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Multi-objective optimization for brachytherapy robotic interventions

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Abstract: Brachytherapy (BT) is a procedure used to treat cancer by inserting needles into a patient to deliver radioactive sources direct to the tumour tissue. The efficiency of the procedure is determined by the number of needles inserted and by the precision of the trajectories of the needles. This paper presents an approach for needle insertion trajectory planning for a BT parallel robot based on a genetic algorithm. Given the locations of the seeds points and the 3D virtual model of the treatement area, the proposed solver allows to minimize the number of inserted needles and to define needles trajectoris that avoid high risk areas.

Keywords: robotic brachytherapy, optimization, genetic alghorytm.

1. Introduction

For the treatment of strictly located cancers, in the last time is used the brachytherapy technique. This treatment involves the use of low-dose local radiation by means of radioactive seeds (Low Dose Rate - LDR), applied directly in the tumor using special needles (Fig. 1) [3].

In conventional brachytherapy cases, an important issue is the positioning of radioactive seeds inside tumor. The classical technology involves the use a matrix template (grid) to guide needles, which helps the surger to position these correctly, manually, according with planned positions of the seeds. For example, the most common surgery of this type is prostate brachytherapy. Surgery planning involves determining radioactive seeds positions inside the tumor, taking into account the tumor size and radiation power of seeds. Also, will be determined the position in the grid and loading to all brachytherapy needles with radioactive seeds. In current medical procedures, putting needles in the human body is made by the physician, based on planning and verified in real time using ultrasound systems (see Fig. 1) [3], [6].

This paper proposes the use of a parallel robot (detailed in other papers), specially designed for this operation. This method of positioning the needles in the tumor has a special feature – it not using the template for guiding the needles. Access to the tumor can start from anywhere in the robot workspace taking into account the imposed conditions related technical characteristics of the equipment and the patient.

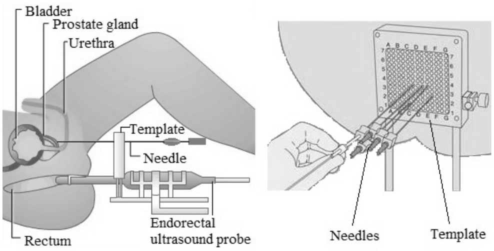


Fig. 1 Classical brachytherapy procedure in prostate cancer treatment [8][9]

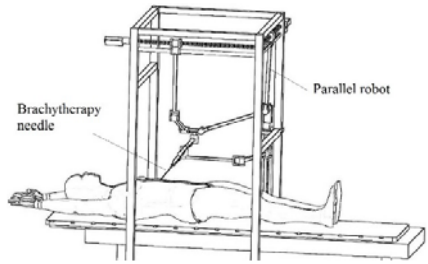


Fig. 2 Robotic brachytherapy procedure

The planning of this operation will follow the following steps: (i) CT or MRI scan of the patient (or his area of interest), (ii) reconstruction of a 3D model of the patient from the CT/MRI images, (iii) calculation of radioactive seeds positioning within the tumor, (iv) calculation of the BT needles trajectories, (v) robot programming. Steps (iii) and (iv) may be carried out by means of optimization methods using genetic algorithms.

2. Literature review

In literature, there are many references regarding the classical (manual) brachytherapy surgery. There is highlighted researches regarding operation planning, in field of calculation the radioactive seeds position inside the tumor. In [3] is presented in detail a mathematical model of the distribution of seeds and determining the insertion position of the needles on the matrix template. This mathematical model uses genetic algorithms.

The use of robots in surgery is detailed in [7]. In brachytherapy robotic technology, there are several research directions. In [1] is presented a trajectory planning of the BT needles in a 2D space using Markov method. The insertion needles are considered flexible and bodies (internal organs), rigid. An important research direction is the study of human body BT needles insertion and tracking their trajectories. Thus, various methods of pierced of tissues were highlighted, were performed calculations and experiments, suggesting optimal solutions. Are taken into discussions rigid or deformable bodies [2], [4], [5].

From literature review, it was revealed that aren't articles that study the problem of trajectory optimization in brachytherapy needles robotic procedure. In Fig. 3 are presented two robotic brachytherapy needle trajectories. The brachytherapy robot has an effector element with translational coupling which will insert the needle, passing through the patient's skin, following a previously set path.

The main problem for programming the robot is to find a linear segment, which starts from a point in the RWS and ends in the target point. All these trajectories will take into account that the needle does not intersect vital organs (ONP) but can intersect other organs (OBP).

3. Description of the optimization approach

In this study, the selection of needle trajectories to formulate optimal solutions is regards as a multi-objective optimization (MOO) problem. The problem requirements state that the distribution of the radioactive seeds should be more or less uniform and it is also necessary to ensure that the BT needles are not intersecting vital organs. Translate these into multi-objective optimisation, we have: (i) optimize needle trajectories to avoid vital organs intersection, (ii) minimize the number of needles insertions to reach all the target points.

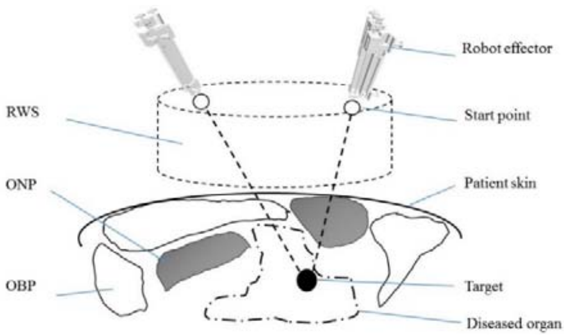


Fig. 3 Brachytherapy needle trajectories (RWS – Robotic Work Space,OBP – Organ that can be penetrated, ONP – Organ that cannot be penetrated)

This section provides the general overview of the genetic algorithm component and operation for optimization of BT needle trajectotries.The following input parameters are provided to the GA algorithm: 3D model of the patient including geometry model of the internal organs, OBP and ONP; position of the pacient treatement area; initial position of the robot; workspace of the robot; position (X,Y,Z) of the target points (radioactive seeds); technical data regarding the radioactive seeds (including the effective volume operation) and about the maximum and minimum doses for every internal organ.

In the genotypic space each candidate solution is represented as a chromosome of *n* genes (needle trajectories) identified by an ID and position of the insertion point in the robot workspace (Fig. 4,a). Initial population necessary to begin the genetic search can be generated using the following algorithm: (1) Process the 3D model of the patient reconstructed from CT images, (2) Load the 3D model of the patient into the application, (3) Define the target area for treatment (tumour position), (4) Define the position of each seed point, (5) Select a random insert point that is inside of the workspace, (6) Simulate the needle insertion process and check whether there is an intersection with vital organs or the treatement area, (7) Repeat the step 5 and 6 until are generated a specified number of needles trajectories.

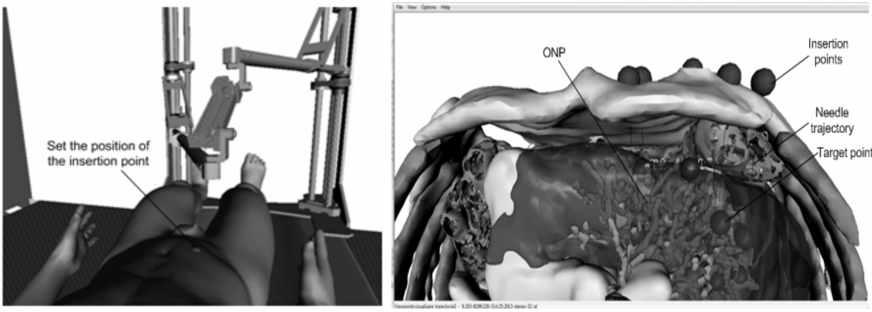
Using the conceived algorithm developed for automatic generation of linear robot trajectories is obtained a set of trajectories $\boldsymbol{T}$:

$$T = \{t_1, t_2, \ldots, t_i, \ldots t_n\} \tag{1}$$

where t_i represents the linear trajectories of a set with:

$$t_i = \{tg_1, \ldots tg_i\} \tag{2}$$

where *i* represent the gene number. These trajectories can be classified into four types: tg_a, tg_b, tg_c, tg_d and $t_i = tg_a \cup tg_b \cup tg_c$. The tg_a type contains the trajectories that do not intersect the vital organs, but intersect the tumour area at a point corresponding to a radioactive seed set by the physician. The tg_b type contains the trajectories that do not intersect the vital organs but the distance between the needle tip and a target point corresponding to a radioactive seed set by the physician is less than a specified threshold.The tg_c type contains the trajectories that intersect the vital organs.



a. *b.*

Fig. 4 a) Generate random brachytherapy needles trajectories; b) present the result obtained using the developed GA algortihm

To evaluate the quality of each chromosome in meeting the optimization objectives, we have to devise different evaluation functions for each objective. The overall fitness is the sum of these evaluation functions. Fitness function for evaluating objectives is calculated using the following steps:

- Each gene from the chromosome can have 0 to 5 points.
- Check whether a tg_i gene intersects a vital organ. If such an intersection not exists, then increase its score. Otherwise the trajectory $tg_i \in tg_c$ and its score is not incremented.
- If there is no intersection with a vital organ, check whether the tg_i gene intersects the tumour. If such an intersection exists, then $tg_i \in tg_a$, and its score is increased.
- If there is no intersection with a vital organ, check whether the tg_i gene intersects the tumour at a target point corresponding to a radioactive seed set by the physician. If such an intersection exists, then $tg_i \in tg_a$, and its score is increased.
- If there is no intersection with a vital organ or a target point corresponding to a radioactive seed set by the physician but the distance between the needle tip and a target point corresponding to a radioactive seed set by the physician is less than a specified threshold, then $tg_i \in tg_b$, and its score is increased.
- If tg_i intersects the tumour at more then one target points, its score is increased.
- The total score of a chromosome is the sum of points of all genes.

- The fitness value is calculated as chromosome total score divided with the maximum score, and maximum score is number of needle trajectories multiplied by 5. The fitness values will be in the range 0 to 1.

Rank Selection method was used to select the parents for reproduction. Each chromosome in the population is ranked in increasing order of their fitness values from *1* to *N*, where *N* is the population size; assume R_i is the ranking for the i^{th} chromosome. The ranking is the used to select the parents for reproduction. Multi-point crossover operator was used to create offspring from two parent chromosomes. For the mutation operation, first the cromosomes with the lowest rank are selected, than are replaced with the new ones to complete the forming of a new generation. The optimization process was designed and coded according to the following scheme:

```
BEGIN
    GENERATE initial random needles population
    INITIALISE the algoritm with following parameters
        POPULATION SIZE (N)
        NUMBER OF EVOLUTIONS (STOPPING CRITERION)
    EVALUATE each candidate based on its fitness value;
    DO WHILE (STOPPING CRITERION is not met)
      • Randomly selects N pairs of parents from the current population
          based on Rank Selection method.
      • Produce N new chromosomes by performing a crossover operation
          on the pair of parents.
      • Evaluate all the new chromosomes.
      • Selects the chromosome with lowest fitness value from the
          current population and replaces it with the best solution
          found on the new ones.
      • complete the forming of a new generation;
    LOOP
END
```

The algoritm run are until the best chromosome reaches a fitness value equal to 1 or the number of evolutions is higher than a specified value.

4. Implementation details and results

In the conducted experiment, a virtual environment has been modeled containing a 3D reconstructed abdominal model of a patient. Our test started by choosing the liver target treatment area. The BT procedure for liver treatement represents a complex process because of the incresed number and density of anatomical elements that are needed to be avoided by the BT needles. In the conducted experiment, a virtual environment has been modeled containing a 3D reconstructed abdominal model of a patient.

The experiment consisted in planning using the developed GA algorithm the trajectories of needles for the BT robot considering eigth preconfigured target seeds point presented in Fig. 4,b. In this experiment failure is defined as colliding with a high risk area or exiting the feasible workspace of the BT robot. For the representation of the 3D model geometry of the liver target area in the developed haptic module was used the ISO standard VRML2.0 (Virtual Reality Modeling Language).

The 3D geometry model is represented using IndexedFaceSet nodes and is composed of a number of vertex and triangles. In order to determine the intersection between the linear trajectories and the high risk areas a rayhit collision detection algorithm was used. This algorithm allows the detection of the contact between a linear segment and the triangles of the virtual object mesh. Control points are defined on the linear segment, used for collision detection. The algorithm returns the intersection point between these points and a line corresponding to the brachytherapy needle mounted on the robot TCP. For the implementation of the GA algoritm was used the C++ language.

Only five needles were needed to reach the eight target points because there are three needles that allow inserting of two seeds at one time. Also the needles trajectories do not intersect high risk areas.

5. Conclusions

In this paper was presented an approach for needle trajectory planning for a BT parallel robot based on a multi-objective optimization. We developed a software application framework that allows to optimize the number of needles and to define needles trajectoris that avoid high risk areas. We validated our approach for a complex BT liver treatement scenario. The performed test showed that the developed GA algoritm make possible to minimize the number of needles requiered for the seeds configurations and to find the needle traiectories that avoid high risk areas. Future work should examine the different types of crossovers and mutation operators that will allow reducing the search effort of the optimal solution.

Acknowledgement

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References

[1] Asadian, A., Kermani, M. R., Patel, R. V.: *Robot-Assisted Needle Steering Using a Control Theoretic Approach*, Journal of Intelligent & Robotic Systems, vol. 62, no. 3-4, pp. 397-418, 2010

[2] Elgezua, I., Kobayashi, Y., Fujie, M. G.: *Survey on Current State-of-the-Art in Needle Insertion Robots: Open Challenges for Application in Real Surgery*, Procedia CIRP, vol. 5, pp. 94-99, 2013

[3] Ferrari, G., Kazareski, Y., Laca, F., Testuri, C. E.: *A model for prostate brachytherapy planning with sources and needles position optimization*, Operations Research for Health Care, vol. 3, no. 1, pp. 31-39, 2014

[4] Gao, D., Lei, Y., and Zheng, H.: *Needle steering for robot-assisted insertion into soft tissue: A survey*, Chinese Journal of Mechanical Engineering, vol. 25, no. 4, pp. 629-638, 2012

[5] Mahvash, M., Dupont, P. E.: *Fast Needle Insertion to Minimize Tissue Deformation and Damage.* Proc. 2009 IEEE International Conference on Robotics and Automation, Kobe International Conference Center, Kobe, Japan, May 12-17, pp. 3097-3102, 2009

[6] Polo, A., Salembier, C., Venselaar, J., Hoskin, P.: *Review of intraoperative imaging and planning techniques in permanent seed prostate brachytherapy*, Radiotherapy and oncology : Journal of the European Society for Therapeutic Radiology and Oncology, vol. 94, no. 1, pp. 12-23, 2010

[7] Rembold, U., Burghart, C.: *Surgical Robotics: An Introduction*, Journal of Intelligent and Robotic Systems, vol. 30, pp. 1-28, 2001

[8] http://www.mycancer.co.za/prostate_content/treatment.html (acc. Aug. 23rd 2014)

[9] http://en.wikipedia.org/wiki/Prostate_brachytherapy (acc. August 23rd 2014)