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Kinematic analysis of a new 5-DOF modular parallel robot for brachytherapy

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A B S T R A C T

Cancer represents one of the main causes of the death. Huge efforts have been made by the scientific community to provide better cancer treatment solutions. An innovative option is the brachytherapy (BT), a local radiation technique for cancer treatment, which enables the delivery of high doses of radiation inside the tumors. BT usage is limited by the insufficient accuracy of the radioactive seeds placement. In order to eliminate these limitations, the authors propose an innovative modular structure which would enable the precise positioning of the BT needles in any part of the patient body. The paper presents the kinematic modeling of the new 5-DOF robotic structure. The workspace analysis and the singularities are studied and the dexterous workspace for a given insertion point inside the patient is also shown. Finally, some numerical simulations of different BT needle trajectories are included.

1. Introduction

Medical robotics is an exciting and relatively new field. Medical robots were initially used in the 1980s, in the field of urology. Robotics plays an important role in medical engineering and various robotic arms were developed and used in many medical interventions [1]. These robots can also be highly specialized and assist in diagnosing and treating patients. While there is still much more work to be done, robots use can enhance medical treatments in terms of both quality and accessibility of care. Robots can help reduce human errors, they bring highly specialized information to remote areas without requiring physicians' direct intervention.

Medical robots have been classified in several ways. Three types were distinguished from an operational point of view: remote controlled, synergistic and automated or semi-automated robots. In the first two types, the physician has direct real-time control of the robotic instrument either from a console, or by handling the instrument itself. For the later class, the physician does not have to continuously control the motion of the robot, but rather define its task and monitor the execution [2].

The usage of robotic systems to improve cancer treatment outcome is a new field. This field overlaps with electronics, computer science, artificial intelligence, mechatronics, nanotechnology and bioengineering. For this purpose, robots can be used in medical facilities to perform different tasks such as delivering radiation sources, real-time tumor tracking during radiation delivery or external beam delivery [1].

In radiation therapy, high-energy radiation from x-rays, gamma rays, neutrons, and other sources has been used to kill cancer cells and shrink tumors. Radiation may come from a machine outside the body (external-beam radiation therapy), or it may come from radioactive materials placed in the body near cancer cells (internal radiation therapy, implant radiation, or brachytherapy).

Brachytherapy (BT) 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 alone or in combination with other therapies, such as surgery, External Beam Radiotherapy (EBRT) and chemotherapy to treat tumors in many other body sites [3], followed by rehabilitation in strong dependence with the specific needs of the patients, like the systems for the inversion therapy [4], robotized massage beds, various assisting devices [5–7] and so on.

In many developed countries, prostate cancer is the second most frequent cancer found in males. For localized prostate cancer, different treatments are proposed depending on clinical stage, like brachytherapy, which consists in destroying cancer by introducing iodine radioactive seeds into the gland through hollow needles [8]. Together with radical prostatectomy and intensity modulated radiotherapy (IMRT), brachytherapy is one of the most frequently proposed treatments for cancerous tumors.

In modern brachytherapy procedures, the needles are inserted transperineally under the guidance of transrectal ultrasound

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(TRUS) images. Both the needle and the TRUS are operated manually and the seeds are deposited with a manual applicator. The needles are inserted through the fixed holes of a physical template. Therefore, the flexibility and maneuverability of needle insertion are severely limited. Sometimes it is difficult to avoid the pubic arch (especially for patients with large prostates) because the needles can only be inserted straight through the template's holes. The consistency and efficiency of the treatment procedure are highly dependent on the clinicians [9].

Huge efforts have been made by multidisciplinary teams to provide better treatment solutions all aiming at improving survival and life expectancy. In order to improve the efficiency of the procedures used in cancer treatment, various devices and robotic structures were developed around the world.

Over the past few decades, various High Intensity Focused Ultrasound (HIFU) devices and systems were made commercially available, as an option for prostate therapy.

A Focal Ultrasound Surgery (FUS) device called Sonablate 200™ (Focal Surgery Inc. of Indianapolis Milpitas, CA) [10] was developed for the treatment of Benign Hyperplasia (BHP) and prostate cancers. Other systems for BPH and cancer treatment are Ablatherm™ and Ablatherm^{R} (Technomed International, France; EDAP TMS S.A., France). A Magnetic Resonance Image (MRI) guided HIFU surgery system, called ExAblate®2000 has been developed in Israel (Insightec Ltd., Israel) and FDA approved for the treatment of uterine fibroids. It uses MRI to visualize treatment planning and monitoring in real time [11].

Other robotic systems, named FUSBOTs (Focal Ultrasound Surgery RoBOTs) [10] were developed for several clinical applications, such as breast surgery, urological surgery and neurosurgery. The robotic system, FUSBOT^{BS} was developed to mechanically scan and ablate a specified target in human breast. The latest version of custom designed robotic system for this application has 5-DOFs (3 for positioning, 1 for the orientation of the end-effector and 1 for imaging) in order to guide an end-effector through a pre-determined and image-guided trajectory. The changeable end-effector in the FUSBOT^{BS} system can allow surgery through the trans-abdominal route to reach urological organs. The version of neurosurgical system is developed for both single and multi-probe approach for the surgery of deep seated targets of the brain through a precise craniotomy. The desired craniotomy is performed using the FUSBOT^{NS} system with 7-DOF composed of a Hexapod system and a surgical drill unit.

Bassan built a 5-DOF hybrid robotic system to perform 3D ultrasound guided percutaneous needle insertion surgery [12]. A macro–micro system has been adopted in the design of the robot. The macro stage is responsible for the orientation of the needle with parallel mechanism and the micro stage for needle insertion and rotation.

Salcudean et al. introduced a 4-DOF serial robot for prostate needle orientation and 2-DOF for needle insertion and rotation with ultrasound imaging guidance [13].

Yu et al. presents a 16 degrees-of-freedom robotic system, 9 DOF for the positioning module and 7 DOF for the surgery module, developed and fabricated for prostate brachytherapy [14].

Zhang et al. provided a 2-DOF needling and seed delivery serial device to assist the manual needle insertion [15].

Fichtinger presents an ultrasound guided robotic system for prostate BT [16]. The system consists of a TRUS unit, a spatially aligned needle insertion device and an FDA approved treatment, a planning and image registering implant system.

Song et al. presents in [17] a robot which consists of a small tubular needle guide attached to a robotically controlled arm. In [18], another robotic system, entitled MIRAB, is designed for the simultaneous insertion of multiple needles. MIRAB is a 6-DOF robot capable of inserting and rotating 16 needles concurrently.

Fischer et al. introduced a 4-DOF hybrid robot for real-time control transperineal prostate needle orientation under MRI guidance, performing the insertion motion manually [19]. Aiming at the special characteristic of needle insertion, the robot generally consists of two parts: one for needle orientation and the other for needle insertion. The main part for orientation must support the upper stage for insertion with enough loading capacity. The slave part is responsible for needle insertion having a compact and stable structure with flexible and precise movements.

Jiang et al. present a prototype and 3D model of a 5-DOF hybrid robot for prostate needle insertion surgery under continuous MRI guidance. The robot is made up of of three stages: the pitch/lift module, the yaw/horizontal module and the insertion module [20].

Another robotic system is the MrBot, which consists of the robot and its controller unit, including a computer, the motion control elements, a series of electro-pneumatic and electro-optical interfaces, a brachytherapy seed magazine and the delivery system [21].

Several robotic structures have been used for robot-assisted BT, some of them designed especially for medical applications, others adapted and improved in this sense. The majority of the robotic systems used for brachytherapy are designed especially for the treatment of the prostate cancer. These robotic systems use the US probe for the imaging. All the systems have the advantage of a real time imaging with low costs and easy handling, but the great disadvantage of these robotic systems is their lack of universality, as they are developed for just one specific medical application, in this case, being limited to the prostate or inguinal zone.

The advantages offered by the robotic systems based on magnetic resonance imaging are the excellent spatial resolution images, a great difference between different types of tissue, the absence of ionizing radiations, the ability to obtain images of the sections oriented along any plane, but these systems have some disadvantages including the high cost of equipment and maintenance.

In some of the robotic systems, for the imaging the CT scanner is used, because of the advantages like short-scan, best browsing acute hemorrhagic and bone lesions and lower costs compared to MRI examination for the standard investigations.

In conclusion, it can be seen that the potential of robotic systems is clearly outlined; there is also a clear need for the development of robotic systems with a high degree of universality, capable of working in different cancer scenarios, general brachytherapy procedures in the abdominal and thoracic areas.

Plitea et al. proposed in [22,23] various robotic structures with 5-DOF for general brachytherapy procedures. The current paper, is focused on the development of a semi-automated robotic system with 5-DOF for general brachytherapy. The main advantage offered by this new structure is that it will be compatible with the CT-Scanners used in the brachytherapy procedures, thus it will improve the accuracy of the needle placement and seed delivery, the consistency of the seed implant, the avoidance of the patient critical areas (like urethra, pubic arch, rectum, bladder), the reduction of the radiation exposure [24].

The paper is organized as follows: Section 2 is dedicated to the presentation of the new parallel robotic system for brachytherapy. Section 3 deals with the kinematic analysis of the studied robotic structure. Section 4 studies the singularities of the robot and illustrates the workspace generation of the mechanism with different scenarios in direct correlation with the brachytherapy task. In Section 5 some numerical and simulation results obtained from the robot kinematics and its validation are presented. The conclusions of this work are presented in Section 6, followed by acknowledgments and references.

2. The modular parallel structure for brachytherapy

A modular robot is commonly built from standard components, making it possible to assemble the modules in a variety of ways to suit a variety of purposes. Modularity has many advantages. In