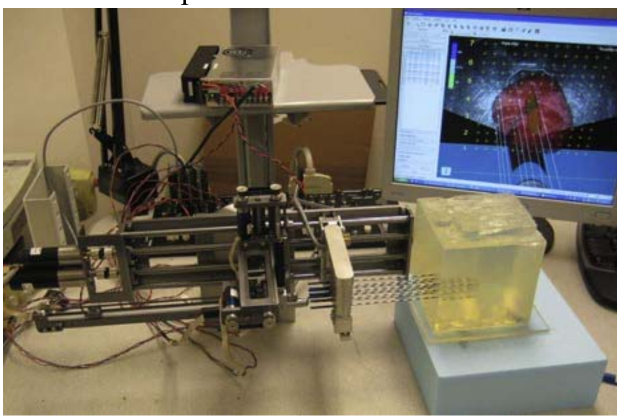

Fig 2. Setup of MIRAB

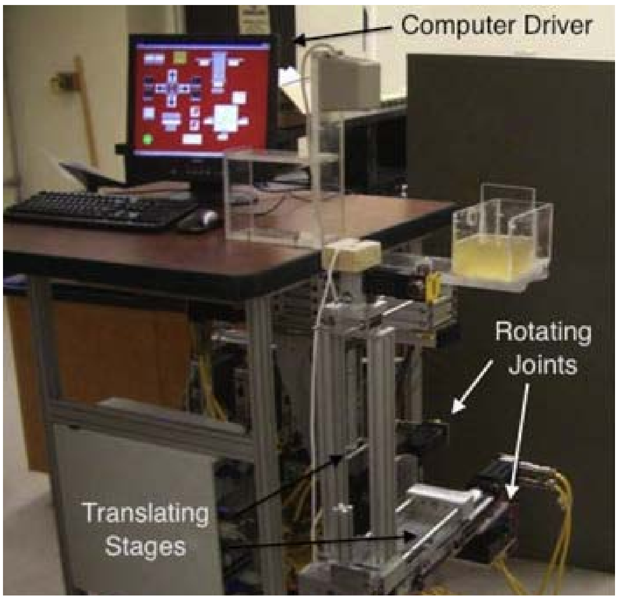

Fig 3. UW robot of the University of Wisconsin

The UW robot of the University of Wisconsin (4) with its 6 DoF structure has enabled manual needle insertion, for aiding the acceptance of robotics into a medical setting, where manual needle placement is the norm.

MrBOT of JHU (5) for a complex MRI compatible solution that is able to perform prostate cancer brachytherapy. It is built around proprietary pneumatic stepper motors, solving one of the main issues with MRI guided robotics, that of the use of non-magnetic materials in both the structure and the actuators. The robot is completely built out of nonmagnetic and dielectric materials.

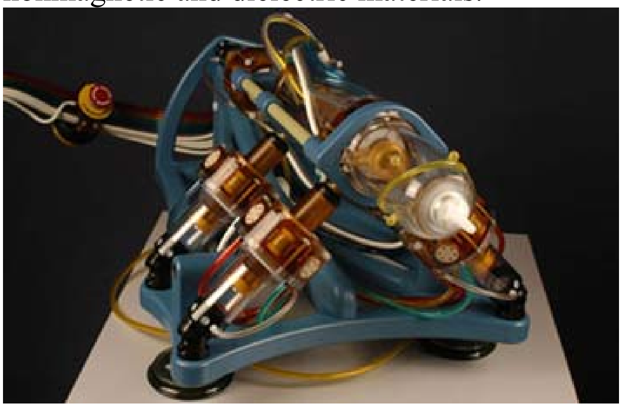

Fig 4. MrBOT parallel robotic MRI compatible structure

BWH-MR also from JHU (6) for another 6 DoF MRI compatible solution, enable medical procedures under this very powerful yet restrictive imaging technique.

3. MATERIAL CONSTRAINTS

For building a medical imagistic guided robotic structure, great care should be taken on the material constrains imposed by both the imaging technique and the procedure itself.

In our case the CT scanner will be used as it offers a very high resolution with little material constrains. X rays are fully capable of passing through most materials being dependent on thickness and density, the main issue appears with the image processing, as when placing a high density material in the scanning plane which will lessen the contrast on the less dense materials (in this case the patient) and the procedure will be hampered. As a consequence any material of higher density that will be in or close to the scanning plane has to be very thin or out of a very light density material. There is little choice for needle materials; most being medical grade stainless steel.

The main body needs to be sterilezable by heat or chemical means and as such plastics are problematic for their inherent surface quality which can retain microbiological media. Metals are better as the surface quality can be made to higher standards, and applying heat is not problematic. Surgical steel, copper and brass are too dense for CT imaging and as such need to be used only where no other choice can be applied. Aluminum is a good choice as it is only twice as dense as human bone tissue and as such will not affect the CT scan image by shadowing the patient.

4. STRUCTURAL DESIGN AND DIMENSIONAL CHECK

The robotic structure is composed of a base that holds the two columns, each of which contains 2 ball-screws and one shaft grooved or cylindrical as can be seen in the Figure 5 out of the patent (7). The original structure necessitated the modification of its initial arm lengths for enabling a farther reach as it would be the case when performing a procedure under a CT scan imager, the CT scan restricting the workspace by its scanning cavity.

The second major design modification from the original patent was necessary out of a reduced workspace resulting from the fact that the needle is directly connected to the end-effector platform which would necessitate more space inside the CT gantry. As such an alternate solution was proposed by the addition of a 6th motor that can push the needle from in-between the two cardan joints thus saving the space necessary for needle insertion.

This modification enabled the use of a plastic guide bushing as seen in Figure 6 that eliminates most of the flex experienced by a needle held by one end and thus contributed positively to the robotic structures overall precision requirements for the medical procedure of brachytherapy.

The added motor of the Needle Insertion Module, does add to the overall weight of the structure but as it can be seen in the kinematical study in (8) It does not significantly influence the structures motion.

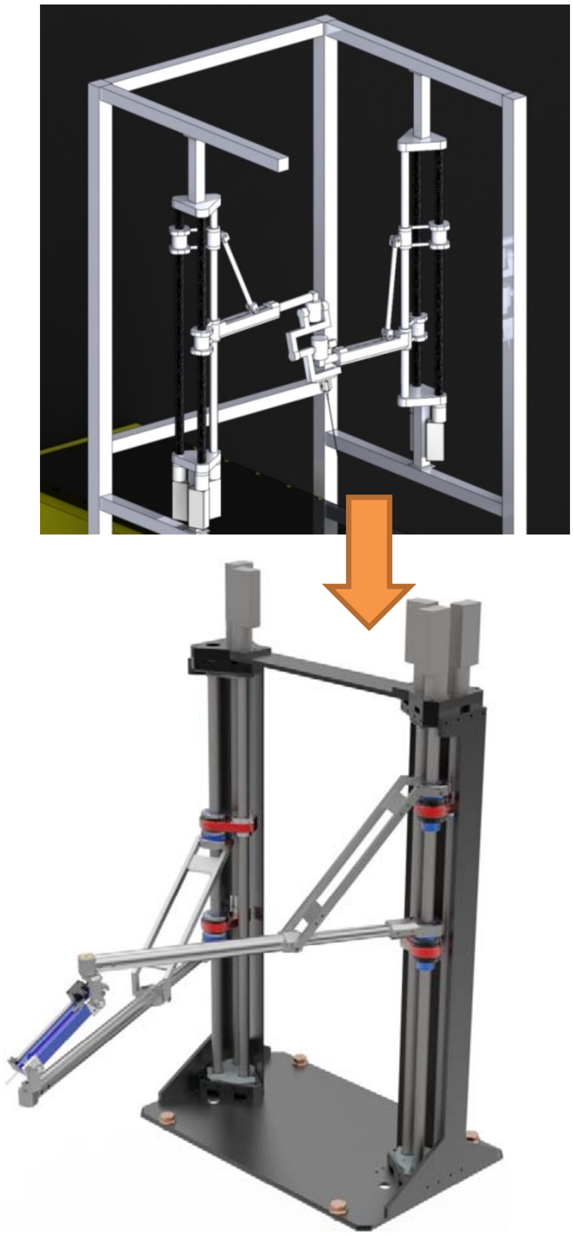

Fig 5. Side by side of the Patented and the brachytherapy designed structure

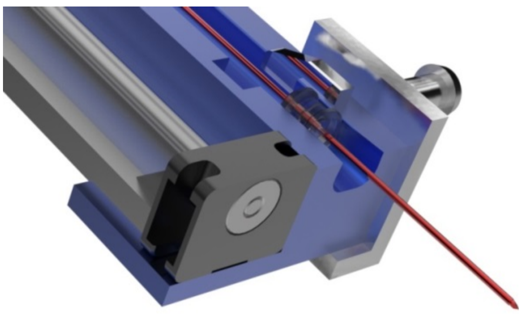

Fig 6. Transparent guide bushing holding the needle inside the guide groove.

The structure was checked in a virtual environment with a CT gantry and virtual patient model for several brachytherapy procedures, and the suitability for inside gantry procedures. The robot is fixed on the CT scanner table and is able to move inside the gantry while performing the needle insertion, during a simulation of a complex brachytherapy procedure, with a full motion, form the robotic homing with positioning orientation and insertion, to the retraction and reloading of a brachytherapy needle.

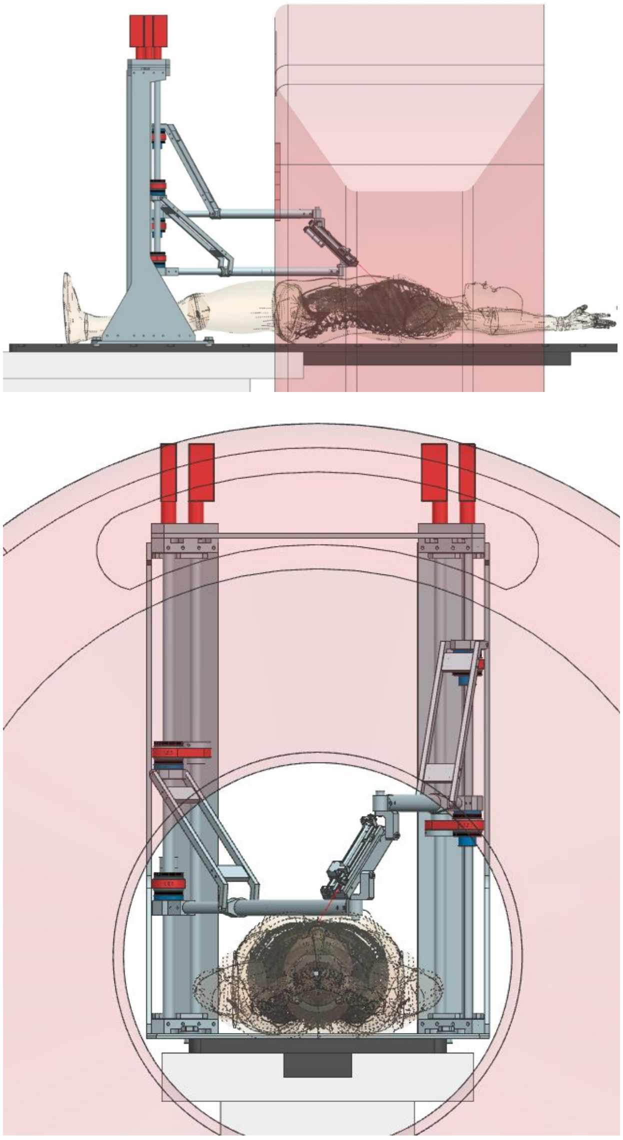

Fig 7. Dimensional check for CT scanner workspace with a virtual patient in a liver needle insertion.

Both CT scanner table motion and robotic orientations were tested, and the useful workspace of the robot has been validated by being able to perform a wide variety of procedures on most cases of brachytherapy procedures.

The virtual testing showed that it is preferable to extend the lower arm more than the top, for placing the bulk of the robotic workspace right in the middle of the CT table.

5. STIFFNESS DESIGN

The stability of the structure is due to its back plates that connect the top and bottom shaft and screw-end holders, where the two back plates form a V shape, intended for space economy and the enhanced stability that it offers by constraining 5 of the general Degrees of freedom, there remaining one rotational DoF around the Z axis.

A Finite Element study of the structure showed the high stability gain offered by a top connector plate, as it constrained the free degree of freedom of one column to the rigid translational freedom of the other column, thus stabilizing both columns with one added part.

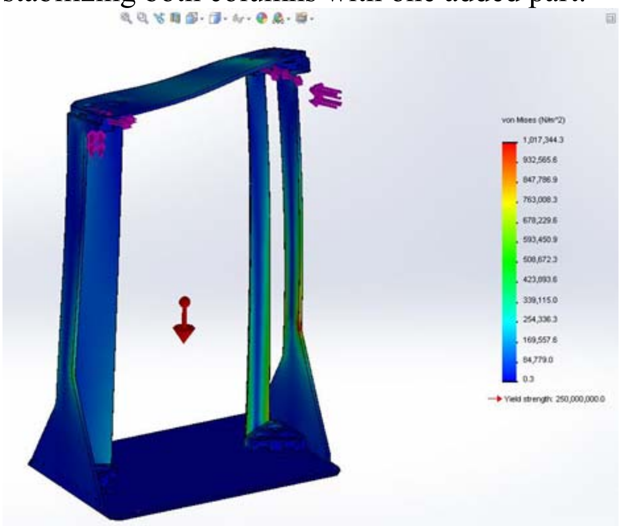

Fig 8. FE analysis of the structural stability and vibration modes

The FE analysis was done on a wide variety of situational forces and torques with high safety factors obtained. As the overall weight of the structure was in line with the requested requirements no weight saving measures were taken, as the added weight served for the rigidity of the two columns and the subsequent arms. The base plate has been selected as wide as possible enabling the insertion of several fixing and port holes for cables and other electronic equipment. The column bridge connector would also serve as a power cable holder, as the cables need to exit on one side only. A FEM analysis and the top connector bridge and back plates employed can be seen in Figure 8.

The robot employed a wide list of standardized and custom components of which of most importance are the 4 ball screws and the 2 shafts with their respective motors. In Figure 8 the standardized and custom components are highlighted against the newly designed components.

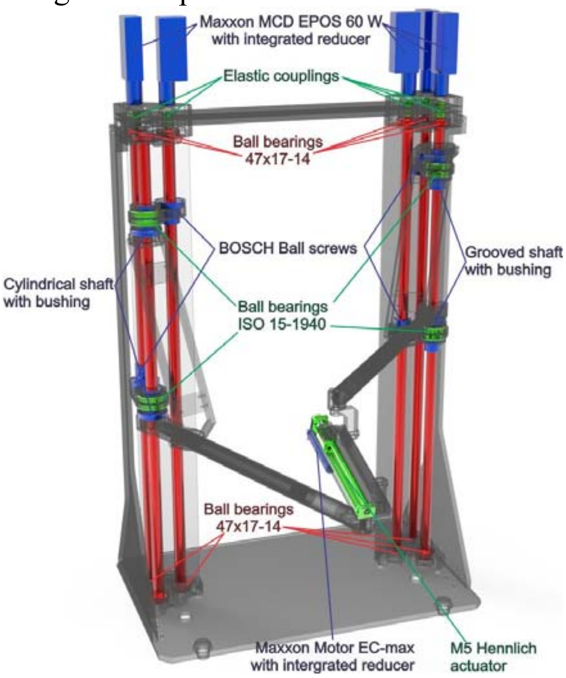

Fig 8. The standardized and customized robotic components, onto which the structure's design was based.

5. MOVING JOINTS

There are a total of 30 moving joints and 26 links, and while the benefit of using rolling friction joints is preferred, the spatial constraints impose the use of fitted couplings for the smaller components. Thus the joints that employ bearings were the largest and experienced the highest forces and torques as the cylindrical and grooved bushings, and of course the screws and grooved shaft. The cylindrical shaft had a rotating bushing and as such was chosen as a fixed component relative to the structural frame.

For fitted couplings a series of fitted screws were used for shaft material and fitted holes were machined inside the respective components. The screws were fixed by threading and fitted to very tight tolerances by the use of plastic bushings and washers.

The two translational joints were built using two aluminum pipes, with the closest being smaller in diameter for a better space economy and the farthest sliding over it the motion being controlled by a connector bridge. The two pipes have 2 contact points, aided in friction by 2 Teflon bushings, especially manufactured for this robotic structure.

The added friction gained by the fitted couplings is useful for stabilizing the structure under various loads, where all friction joints offer a more stable platform.

6. CONCLUSIONS

The paper shows the design and constructive parameters which define the engineering challenges of a robotic structure for brachytherapy. The robotic structure was taken through a wide process of virtual modeling testing and a virtual environment for workspace adjustment was used. The robotic structure was stabilized form a structural point of view and several rigidity issues were solved by the addition of specialized components and new constructive solutions, with a clear explanation of the used solutions and parameters. The virtual environment and virtual patient model simulation validated the found solution of workspace and mobility for several custom brachytherapy procedures and emphasizes the high modularity of the robotic structure in a medical setting.

ACKNOWLEDGEMENT

This paper was supported by the Project „Inter-University Partnership for Excellence in Engineering - PARTING - project coordinated by the Technical University of Cluj-Napoca" contract no. POSDRU/159/1.5/S/137516, project cofounded by the European Social Fund through the Sectorial Operational Program

Human Resources 2007-2013 and by the Project no. 173/2012, code PN-II-PCCA-2011-3.2-0414, entitled *”Robotic assisted brachytherapy, an innovative approach of inoperable cancers - CHANCE*” and the Bilateral Austria – Romania Project 745/2014, entitled “*Developing methods to evaluate the accuracy of potential parallel robots for medical applications*” both financed by UEFISCDI.

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DESIGN STRUCTURAL ŞI MEDICAL AL UNEI STRUCTURI ROBOTICE PENTRU BRAHITERAPIE

Lucrarea prezintă problemele constructive şi de design ale unui robot paralel construit pentru brahiterapie. Procedura medicală de brahiterapie presupune plasarea de capsule radioactive cu ajutorul unor ace în interiorul țesuturilor canceroase cerând o precizie de plasare ridicată și mai multe cobnstrângeri medicale, ce rezultă din necesitatile procedurale şi de siguranţă. Astfel, structura robotului prezentat a fost reproiectat pentru sarcina dată printr-un set de parametri de proiectare și a articulațiilor mecanice alese.

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