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Optimisation of path planning for minimally invasive interventions on prostate using MR-robot: Application to on-live pets

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Abstract: The robot-assisted biopsy system under Magnetic Resonance Imaging (MRI) guidance is a promising candidate for prostate cancer diagnosis in terms of improving the reliability and accuracy of reaching micro-lesions of perineum organ tissues. This has been explored for the last decade. A pre-requisite for effective interventional diagnosis is an accurate intervention planning that is difficult to achieve manually. This is due to multiple factors mainly, the fact that the insertion needles trajectories should avoid organs at risk and limited manoeuvrability, under clinician control. Thus, Biopsy-robot is a feasible solution to improve targeting accuracy. However, the planned trajectories should be consistent with the needle-driven robot's kinematics capabilities. To eliminate these problems, we present an integrated concept composed of MRI-robot and Brachytherapy (BT) path planning algorithm, allowing to minimise the number of entry points of BT needles, from a physical grid to reach all the treatable volume of the prostate gland. This means minimising the number of inserted needles from the perineum, compared to a conventional straight insertion of multiple needles. Indeed, the proposed method is able to set-up safe percutaneous routes defined by a set of oblique straight-line paths linking a minimum number of feasible entry points and desired finite target points, defined within the prostate volume. By adopting such a procedure, the aim is to contribute in minimising tissue damage and patient trauma, and risk of infection, and shortening recovery time. A combinatorial approach is proposed for the minimisation of the insertion point. The development, implementation, and experimental evaluation of the needle path planning method for the 5 Degree of Freedom (DoF) robot guide is presented and performed within a 1.5 Tesla MRI to evaluate how the proposed approach is efficient and reliable on-live pets.

Keywords: Medical robot, Optimisation, Path planning, Magnetic resonance imaging

1. INTRODUCTION

Prostate cancer is the most prevalent disease among men. Localised prostate tumours can be treated by surgery, external radiotherapy, or brachytherapy (BT). These treatments are validated by the High Authorities for Health (HAH). The management of the prostate organ treatment is multidisciplinary: the treatment proposal is made by the urologist and the radiation oncologist; the final choice being made by the patient. Surgery involves removing the entire prostate, while radiotherapy involves delivering 70Gy (amount of energy absorbed by living or inert matter per unit mass) in 35 daily sessions and lasts at least 7 weeks using a particle accelerator. In parallel, BT is a technique better tolerated by the patient, aiming to irradiate a target volume by placing within it or in contact with radioisotopes emitting low-dose ionising radiation (LDR) or high-dose ionising radiation (HDR). These last treatments are

obtained under the guidance of ultrasound (US) images. Prostate BT is conventionally performed manually using a standard grid template with trans-rectal US imagery, called TRUS-BT. Still, there are many limitations with the TRUS-BT to account for better accuracy; such as *Needle manoeuvrability, Prostate motion, Accuracy and precision.*

To address these issues researchers have proposed robotic solutions, summarised in (Podder et al., 2014). Different approaches are proposed in order to robotise the prostate BT. The first approach tends to reproduce the gesture of the manual BT, where the grid, used for guiding the needles during the insertion, is simulated by the robotic system (Jain et al., 2012); while the second approach consists in completely freeing oneself from this grid (Moraire et al., 2017). With the advent of technology in the imaging modalities in recent years, MRI has gained a lot of interest over conventional US imagery to detect small

lesions which go undetected by TRUS (Bi and Zhang, 2020). Thus, Magnetic resonance imaging (MRI) is the preferred imagery to detect small lesions due to its better soft-tissue contrast. This allows the development of new robots compatible with MRI (Fischer et al., 2008; Krieger et al., 2012). To avail the advantage of MRI visualisation, the robotic-system must be MRI-compatible and perform intra-operative real-time needle intervention. Numerous robotic solutions for prostate intervention under MRI have been developed and proposed (Dhaliwal et al., 2021b). Also, recently, a cooperative-BT (CoBra) robotic system for LDR-BT and HDR-BT based on intra-operative real-time MRI tracking has been developed (Dhaliwal et al., 2021a; Navarro et al., 2021). Authors study in the following, the opportunity of associating to the robotic-system a grid, allowing both to guide and orient the conventional rigid needles of BT with the precision required for BT. The objective is to perform insertions with a minimum of needles to insert, which can cover the entire treatable volume of the prostate gland. Authors intend to propose a minimum perineum entry points (MPEP) concept for prostate targeting to reduce edema and trauma, e.g., (Xu et al., 2009), (Satt-Nord, 2020). Van Gellekom et al. (2004) proposed a single needle entry method that is capable to cover adequate prostate volume and stated isodose was comparable to the conventional method with multiple parallel needles.

From clinical side, Ryu et al. (2012) state that oblique insertions are efficient as compared to parallel needle insertions for large prostate glands to solve pubic arc interference issues. Also, Vyas et al. (2015) proposed that robotic devices, that have the potential to place needles at variable distances compared to conventional practice, allow reducing the dose to the rectum and urethra while covering the whole prostate dosage. Thus, a robotic-BT concept with MPEP has the potential to result in a significant clinical advantage.

This introduces the problem addressed in this paper, in terms of minimising the number of entry points from the grid of BT needles, using a minimally invasive robot under MRI guidance. This is a Combinatorial optimisation Problem (COP) (Peres and Castelli, 2021), which appears in various social, industrial and biological applications, allowing to make them more efficient. However, in almost all cases, this problem is difficult to resolve due to combinatorial explosion. In the framework of this work, COP is used for tracking multi-biological targets in the context of BT treatment planning using an MR-based mini-invasive robot. In this case, combinatorial optimisation consists of finding optimal entry points from a finite set of tissue target points, where the set that is made up only of isolated points is called also a discrete set. Main known COPs are the travelling salesman problem (TSP) (Ross et al., 2020), the minimum spanning tree problem (MST) (Chazelle, 2000), and the knapsack problem (Wu et al., 2011).

In the context of the tracking of multi-target points with minimum entry points from the grid, the exhaustive search is not tractable using the previously mentioned COPs. The paper is organised as follows: Section 2 describes the combinatorial approach used to minimise the number of insertions. Section 3 describes the workflow and in-vivo biopsy applied on live dogs in bore the MRI scanner.

Finally, Section 4 gives the conclusions and prospective works.

2. PATH PLANNING OPTIMISATION PROBLEM

2.1 Problem Statement

The conventional biopsy practice uses a grid that allows only parallel insertion. This involves multiple insertions to reach several target points in the prostate, as shown in Fig. 1-(A). In order to minimise this problem, the authors propose the MPEP approach to target a maximum of tumours with a minimum of entry points. The CoBra template grid (CTG) to be installed along the perineal skin describing a grid of entry points, which serves as a guide for the needle to cover the entire prostate with different insertion angles, shown in Fig. 1-(B).

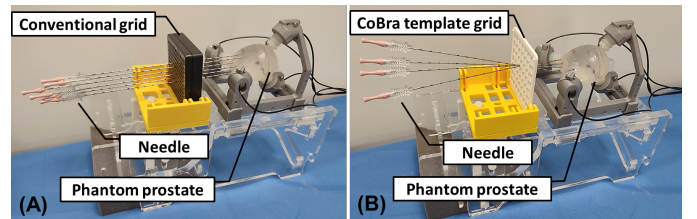


Fig. 1. (A) Conventional parallel needle insertions: a practice that causes oedema and trauma to patients due to multiple insertion points; (B) Optimal oblique insertions point prostate targeting: multiple needles are inserted at varying orientations for optimal coverage of the target volume, which means a faster and less traumatic treatment for the patients.

However, the orientation of the needle depends on the architecture of the robot-guide, which may reach its joint limits for an entry point and a target point, due to its mechanical constraints, shown in Fig. 2.

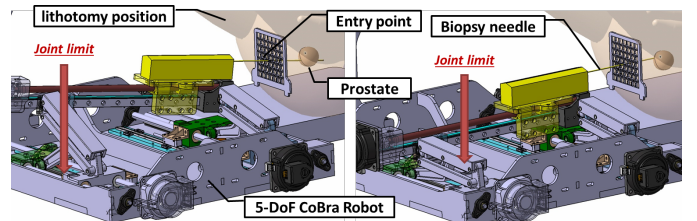


Fig. 2. CoBra template grid concept with minimum entry point prostate targeting.

In the next section, we propose a needle path planning, based on a combinatorial optimisation approach, allowing to reach the tumour target points with a MPEPs while avoiding the organs at risk, but also avoiding reaching the limits manoeuvrability of the robot.

2.2 Formal problem definition

The COP addressed in this work is a process of finding an optimal set of solutions from a discrete set of finite feasible solutions. In the case of BT using the CTG, the challenge is to minimise the number of insertions to achieve

the selected number of target points. As illustrated in Fig. 3, each needle path is defined by a the target tumour point and an entry point. The term "path" is used to define the path of the needle through the human body from an entry point to a target point. Thus, a complete treatment involves N paths to visit all N specified target tumours in the prostate. The problem can be formulated as follows. let I_t be a finite set of N target points P_t and I_e be a finite set of Ne entrance points P_e selected on the grid. A treatment involves N paths to visit N target tumours in the prostate, thus a feasible solution is a finite set of N feasible paths $P_e P_t$ such as $P_t \in I_t$ and $P_e \in I_e$. Note that one entrance point can serve to join various target points. The question is to found the best combination of N feasible paths $P_e P_t$ minimising the number of entrance points that systematically minimise the robot travel inside the prostate. A treatment involves N paths to visit N target tumours in the prostate

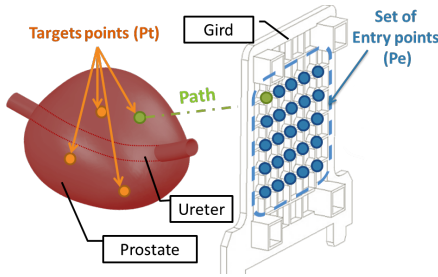


Fig. 3. Optimisation Problem : The blue points describe the set of entry points of the grid installed along the perineal skin. The orange points represent the target tumours in the prostate. Each needle path (green) is defined by a point in the target and an entry point.

2.3 Path Planning Procedure

The proposed offline planning algorithm is developed in three successive steps:

Step 1 : It consists of establishing a database of feasible combinations in regards of imposed constraints such as obstacles avoidance and robot's kinematic limits (Table 1). This database contains all paths ($N * N_e$ combinations) to reach all specified target points inside the prostate. Each path is identified by a number and assigned the coordinates of the corresponding j -th entry point and the i -th target point. Actually, the distance between the entry point and the target point describes the cost function F_{obj} of this elementary travel. The "Verifying constraints" column in Table 1 is determined using the inverse kinematic model (IKM) of the CoBra robot developed in (Belarouci et al., 2022). Knowing the mechanical limits of the robot joints, the feasibility of the paths can be verified.

Table 1. Database of combination

No. path	No. Entry Point	No. Target Point	Verifying constraints	F_{obj}
1	j_1	i_1	True	...
2	j_2	i_2	True	...
..	False	...

Step 2: From the database of Table 1, For each target point P_t (1, ..., i_1 , i_2 , ...,N), it is possible to set up a list of possible entry points P_e identified by their number in

the grid j_1, j_2, j_3, \dots . Consequently, the following N lists of indices are established:

$$\begin{aligned} List[i_1] &= [j_1, j_2, j_3, \dots] \\ List[i_2] &= [j_1, j_2, \dots] \\ &\dots \end{aligned}$$

These lists permit to easily construct solution candidates, recall that a feasible solution is a set of N elementary feasible paths linking the specified N target points to a subset of possible entrance points on the grid.

Step 3 : This step consists of finding the best possible combination minimising the number of insertion points allowing to attain all specified target points. The global cost function FG_{obj} that must be minimised is the total distance to be travelled by the needle to visit all target points. The algorithm 1 describes the heuristic for obtaining the best possible combination (P_t, P_e) with the minimum number of possible insertion points.

Algorithm 1. Combinatorial optimisation algorithm

Data: $P_t[1 \times N] \in Database, N \leq Size(Database)$
Result: $BestCombin$
 $BestCout \leftarrow 1e20$; //Initialization//
 $BestCombin \leftarrow []$;
 $Combin \leftarrow [[]]$;
 $k \leftarrow 0$;
while $k < Iteration\ Number$ **do**
 $Cout \leftarrow 0$;
 for $i \leftarrow 0$ **to** N **do**
 $j \leftarrow \text{random value}$;
 $NoPath \leftarrow List[P_t(i)][j]$; //random selection the set of feasible entry points and target point//
 $Cout \leftarrow Cout + F_{obj}(NoPath)$;
 $Path \leftarrow NoPath$;
 end
 $BestCout \leftarrow Cout$;
 $k \leftarrow k + 1$;
 $Combin[k][1] \leftarrow BestCout$;
 $Combin[k][2] \leftarrow NumberPoint$;
 $Combin[k][3] \leftarrow Path$;
end
 $k \leftarrow \text{find}(\min(Combin[:,1]), \min(Combin[:,2]))$;
//selection criteria//
 $BestCombin \leftarrow Combin[k][3]$

2.4 Numerical results

Fig. 4 shows the number of possible combinations based on the number of P_e and the count value, obtained by Algorithm 1 : "Combin". Thus, by using the minimum values of P_e and count, we can identify the corresponding "BestCombin". The algorithm was tested on a 3D representation of a prostate reconstructed from MRI images, as illustrated in Fig. 5. The prostate was sliced with a 2mm step size, and a grid of points spaced 5mm apart was then overlaid on each slice. A database was generated from these point clouds by removing points outside the prostate, in the urethra, and points inaccessible due to the robot kinematic limits. As described in the previous paragraph, a list of feasible entry and target points was established from this database. A first representation can be visualised from a set of desired target points, as shown in Fig. 5.(A). This representation displays all the possible entry points P_e through the robot kinematics to reach the selected target points. The combination that minimises the

number of inputs and the cost function ($BestCombin$), circled in red in Fig. 4, is illustrated in 3D in Fig. 5.(B).

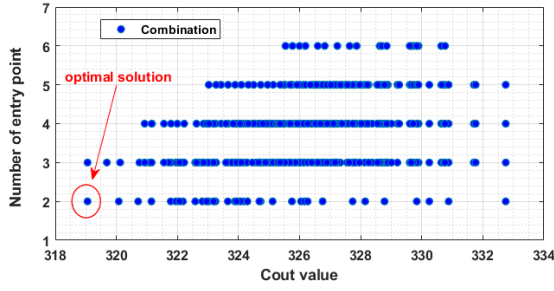


Fig. 4. Criteria for selecting the optimal solution according to the application

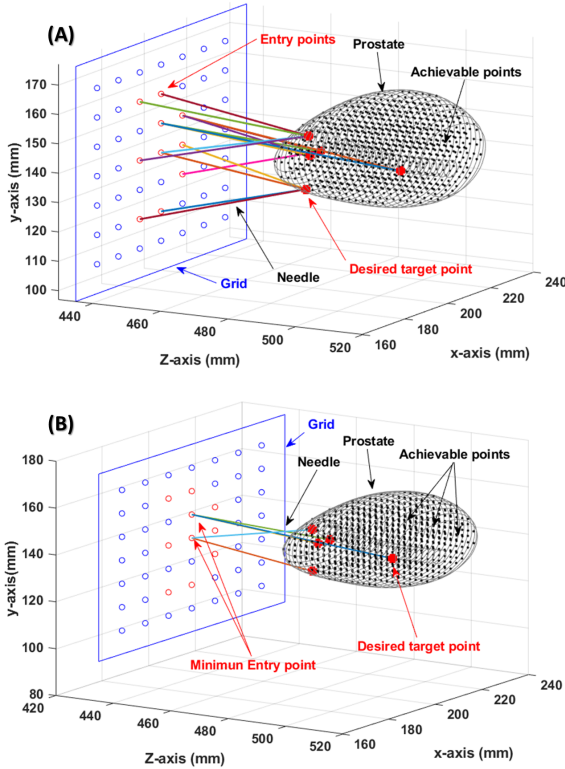


Fig. 5. Top:(A) All possible paths connecting each selected target point in the prostate from the P_e corresponding to the accessibility of the CoBra robot; Below:(B) Minimisation of the number of entry points to reach all target points corresponding to the criteria of the selected solution in Fig. 4

3. PRELIMINARY CLINICAL PETS STUDY

This paper reports on the reliability of the approach presented through a clinical prostate biopsy procedure performed on a male Beagle dogs of *Canis lupus familiaris*, 2 years old at the time of the intervention, inside a 1.5T SIGNA scanner, as shown in fig. 6

3.1 CoBra BT-Robot Description

The CoBra system is based on the integration of different component systems (active and passive) to achieve the

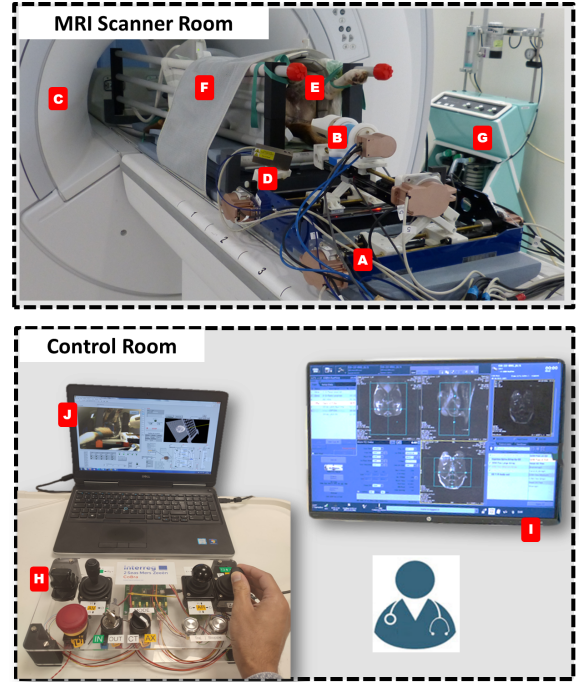


Fig. 6. The CoBra system integrates a robot-guide of 5-DoF parallel robot (A), a module of BT (B), MRI-scanner (C) and MR-camera (D). The dog (E) is placed on a support (F) in a lithotomy position and under sedation (G). CoBra system architecture is tele-operated by joystick (H) from the control room using the MRI console (I) and graphical robot control interface (J)

single common task of tumour/lesion targeting. Thus, active systems form a cooperative control by communication among each other to fulfil the needle insertion task to the desired lesion site. The CoBra system (Fig. 7) is composed

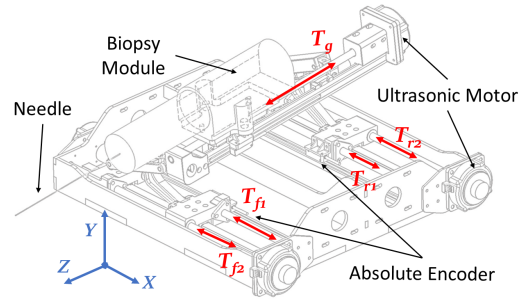


Fig. 7. The CoBra 5-DoF parallel robot

of a robot-guide of a 5-DoF parallel robot, actuated by ultrasonic piezomotors (USMs) $PSM60N - E2T$ ¹ and equipped with MR-safe absolute encoders ($LAK14 310A Prototype-glass^* ceramic scale$)². The CoBra setup is associated to an Uni-Lift system for in-bore patient stability in lithotomy position for transperineal access, shown in (Dhaliwal et al., 2021a). For operator accessibility and to gain real-time visualisation for tele-operation control and patient monitoring, CoBra setup is equipped with MR-safe camera.

¹ <https://www.piezo-sonic.com/products/general/psm60s-e2t>

² <https://www.numerikjena.de/en/linear-encoders/>

3.2 Clinical Workflow

This section describes the adopted robot clinical workflow for achieving a biopsy, from calibration to target selection, robot control and needle insertion. The robot is manually mounted on the scanner bed and registered to the MRI scan space. It is then followed by the selection of target points and identification of obstacles. For this, an MRI-compatible grid is placed against the perineum using a suitable support (Fig. 8.(A)). The grid has 4 pockets filled with agar-agar, visible under MRI. The tip of the needle is then placed at a midpoint of the grid (Fig. 8.(B)). A pre-operative scanning will permit to identify in the operational space the different frames attached to the robot, the needle and the prostate gland using the MRI console and the IKM of the CoBra robot.

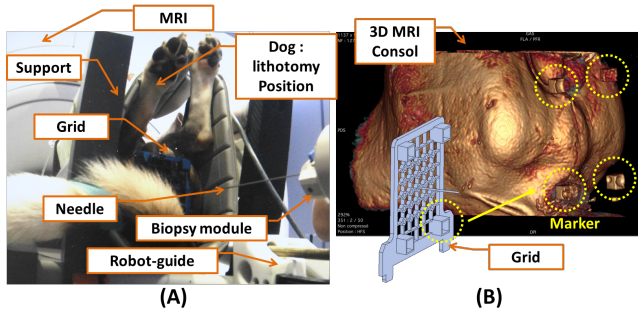


Fig. 8. (A) System configuration for the pet study. The dog lies in a prone position with its legs supported by the support. The sterilised grid is fixed to the dog support between the dog's leg. The robot-guide CoBra is positioned on the MRI board, and locked into place. (B) 3D view of an MR image of the dog in lithotomy position with markers to register the robotic system with the MR scanner coordinate system.

After frame registration, a new set of images of the prostate region was acquired allows the veterinary doctor to define the target point in the robot frame. From the target coordinates and the solutions provided by the combinatorial approach, a preoperative check is essential to avoid damage to organs at risk, as shown in fig. 9

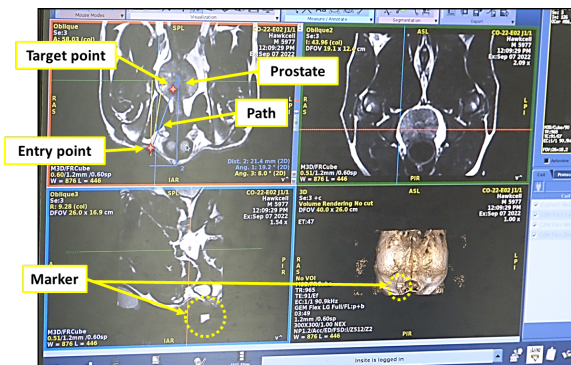


Fig. 9. Path validation : The MRI console allows visualising pre-operative and intra-operative images produced by MRI scans.

3.3 Results

Results from the clinical study are represented in Fig. 10 A control based on IKM is executed on the CoBra robot

for positioning and orienting the needle tip on the P_e before insertion. A small, non-invasive incision was made to facilitate needle insertion due to the dog's tough perineal skin. The needle insertion was performed with longitudinal control joint via a joystick for safe control. The needle deflection was reduced by the weaving motion caused by the biopsy module around the longitudinal axis of the needle. This continuous rotation of the needle reduced the effects of friction during insertion. The insertion was performed in steps of 5 mm with waiting times corresponding to a scanning process (T2 scan sequence) while the robot was stationary, in order to obtain detailed static images of the needle placement inside the prostate. The Fig. 10, shows the visualisation of the biopsy in the bore from MR imaging. This is the scan with the needle still in the body of the living dog.

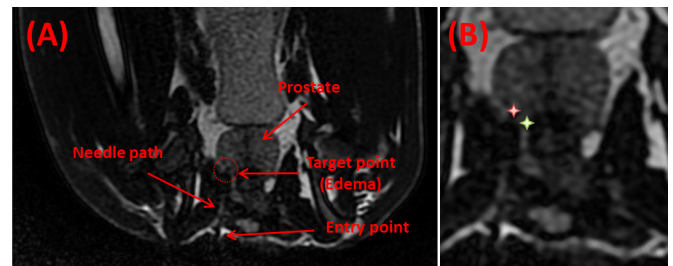


Fig. 10. (A) In-bore biopsy visualisation from MR imaging: the needle reaches the surface of the prostate with an insertion depth of approximately 35 mm. The triggering of the biopsy system is obtained for the prostate tissue extraction. A trace describing an edema is visible on the image. (B) Zoomed view of a cross-sectional image slice showing the targets and the needle trajectory. The green point represents the desired target and the red point represents the achieved target.

Insertion accuracy was achieved only by guiding the needle longitudinally by the robot, no orientation adjustments were applied. The accuracy of the biopsy position within the living tissue varied around $3.8mm$ for a $26mm$ diameter prostate. The Fig. 10 shows a slight deviation of the needle during insertion. It should be emphasised that the observed positioning error can be attributed to the fact that the biopsy needle used in the procedure was designed for human tissue biopsies, which are less dense compared to canine tissue. Moreover, during the first scan to define the desired target point and the duration of the intervention, the prostate moved according to the respiratory movements. The total procedure time is estimated to be around 20 minutes due to the gradual insertion to ensure organs at risk are properly avoided, which is an acceptable time compared to the 30 minute MRI diagnosis.

4. CONCLUSION AND FUTURE WORKS

In this work, an approach of the combinatorial optimisation problem (COP) is developed for path planning of MR-robot-assisted biopsy for prostate gland cancer treatment. The COP's algorithm allows minimising the needle entry points from a guiding grid to reach a treatable volume of the prostate gland. Such an approach has technical and

clinical advantages; technically, it aims to make oblique insertion and to reach in multiple target points from a few entry points. Clinically, it contributes to minimising tissue damage and patient trauma, and risk of infection, and shortening recovery time. The approach was tested with a new minimally invasive 1.5T MR robot with 5-DoF called CoBra by performing a biopsy on a live animal. For future work, we focus on improving the algorithm by minimising calculation time and enabling real-time adaptive tracking of target points based on MRI. One of the main challenges is dealing with target points that are in relative motion during needle insertion, leading to prostate gland inflammation or tissue deformation. Therefore, it is important to develop an effective workflow to address this issue and ensure the reliability and precision of the biopsy. Additionally, other optimisation techniques will be tested and compared to further enhance the algorithm proposed in this paper.

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