CoBra robot for localized cancer treatment and diagnosis under real-time MRI

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Abstract: Cooperative Brachytherapy (CoBra) project intends to perform localized cancer treatment and biopsy of soft-tissues. The robot executes needle insertion within the MRI-scanner, performing adaptive prostate brachytherapy under real-time (RT) imaging. An active steerable-needle under closed-loop control is used to achieve precise positioning of the seed. Dose calculation under RT-MRI is achieved by the generation of synthetic-CT datasets based on a Machine-learning algorithm. Needle trajectory planning based on a steerable needle with minimal entry points is optimized by an algorithm depending upon the target, seed plan, and prostate contours attained from MRI. A bio-inspired active phantom is designed for concept validation.

I. Introduction

Prostate cancer is the most common and one of the major reasons for death among men. International agency for research on cancer estimates an increase of 16.9% incidence rate and 26.2% mortality rate in prostate cancer of European population by 2030 since 2020 [1]. The CoBra project is developing a semi-autonomous robotized solution aiming to perform biopsy and treatment of localized cancers under MRI-guidance, initially for prostate cancer. MRI has superior image quality compared to trans-rectal ultrasound to detect small lesions, and has been explored for two decades for localized cancer treatment under real-time (RT) intraoperative MRI.

In the literature [2], related to the MRI-guided prostate intervention robots, most demonstrated needle placement only. Thus, demanding the manual intervention of physicians for seed delivery. In addition, the key requirement is RT intraoperative needle intervention to take an advantage of MRI-guidance and robotic systems. The strong magnetic field of MRI restricts the use of conventional actuators and sensors.

We present an integrated design of the CoBra concept with different modules as sub-component systems with specific tasks to achieve the final mission of prostate brachytherapy (BT) or biopsy (BX). The modules can be stated as: an MRI-system, a dosimetric treatment planning system, a needle trajectory planning software (NPS), and the MR-conditional robot. The CoBra partners have developed an MR-conditional robot, dosimetric algorithm, curved steerable needle, MR-biopsy module, needle trajectory planning software, and proof-of-concept for active bio-inspired prostate test phantom (BIP).

II. Material and methods

The MR-conditional robot has been developed to perform in-bore prostate adaptive-BT and BX with the aid of a steerable needle targeting the lesion sites under RT-MRI. The robot is actuated using ultrasonic-piezo motors (USM) in closed-loop feedback with absolute linear encoders. The patient is positioned in lithotomy with the help of Uni-Lift, maintaining the patient in-bore intraoperatively in a comfortable position throughout the procedure [3]. The robot with 5 degrees-of-freedom is capable of performing oblique insertions to avoid organs-at-risk (OARs) with minimal insertion points without the aid of any template-guide. The robot is designed with a quick-lock mechanism for an easy exchange of BT or BX modules. An automated seed delivery device has been developed for the BT module actuated using USM motors.

The novelty of the concept is to deliver dose adaptively under RT target tracking intraoperatively. The curved steerable needle is able to reach a new target position when pre-defined target shifts during needle insertion, prostate motion, tissue deformation, or inflammation. Targets are planned based upon an initial dosimetry plan under RT-MRI, then tracked and updated in parallel using rapid creation of accurate synthetic-CT (sCT) datasets from the live MR images and are used to update the NPS to deliver the seed with more accuracy using curved steerable needle. Thus, the dosimetry plan integrated to NPS and robot helps to deliver dose to the new target position.

In order to attain an RT dosimetry plan using sCT datasets, the team use an augmented cycle Generative Adversarial Network (AugCGAN) algorithm [4]. AugCGAN is more robust with the erraticism of MR-images as compared to the standard cycleGAN. This study incorporated T2w MR and CT pelvic images of 38 patients from 5 centers. The AugCGAN was trained on 2D transverse slices of 19 patients from 3 different sites. The network was then used to generate sCT images of 19 patients coming from two other sites. Mean Absolute Errors (MAE) for each patient were evaluated between real and sCT.

The novel steerable needle has been manufactured and omnidirectional steering at the distal tip can be achieved by a jointless integrated pull-push mechanism. The degree and direction of needle steering are controlled by four piezoelectric motors at the proximal end of the robotic BT module as shown in Fig. 1. The inner needle and outer catheter with a 1.4 mm and 2.0 mm diameter, respectively. After needle placement, the inner needle can be retracted leaving behind a channel for seed delivery. Artifact formation of the needle and piezoelectric motors is evaluated in 3 T MRI.

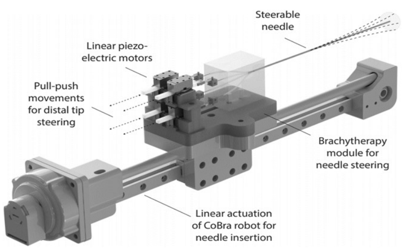

Figure 1: Steerable needle concept under the CoBra project

CoBra's needle path planning algorithm is designed for steerable needles based on the seed plan and prostate contours received from MRI. It clusters the seeds and creates candidate path plans to reach all seed positions, using a single insertion point. Fig. 2 is an example of Seed plan using single entry point. Acceptable results are those that allow all seed positions to be reached, while keeping a minimum, pre-set distance between the needle and the urethra. From all candidates, the one that causes the least amount of tissue damage is chosen.

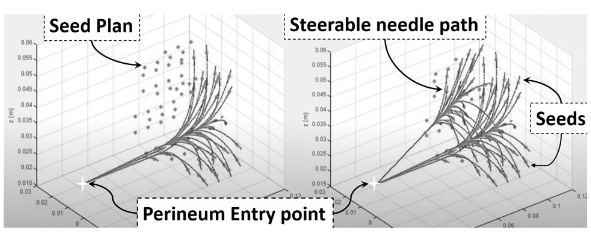

Figure 2: Seed plan using single entry point.

For CoBra robot testing, the team developed a BIP, depicting the motion, deformation, and inflammation of the prostate seen clinically during needle insertion. The BIP is connected to SOFA (Simulation open framework architecture) to estimate the changes in the prostate, thus enabling tracking of target position interactively (Fig. 3).

III. Results and discussion

CoBra robot was tested under a 3 T Philips MRI scanner at Lille Hospital, France. The absolute encoder and USM actuators resulted in normal functioning under a strong magnetic field without influencing the MR-images during the scan. Zipper artifacts were detected from an unshielded wire. Straight needle insertions were performed on Agar phantoms and BIP. Tests of the BIP and robotic needle insertion in RT-MRI showed that the BIP features could be extracted with good fidelity and the needle tip identified under T1w, T2w, and DYN-B FEE sequences. sCT datasets showed a mean MAE of 59.8 HU and 65.8 HU for first and second test sites, taking on average 8.5 s to generate a complete sCT (90 slices) on our GPU (Nvidia Quadro P6000). The in-bore testing of the BX-module and steerable needle weren't influenced by the 3 T field.

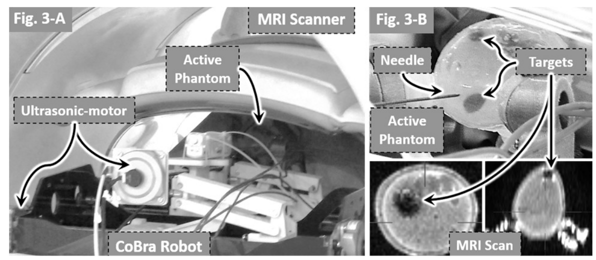

Figure 3: (A) CoBra robot-guide, (B) Active prostate phantom and Phantom MRI scan.

IV. Conclusions

This abstract reports the recent progress attained from the CoBra project, as it reaches the phantom testing stage. BIP helped the team to replicate the actual condition of prostate intervention, as in biological tissue, the target shifts due to multiple needle insertions and prostate motion. The CoBra concept contributes towards adaptive treatment and diagnosis, which consists of adapting the control of the robot for precise deposition of seed with a minimal perineum entry points and reducing the tissue damage. The novel curved steerable needle concept helps further to reach the targets which are inaccessible to conventional prostate brachytherapy treatment with straight needles in a grid. The CoBra concept, a multi-system model, integrates the robotic sub-systems using MRI-guidance in closed-loop feedback to implement an adaptive MR-robot control, for the treatment of localized cancers.

Acknowledgments

We thank our observer partners for assisting us with their components, TPS by Eckert & Ziegler BEBIG, Uni-Lift by NORAS, MR-guidewire by MaRVis, and absolute encoder by Heidenhain-Numeric Jena.

Author's statement

This work has been co-funded by the European regional development Fund under EU Interreg 2 Seas, Grant 2S04- 022.

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