Received: 28 April 2022 | Revised: 12 June 2022 | Accepted: 28 June 2022
DOI: 10.1049/ccs2.12067
Cognitive Computation and Systems

REVIEW

A review on the techniques used in prostate brachytherapy

Yanlei Li[1] | Chenguang Yang[1] | Amit Bahl[2] | Raj Persad[2] | Chris Melhuish[1]

[1]Bristol Robotics Laboratory, University of the West of England, Bristol, UK

[2]University Hospitals Bristol and Weston NHS Trust and Bristol Robotics Laboratory, University of the West of England, Bristol, UK

Correspondence
Chenguang Yang, Bristol Robotics Laboratory, University of the West of England, Bristol, BS16 1QY, UK.
Email: cyang@ieee.org

Abstract

Prostate brachytherapy is a validated treatment for prostate cancer. During the procedure, the accuracy of needle placement is critical to the treatment's effectiveness. However, the inserted needle could deflect from the preset trajectory because of the needle deflection, tissue shifting caused by the interaction between the needle and soft tissue, as well as the effects of pre-inserted needles. There are significant challenges in needle placement areas, especially in prostate brachytherapy, because multiple needles are required for the effectiveness of radiation. To overcome these limitations, relevant research is carried out in mechanical, computer science, and material science areas. With the development of surgical robotics, researchers are also exploring the possibilities of raising the accuracy of needle placement with surgical-assisted robotics. This study provides a review over the last 3 decades in each of the component research areas that constitutes a surgical robotics system, including needle steering approaches, needle-tissue deformation models, path planning algorithms and different automatic level surgical robotics systems used for prostate cancer treatment, especially prostate brachytherapy. Further directions for researchers are also suggested.

1 | INTRODUCTION

Prostate cancer is one of the most common cancers in men, especially men over 50. According to Ref. [1], about 1.2 million prostate cancer cases were diagnosed globally each year. Permanent brachytherapy is an efficacious treatment for prostate cancer due to its excellent success rate [2]. The procedure provides radiation to the tumour by implanting radioactive seeds near or inside the tumour through long, hollow needles. The detailed brachytherapy procedure is as follows. First the patient arrives in the theatre and receives spinal anaesthetic and places transcrectal ultrasound probe in position on the stepper arm with an attached needle guide template. Then, use ultrasound to guide the needles into the prostate using a grid on the ultrasound, which matches the external template. In this step, currently, the most common clinical used imaging device is transrectal ultrasound scan (TRUS). With the use of TRUS, needles are placed from the top of the prostate to the bottom (anterior to posterior) due to ultrasound shadowing if done the other way. This is the end of the needle insertion process. After the needle insertion process, the patient would be delivered to the CT room. The surgeon would make a physics treatment plan based on the needle steering positions. The patient would be connected to the treatment afterloader via guide tubes from the machine to needles. The radioactive seeds would be delivered remotely to the patient based on the treatment plan by the surgeon. After the treatment is finished, the needles would be removed.

Despite the clinical benefits, there is still scope for the improvement of prostate brachytherapy. Improving the accuracy of placing radiation seeds and reducing the damage to normal tissues are major challenges for prostate brachytherapy. With the rapid development of medical robots in the past decade, surgeons often take surgical robots as assistants, as the use of surgical robotic systems enhances and expands the ability of surgeons to provide a high degree of flexibility and accuracy in diagnosis and treatment. One of the prime challenges is the accuracy of the placement of the radioactive seeds due to the deflection of the needle and the placement of the tissue [3]. To overcome this problem, researchers have made a considerable effort to develop robotic systems to achieve the automatic steering and guiding of the needles. One of the earliest fully automatic surgical robots is proposed by Harris et al. [4], which is applied to perform prostate resection. Since then, relative topics such as modelling and trajectory planning that could achieve the automatic level of surgical robotics have been proposed and researched. Researches for the fully automatic surgical robotics are proposed [5–13]. Due to both technical and ethical issues, currently fully automatic surgical robotics still only exists in research. The raise of automation level of robotics is an achievable goal both in the research areas and in real clinics. Another research direction is to improve the design of surgical puncture needles. Currently, the high stiffness needles are mostly used to reduce the effect of target shifting and needle deflection. Okamura et al. [14] proposed a design of diamond-tip needles, which provided a lower resisting force compared to normal bevel-tip needles during insertion. A prostate fixation technique was proposed by Dattoli & Waller [15] that could restrict the motion to 0.2 mm. Podder, Clark, Sherman, et al. [16] defined the needle insertion force requirements for a typical clinical-used needle (18G) at the skin of around 8N–10N to puncture the prostate. In addition, the authors also state that the use of axial force could reduce the internal deformation of soft tissue. Podder, Clark, Fuller, et al. [17] proposed that controlling the needle through the axial rotation during the puncture process inside the soft tissue could reduce the deformation and trauma of the soft tissue. Compared with the characteristics of a high stiffness needle, the flexible needle (which is the low stiffness needle) could utilise the deformation generated by the needle-tissue coupling effect to bypass normal tissues and reach the target position. This has attracted extensive attention in the surgical robotics research community. Researchers have conducted considerable research on the solutions of using flexible needles for prostate brachytherapy based on bevelled tips. However, it is an under-actuated system which has non-holonomic constraints that inserts a flexible needle into soft tissue. The steering with the flexible needle is challenging due to measurement errors, tissue heterogeneity, and uncertainty in dynamic models. This study reviews the cross-section between robotic surgery and needle-based prostate brachytherapy. The main contribution of this study is to provide a review over the last 3 decades in each of the component research areas that constitutes a surgical robotics system, including needle steering approaches, needle-tissue deformation models, path planning algorithms, and different automatic level surgical robotics systems used for prostate cancer treatment especially prostate brachytherapy. Several further research areas are also discussed to give readers potential directions for further research. The structure of this review is as follows: Section 2 provides the main needle steering approach based on different characteristics of the needle Section 3 provides an introduction to the mainstream needle-tissue coupled deformation model. Section 4 provides an introduction to different path planning methods. And Section 5 concludes the current clinical and research use of needle steering devices based on different levels of automation. Section 6 provides the conclusion for this review.

2 | NEEDLE STEERING APPROACHES

Needles used in the treatment can usually be divided into two types of needles which are high stiffness needles with symmetric needle tips and low stiffness needles with asymmetric needle tips. The former is usually the tip of a conical needle, while the latter is a slant. Currently, the high stiffness needles are the most commonly used needles in the clinic. During the needle insertion process, the high stiffness needle aims to reduce the effect of target shifting and needle deflection, which is straightforward for the surgeon to use and check the needle insertion situation. However, the research area tends to research the possibility of using low stiffness needles in prostate brachytherapy. During the needle insertion process, the bevelled shape tip generates force at the needle-tissue interface that exerts bending force on the needle during insertion. As a result, the bevelled tip needle tends to bend due to its tip asymmetry. The current surgical robotics researches tend to emphasise this deformation to explore novel approaches for cancer treatment and radioactive seeds placement. There are two main asymmetric needles which are bevelled needles and pre-bent needles. The needles and their controlling approaches would be discussed in detail in the following sections.

2.1 | Bevelled tip needle

The most basic method of needle steering is to use a bevelled tip which is straightforward to manufacture and control. The advantage of using a bevelled tip is that it is intuitive for the operator to understand and control manually, which makes it also amenable for designing a surgical robotics system to control. The basic bevelled tip controlling approach consists of inserting the needle and rotating the needle shaft. Webster III et al. [18] proposed a non-holonomic model of a flexible needle steering into soft tissue using an asymmetric tip needle. This model envisages the movement of the needle tip as a small bicycle with a locked front wheel, so the trajectory of the inserted needle is an arc on the plane. The direction of curvature is controlled by the orientation of the bevelled tip. And the bevelled tip could be controlled by rotating the base of the needle from outside the tissue through the needle shaft. These would be formally discussed in Section 3. Because of the advantages of ease of use and manufacture, the bevelled tip needle is the most common type of asymmetric needle used in brachytherapy research. And it is commonly controlled by the movement of the needle base as mentioned above. DiMaio & Salcudean [19] developed a needle tip model that is expressed in terms of the motion of the substrate, representing the relationship between the trajectory of the needle tip and the translational and rotational velocities of the substrate. One of the limitations of the model is that it requires a finite element method, which limits the application of offline planning rather than online simulation. Glozman & Shoham [20] proposed an accelerated base-centred model that took the flexible bevel-tip needle insertion problem as an inverse kinematics problem, which assumed the location and orientation of the tip trajectory then deriving the moving sequence of the base of the needle.

2.2 | Pre-bent needle tip

Another needle steering approach is the use of a pre-bent needle tip. Its curvature radius varies with the length of the needle and the degree of asymmetry. It is also feasible to modulate the curvature of the needle by varying the curvature of the needle tip. Reed et al. [21] demonstrated a needle steering system based on pre-bending needles that integrate image-based control, torsion compensation, and real-time motion planners. Achieving a smaller radius of curvature under a large perpendicular force is one main advantage of using the curved needle. However, due to the lack of intuitive manual controls, especially in the deployment of concentric tubes, it is necessary to design an automated control model or design the constraints to limit the change of curvature when using the pre-bent needle. Konh et al. [22] proposed a method using shape memory alloy to control the needle tip curvature. Another approach is proposed by Ebrahimi et al. [23], which is to cover the bent part of the needle shaft within the cannula to constrain the curved needle. The stiffer covering could straighten out the shape of the inserted needle. The needle could be controlled by the length of the uncovered part of the needle. Based on the previous design of cannula [23], Dupont et al. [24] proposed a design of concentric tube robots for needle steering. By the interaction and rotation between the tubes, they cooperatively pass an arbitrary 3D path to the surgical robot to control the needle's shape along its shaft. A general coordinate-free energy formulation was proposed by Rucker et al. [25], which models the shape of the concentric tube continuum robots that consider stiffness and pre-curvature as they vary with the length of the tube. Compared to bevelled tip needle, the pre-bent needle tip is not intuitive enough for surgeons to work with and manually control, it still has the potential for fully automatic robot control.

3 | NEEDLE-TISSUE COUPLED DEFORMATION MODEL

In this section, the steerable flexible needle with an asymmetric bevelled tip will be considered and analysed. During the insertion process, the behaviour of the needle depends on the coupled deformation effect between the needle shaft and the soft and calcified tissues, as well as the effects of pre-inserted needles. The force applied to the needle could be summarised into four categories which are the needle puncture force, cutting force, friction, and deformation force. The needle puncture force is generated in the duration between the first contact of the needle and tissue and the moment the needle penetrates the skin. After the needle has penetrated the skin, the numerical value of force will drop greatly and the puncture force will be converted to the cutting force. At the moment, the friction and deformation forces are also generated. With the steering process proceeding, the increase in the interaction area will lead to the increase in the deformation effect and then could result in the change of deformation force. Because of using bevelled tip, the deformation force could affect greatly on the heading direction of the steered needle, which also provides opportunities for bending the flexible needle to bypass the normal tissue to reach the target location. The needle could be controlled outside the soft tissue by reorienting the bevel-tip through rotating the needle base. In most of the needle-tissue coupled models, the soft tissue is considered as homogeneous tissue. Unless it is mentioned, this condition is used as the premise of the following needle-tissue interaction force model.

3.1 | Non-holonomic model

Webster III et al. [18] proposed a non-holonomic model of the kinematics of a bevelled tip needle, which compares the steered needle with the locked steering bicycle. Based on this model, the needle tip moves forward along a pre-defined trajectory. Although the front wheel does not move sideways, the needle tip could reach any pre-defined location within the plane. As depicted in Figure 1, the angle parameter ϕ and the L_1 determine the curvature k of the needle insertion path. The needle tip would be constantly pressured by the deformation force which comes from the direction of y and which is perpendicular to the tip of the needle. By controlling the direction of y, the angle ϕ could be affected by the deformation force accordingly, which further led to a change of needle curvature. L_2 are the points along with the bicycle that is attached to the needle tip. If we simplify the model and ignore the parameter L_2, the model could be considered as a unicycle. Like a unicycle, the needle could reach any point within a plane by changing the curvature and the curvature can be modulated by controlling the insertion speed U_1 and rotation speed U_2, in conjunction with a duty cycle strategy to control the needle trajectory. The research of Engh et al. [26] has shown that constantly spinning could eliminate the deformation forces and lead the needle to follow a straight-line path (In 3D space, the path is helical actually). It is that the asymmetric force exerted on the tip of the bevelled needle could be eliminated by a continuous spinning, which results in a straight insertion trajectory. On the contrary, the needle would produce a trajectory with maximum curvature without any spinning. And the needle would produce a halfway trajectory between the straight trajectory and the maximal curved path with a 50% of duty cycle. As depicted in Figure 2, a complete absence of spinning of the needle will produce a curvature closer to the maximal curvature which is the needle's original curvature. A continuous spinning will be closer to a zero curvature. However, when applying duty-circle strategy in surgery, it needs to make corresponding changes in real control based on different parameters of the soft tissue. The real soft tissue is inhomogeneous medium and it could vary for different patients. So it is more

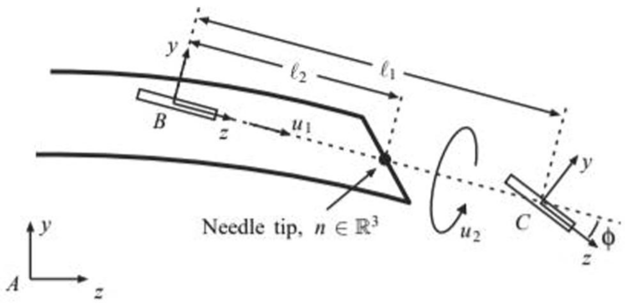

FIGURE 1 A unicycle non-holonomic model. U1 is the insertion speed and U2 is the rotation speed. Data from Ref. [18]

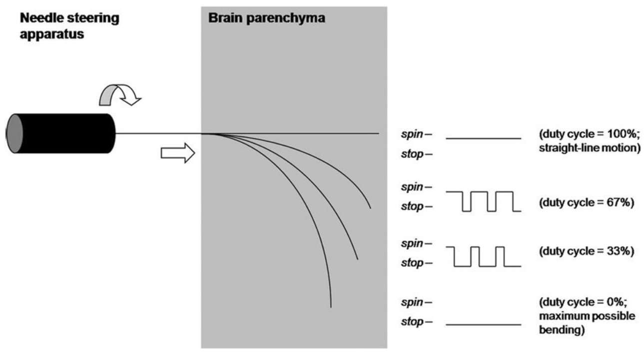

FIGURE 2 Relation between the duty cycle and the curvature of the inserted needle. Data from Engh et al. [26]. So the operator could control the needle curvature using this strategy by proceeding and stopping the rotating operation. Then the trajectory of the steered needle could be controlled. The workspace of the needle is the space between the upward curved original curvature of the needle and the downward curved original curvature of the needle

complicated when applying it to real scenario. Still, it is a commonly used strategy in researching area when combining it with haptic or visual feedback.

Carriere et al. [27] proposed a depth-dependent, three-dimensional non-holonomic model to monitor the motion of needle tip during insertion. Based on this model, a surgeon-central needle deflection controller is also proposed. The system provides haptic feedback which assists the surgeon to keep the needle on its desired trajectory. The use of lightweight device suits the need of the current clinical and reduce the negative impact caused by equipment failure. Majewicz & Okamura [28] presented a non-holonomic teleoperation system that allows the user to specify a desired location in Cartesian space for the needle to reach. They state that steering asymmetry needles under non-holonomic constraints are difficult to be manually controlled in joint space. In their proposed system, while respecting needle kinematic constraints, the needle is controlled from a haptic teleoperation device by pointing out the desired needle insertion trajectory. This proposed teleoperation system aims to decrease the difficulty of controlling steerable needles by converting a non-holonomic task to a Cartesian positioning task. Based on their statement, humans prefer to make movement in spatial space rather than joint space because spatial space control is more intuitive for humans.

3.2 | Beams model

To explain the needle deflection and tissue deformation coupling effect, researchers have developed mechanic-based models to explain the needle motion in tissue. Glozman & Shoham [20] proposed a beam model to represent the interaction between the inserted needle and the penetrated tissue. It considers the interaction to be a set of virtual, distributed aggregation of springs that can be linearised and formalised as a collection of forces as shown in Figure 3.

At each virtual interaction point, the force could be expressed as

$$F_i = K_i(W_i - W_o) \tag{1}$$

where F_i is the virtual spring coefficient, W_i is the displacement at each point, and W_o is the position of freed spring. Since forces are proportional to the deflection, the deflected motion can not be estimated by one element. It is necessary to convert the simple beam model into a finite collection of beam models. Each beam element is subject to two neighbouring forces applied at its end-points. Each set of springs has a different spring constant to monitor the different forces received from the different parts of the soft tissue, which leads to a variety of stiffness coefficients of springs along the needle shaft. The needle deformation then could be expressed as:

$$Y(x) = N_1\phi_1 + N_2\phi_2 + N_3\phi_3 + N_4\phi_4 \tag{2}$$

where N_1, N_3 are the coordinates and N_2, N_4 are the slopes at $x = 0$, $x = l$. ϕ represents the shape function of the third degree. Combining the beams model and the forward and inverse kinematics, path planning and correlation could be achieved in real-time. Similar models were proposed by Abolhassani & Patel [29], which modelled the infinitesimal force, as a function of unit tissue. And Abolhassani et al. [30] have also updated the needle deflection condition based on a beam with spring support. They have investigated the relationship between the needle base torques and needle deflection in order to estimate the level of needle deflection during the insertion process, which provides the theoretical basis for the design of path planning algorithms.

Lehmann et al. [31] have presented three tissue-independent models to estimate needle deflection based on the beam model to further improve the beam model depending on the different sources of force. One advantage of this improved model is that it is tissue-independent, which means it is unnecessary to know the parameters of the soft tissue. Only measurements from the force sensor are needed. However, it assumes that the inner tissue is homogeneous, which makes it unsuitable for real scenarios. Barbé et al. [32] have developed a haptic feedback needle insertion device combining force sensors and beams model to provide haptic feedback to the user. Using the data of the force sensor and the calculation of the pressure force on both sides of the needle using the beam model, the device could provide inner needle force conditions to the operator through haptic. One

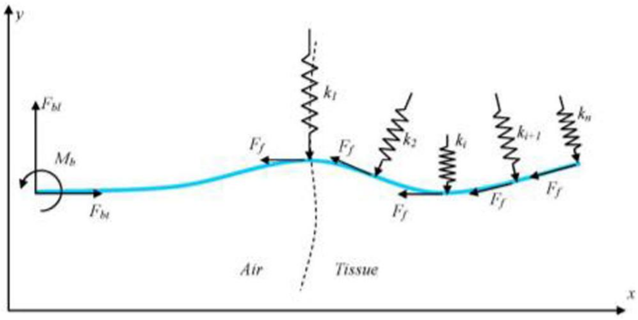

FIGURE 3 Beams model: Considering the interaction force between the needle and the penetrated tissue as a set of spring data from Glozman & Shoham [20]

main advantage of this model is that it has considered the inhomogeneity and non-linearity properties based on the model of Abolhassani et al. [30]. And the provision of force feedback gives the surgeon more information about the inner steering during the surgeon-central control loop.

3.3 | Data-driven model

The reason for researchers to investigate the data-driven model is to compensate the uncertainties caused by the unmodelled factors like tissue heterogeneity, needle buckling, and the previous needle insertion tracks. Yan et al. [33] proposed a framework using depth varying mean parameters to consider the tissue property such as tissue stiffness and viscosity. They designed an online parameter estimator to predict the tissue parameters based on the least square method with forgetting factors and an online dataset. Carriere et al. [34] proposed a real-time model to predict the shape of a flexible needle that uses image segmentation from transrectal ultrasound (TRUS) and a particle filter to inform the kinematic model about the flexible needle shape to construct the self-updated loop to predict the radius curvature of needle. It updates the parameters from each ultrasound image and predicts the needed curvature for the needle tip to follow the pre-defined path. At the same time, Moreira & Misra [35] proposed a method to predict the needle curvature using the tissue properties. It could continuously adjust the needle spinning force to maintain the needed curvature based on tissue property parameters. However, the current method for obtaining the property parameter is through prior insertions, which have a significant pragmatic limitation in the real clinic and the prostate tissue differs for different patients. Rossa, Khadem, et al. [36] proposed another framework to estimate the parameters for local tissue properties without prior insertions. It combined the insertion force parameter obtained from the force sensor, and the image from an ultrasound probe, using the minimum potential energy method to predict the local variability in the tissue properties. By building a model from the needle-tissue interaction to predict the local tissue property parameters, the framework is valuable for estimating the system output without knowing the accurate tissue properties.

4 | PATH PLANNING

4.1 | Minimise deflection

One proposed path planning direction for needle insertion is to minimise the measured deflection at all points along the steering trajectory. It could be seen as a straight line connecting the insertion location to the target location inside the tissue. One common and intuitive approach to minimise deflection impact is to control the needle base with the duty-cycled rotation strategy. As mentioned in Engh et al. [26], the needle will follow a trajectory of nature curvature when the orientation of the bevel angle of the needle tip remains the same. A constantly spinning could eliminate the deformation forces and lead the needle to follow a straight-line path. This controlling idea is implemented in the research of Wood et al. [37] and Majewicz et al. [38]. The shortcoming of this approach is that due to the tissue heterogeneity, the original curvature of the inserted needle could not remain the same, which means even executing continuous spinning to control the needle to follow a straight path, the inserted trajectory could differ because of the different local physical property of the soft tissue.

Another problem is that this approach requires continuous rotation of the needle base, which leads to a limitation of the use of equipment, such as electromagnetic trackers and six-axis force sensors as well as the tissue trauma and drilling effect. Another design to minimise deflection is to combine the needle-tissue deformation model into the path planning and adjust the heading direction based on the model-based dynamic model. Maghsoudi & Jahed [39] built such dynamic equations based on the force distribution along with the needle, which is analysed from the need-tissue deformation model. Based on the proposed equations, they presented an inverse-dynamic controller for needle steering. Similar models are also presented in [40, 41]. One problem of this controlling method is that it heavily relies on the deformation model accuracy, which implies that the mismatch of model parameters could lead to a significant impact on the result. The complexity of the physical parameters of subcutaneous tissue limits the practicability of this kind of controller. To reduce the effect of model parameters on the steering result, a sliding control model, which requires no prior knowledge of model parameters was proposed by Rucker et al. [25]. This allows the needle to follow the pre-defined trajectory within a specified error without knowing the specified parameters for the deformation model. Based on this sliding control model, Fallahi et al. [42] proposed a control structure for the steered needle to follow a planned trajectory inside the soft tissue, which leads to another solution for needle steering control that is trajectory tracking.

4.2 | Trajectory tracking

Another approach for needle insertion is to pre-define tissue parameters to plan a steering route for a needle to follow from the insertion point to the target position. The route could be a curved path to avoid hurting vital organs and normal tissue.

This category could be divided into three sub-categories which are stochastic planning, intra-operative imaging path planning, and bias compensation.

4.2.1 | Normal planning algorithm and stochastic planning

This category involved many mainstream path planning algorithms that could be applied to needle steering, such as rapid-exploration random tree algorithm [43, 44], genetic path planning algorithm (F. [45]), and potential field algorithm (P. [46, 47]). Most of the algorithms concentrate on minimising the trajectory from the insertion point to the target location. Lehmann et al. [48] proposed a path planning method without image feedback to minimise the trajectory length based on the unicycle model. Vrooijink et al. [49] presented a steering system using the potential field algorithm for its motion planner. Khadem et al. [50] presented a predictive controller with a non-linear model to improve the rapid-exploration random tree algorithm designed trajectory using iterative optimisation of the predictions of the needle steering model. Some similar steering algorithms are also reported in other literature [19, 51]. One planning idea worthy of mentioning is the stochastic planning approach. Stochastic planning uses formal state space to represent the inner motion, which generates a roadmap that includes all the trajectories under the uncertainty of the possible tissue configuration and considers the desired path plan as a Markovian Decision Process. It ultimately implements the solution through dynamic programing, maximising the likelihood of successful needle steering [52, 53]. This framework allows to compute the steering needle paths in two-dimensional models. The needle trajectory plans would be conditionally different from the traditional shortest path using this algorithm. The algorithm is to maximise the possibility of generating a successful steering trajectory rather than the shortest length route. Based on stochastic planning, Patil et al. [54] proposed a needle steering system that combines the information from intra-operative images to update the stochastic model in real-time, which leads to the next solution category that is intra-operative imaging path planning.

4.2.2 | Intraoperative imaging path planning

It is common to apply the image information during the needle insertion process to raise the accuracy of the seed placement. The imaging information could provide inner tissue information, including the range of tissue physical parameters, the needle deformation situation, the shift of normal tissue, and the target location. Currently, most research and clinically used needle steering systems are systems with the function of providing image feedback. Interventional magnetic resonance imaging (MRI) and ultrasound can be used for monitoring tissue deformation, path planning, displaying real-time insertion, and ensuring the placement of the needle tip. Many magnetic resonance compatible surgical assist robot systems have been developed by researchers in recent years [55–57]. Combining machine learning algorithms and human-in-loop controlling design, the MRI system is widely used in prostate brachytherapy. Chinzei et al. [58] proposed a surgical robotics system that is compatible with magnetic resonance. The main function of it is to work with surgeons to locate and guide biopsy catheters and needles. Another research from Dai et al. [59] applied the deep learning-based method, which is deep supervised attention U-Net with total variation regularisation to design a human-in-loop controlling framework to raise the accuracy of the needle steering process. However, one of the limitations of the use of MRI is that it requires the asynchronous insertion of a surgical needle because of the characteristics as mentioned before. The doctor can only check the image at a certain time point during the surgery. So researchers are also investigating the possibility of using the needle inside the MRI bore to provide real-time imaging during the insertion process. Tadakuma et al. [60] have presented a robot manipulator design based on elastically averaged binary dielectric elastomer actuators that are compatible with MRI systems. Combined with a teleoperation controller, the surgeon could manipulate the inserted needle while acquiring in-time MRI images. One limitation of this design is that it requires high accuracy of teleoperation system, which could be solved through the shared control strategy that this review will mention later. Similar designs are also presented in Ref. [61, 62].

4.2.3 | Bias compensation

Due to tissue deformation and needle shifting, there exists bias between the prescribed route and the real location. This is another valuable research area to remedy the bias during the needle insertion. A programing algorithm was developed by Chentanez et al. [63], which is used to insert flexible bevel-tip needles into prostate phantom with obstruction on a two-dimensional planar under the guidance of 2D images. The simulator uses a finite element model to compute soft tissue deformations, which combines the effects of needle tip and frictional forces using a two-dimensional grid. The plan could generate a desirable needle insertion route combining needle-tissue force modelling and parameters optimisation based on the input of an initial pre-defined insertion plan that includes target location, needle orientation and bevel rotation. It could compensate the needle and tissue deformation and minimise the needle steering trajectory. A dynamic remeshing approach is proposed in Ref. [64, 65], which increased the resolution of the penetrating needle in real time. It uses a posteriori error estimate, which is used for local remeshing in surgical simulations. Courtecuisse et al. [66] presented a new pre-conditioning technique based on asynchronous updates. The preconditioner can both raise the computation accuracy of the deformation of soft tissue and further simulate the contact response of heterogeneous and homogenous tissues with similar precision. It improved the accuracy of contact response in heterogeneous and homogenous tissue models when applied to topological changes. Another factor affecting the bias is the change of the parameters of the soft tissue. Ensuring the correct parameters of soft materials could be essential for improving the accuracy of seeds placement. According to Rappel et al. [67], using Bayesian inference could accurately identify solid material parameters used in models. The Bayesian inference could also be applied to inhomogeneous materials. A stochastic approach which combines Bayesian Inference is proposed by Mohamedou et al. [68]. This method could identify the intrinsic parameters of the model assumptions as well as the variability of composite material.

5 | ROBOTIC SYSTEMS OF PROSTATE CANCER

This section is to discuss the different automation levels of surgical robotics in prostate treatment. As mentioned before, there are two main controlling approaches to needle insertion. The first is to push the needle inside the tissue. The second is to rotate the needle around its shaft to control the heading direction. According to Dhaliwal et al. [69], the current surgical robotics could be split into four automation levels. The detail is shown in Table 1. Because Level 0 is without any robotics assistance and surgeons do the steering all manually, it is not included in this study's scope. The following sections will discuss the remaining three levels of automation in detail.

5.1 | Manual assisted steering

In this category, assisted robotics mainly provides additional information about the inner needle and tissue without direct intervention. The surgeon fully controls the insertion and rotation action. The surgeon could decide whether to follow the calculated suggestions based on previous surgical experience. Depending on the different provided information types, the assisted system could be divided into two main categories which are visual devices and haptics device systems.

Krieger et al. [70] first proposed a teleoperation needle steering system with the use of MRI and a needle with a tracking coil. With the use of an MRI bore, the surgeon could get more specific information about the needle position in tissue and the situation of needle deflection. One important aspect is that for a clinical MRI system used in prostate treatment, the components of the system are strictly required to be non-magnetic, non-conductive, and non-metallic. Thus, the material of the needle that is used inside the MRI bore also has a high restriction. The high resolution image provided by MRI and the high restriction of MRI attracts the researchers' attention. An MRI compatible needle guide template which is similar to the transrectal of ultrasound (TRUS) prostate template was presented by Song et al. [71]. It minimises image degradation and could offer sub-millimetre targeting accuracy. Similar frameworks are also proposed by Fischer et al. [72] and G. Li et al. [73]. Apart from the normal imaging devices like MRI and ultrasound, another imaging method that could transfer the simulated internal tissue situation to the real clinical workplace is also worthy of further exploration.

Blackwell et al. [74] have proposed an image overlay system which is later more accurately defined as an augmented reality system to provide extra imaging information of inner tissue. The overlay images are processed and projected into the real clinical workspace so it appears the surgeon is an integral part of the surrounding environment. Based on this design, Weiss et al. [75] have proposed a surgical system using augmented reality to reconstruct the inner tissue using multiple layers from different imaging modalities. Providing extra 3D information of inner tissue makes the surgical relatively simple and straightforward. It could improve the surgeon's ability to visualise the anatomical structure of inner tissue and the ability to control the steered needle. One limitation of the proposed design is the inability to provide real-time imaging. It does provide more visual information but does not solve the problem of real-time imaging the same as most of current MRI devices. The potential of augmented reality is also developed in the surgical training area. Magee et al. [76] presented an augmented reality training system for needle placement. The virtual anatomic images are constructed from full body segmented CT scan. However, due to limitations of the current technical level, the realism of the image is not satisfied and a certain level of image quality needs to be sacrificed to guarantee the positional accuracy and maintain the low manufacturing price. The authors also state that the incorporation of haptic (force) feedback was unnecessary and would affect the ergonomics of the simulator. In this case, the device provides poor haptic feedback, which can be considered as another flaw of this training system. According to Rossa, Khadem, et al. [36], tactile feedback would provide vital information about the force condition of the inserted needle and assist the surgeon to judge the inner information combined with the image provided by CT or MRI.

Another option as previously stated is to give the haptic feedback to the surgeon. Basu et al. [77] presented a robust closed-loop guidance system with haptic device. Based on their research, Rossa, Fong, et al. [78] presented a design of a wristband with haptic feedback to assist surgeons to guide the steered needles. The wristband has eight mini actuators around the wrist and each of the actuators produces a different vibration mode to assist the surgeon to guide the steered needle. In recent research, researchers combine the imaging-guide and haptic-guide together to provide more information to the surgeon. Abayazid et al. [79] presented a needle steering system which provides imaging information from ultrasound and vibratory feedback for the surgeon. The system could keep the needle steering at a certain speed and the surgeon controls only the rotation. It could improve the surgeon's ability to judge the internal situation based on visual and haptic feedback. Because the robotics system could be responsible for the insertion action, the surgeon could primarily concentrate on the rotation. A similar framework is also presented in Ref. [80] which

TABLE 1 The different automation levels and definition. Data from Dhaliwal et al. [69]

Automation level	Robotics operation	Detailed definition
0	Fully manual insertion	Surgery without any robotics' assistance
1	Manual-assisted steering	Robotics provide sensor feedback to the surgeon
2	Semi-automated steering	Surgeon-in-loop control
3	Fully automated steering	Surgery without any surgeons' assistance

raises the accuracy of needle placement according to the author's statement. And this leads to another automation level of surgical robotics which is the semi-automated steering (human-in-loop steering).

5.2 | Human-in-loop steering

In this category, the robotics system is in charge of either rotating the needle or moving the base laterally while the surgeon is still in the dominant position in the whole control loop. It can maintain a physician's control of the insertion procedure while incorporating the benefits of robotic accuracy. Besides the use of the human-in-the-loop control strategy could apply the doctor's experience to the insertion process to improve the inserting accuracy and also avoid relevant ethical problems, for example, the responsibility issues. Salcudean et al. [81] proposed a four-degree freedom robot for prostate brachytherapy. The robotics could move the needle in the X-Y plane for insertion and rotate around the X and Y axis to provide accurate control of the insertion angle and tip point. The surgeon could manually control each motor for locating a suitable insertion position with or without the guidance from the system. Similar frameworks are also presented by Fischer et al. [72] and Schneider et al. [82]. Another design uses the shared control in which the robot system is in charge of insertion depth and the operator is in charge of rotating the needle base to determine the trajectory direction like the previously mentioned work of Abayazid et al. [79]. One limitation of the previously mentioned work is that the needle could only be inserted horizontally. Bebek et al. [83] presented a kinematic calibration system for positioning the orientation of a 5-DOF robot with an optical position sensor. This allows angled insertion of the needle. Another framework for human-in-loop control is to compensate for the bias between the insertion and pre-defined trajectory while the surgeon controls both insertion and rotation. Wartenberg et al. [84] presented an algorithm of proactively compensating for deviations from the initial trajectory by rotating needles with asymmetric tips to achieve higher precision using a shared-control strategy. Based on the insertion force and the force received by the needle, the system could provide haptic sensation as continuous feedback to the surgeon and the system itself to further control rotation and insertion velocity to achieve the goal of following the desired trajectory.

While combing the MRI imaging and shared control strategy, Moreira et al. [85] and Wartenberg et al. [86] both have presented a similar shared control MRI-compatible system with robotics controlling the insertion direction and the surgeon controlling the insertion depth. An magnetic resonance (MR)-compatible single needle delivery robotics system is presented by de Battisti et al. [87]. Based on identifying the most sensitive needle track, the proposed method could determine and automatically update the needle insertion route. It could enable the needle insertion process with the patient in the MR bore. A 5-degree-of-freedom parallel pneumatically actuated modular robot which is compatible with MRI is presented by Seifabadi et al. [88]. The proposed system solved most of the compatibility problems, including workspace limitation, sterilisation, and improving the accuracy of needle placement during the use of MRI. The Fiber Bragg Grating force sensor used in the system could enhance the ability of the operator to distinguish between the different stages of needle insertion. Van den Bosch et al. [62] developed a surgical robotics system that is composed of only non-ferromagnetic materials. The system could be used in conjunction with MRI to assist prostate brachytherapy and biopsy. It could be set between the patient's legs during the needle insertion process.

Apart from the heavyweight surgical robotics, the lightweight robotics system for assisting needle insertion is another area worthy of further research. The use of a lightweight robotics system could offer extra freedom and dexterity to the surgeon. And the implementation of a lightweight robotics system in a clinical scenario is also more realistic. Ebrahimi et al. [23] presented a motorised hand-held needle steering system which drives the needle base to produce the desired deflection to follow the desired trajectory while the surgeon holds the device and provides the insertion force to the needle. This framework lays the foundation for the later design of lightweight insertion devices. A lightweight hand-held system possessing six degrees of freedom is proposed by Poquet et al. [89]. The aim of this system is to assist the surgeons to reduce their workload during the prostate biopsy process. The system has a free mode and a block mode for surgeons to use in which the system would lower the inertia and friction for surgeons to insert the needle under the free mode, while the blocking mode allows the placed needle to maintain an accurate location and orientation of the probe relative to the prostate. Khadem et al. [50] introduced a semi-automatic needle placement system which provided the function of automatically rotating the needle to raise the accuracy of needle placement. When the surgeon inserts the needle, the device would rotate the needle base automatically in conjunction with the duty-cycle strategy to follow a pre-defined needle tip trajectory. Based on this design, Rossa, Usmani, et al. [90] proposed a further improved hand-held system with a controlled longitudinal vibration to lower the friction between needle and tissue to increase the accuracy and stability.

5.3 | Fully automated steering

In this section, the robotics system carries out all the insertion and rotation actions with the appointed insertion point and target location. The system should calculate the desired trajectory and guide the needle towards the endpoint and avoid damaging normal tissue. This kind of robotics will replace the surgeon and provide a more precise needle steering, raise the accuracy, and lower the damage to tissue. However, it is a challenge to put such a robotics system into clinical use. Compared with the current clinical facilities, it needs multiple modifications before using the system in the desired workspace. There are also serious ethical issues in using a fully automated surgical system. Without the control of surgeons, it could lead to responsibility problems when a surgical accident happens due to system instability and resultant failures. Currently, most of the fully automated steering systems are, therefore, only exist in the laboratory environment. Bassan et al. [5] designed a 5-DOF micro manipulator for the fully automated insertion and rotation through the needle base in prostate brachytherapy. A similar design was proposed by Long et al. [6] which combined intraoperative prostate tracking to provide a higher placement accuracy. With the imaging device, Hungr et al. [7] combined the automated system and ultrasound device to track prostate motion intra-operatively in order to calculate the further action for the needle steering and provide the inner steering trajectory to the supervised surgeon in real time. Similar designs are also proposed in other literature [8–10]. To improve the steering accuracy, Adebar et al. [11] proposed to use elastography for better imaging quality. In their research, the only commercialised fully automated system is SeedSelectron by Nucletron [12]. Another automated system that is approved by Food and Drug Administration is MrBot which is still under development [13]. Though the fully automated system is still facing ethical and technical problems as mentioned before; however, the surgical and robotics research area is moving towards full automation, this is an inevitable research and development direction for robotic-assisted needle steering.

6 | CONCLUSION

This study provides a review of the intersection of surgical robotics and needle-based prostate brachytherapy over the last 3 decades, to enable readers to capture the recent research and the developing directions. The review has introduced the areas in needle steering approaches, deformation models, path planning algorithms, and current surgical robotics for prostate cancer, especially for prostate brachytherapy.

The main difference between brachytherapy and other procedures like biopsy is that it requires multiple needle insertions at the same time. The interaction between each inserted needle could also lead to deformation of the needle tip even if the former tip has been placed in the right location. This makes brachytherapy more challenging than other procedures. Besides, most of the current deformation models are restricted to a single steered needle and the analysing model for multiple low stiffness needles will necessarily be more complicated than for the single needle case. Further work for an updated model that could improve the accuracy of prostate brachytherapy under such complex force conditions is therefore needed. Currently, the mainstream robotics used in clinical scenarios is surgeon-centred, which assists the surgeon in needle insertion process. However, the appearance of data-driven models and the emerging algorithms for path planning give new approaches to update the automation level of surgical robotics. Researchers are also investigating the possibility to bring fully automated robotics into clinical scenes. This review highlights the area for researchers to consider the main developing directions and advances in order to explore the further potential to address the current barriers of surgical robotics for prostate brachytherapy.

ACKNOWLEDGEMENTS

This work was financially supported by Bristol & Weston Hospitals Charity (formerly Above & Beyond).

CONFLICT OF INTEREST

The author declares that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

ORCID

Yanlei Li https://orcid.org/0000-0002-1385-6743
Chenguang Yang https://orcid.org/0000-0001-5255-5559

REFERENCES

1. Moreno, A.C., et al.: Mri image-guided low-dose rate brachytherapy for prostate cancer. In: Handbook of Image-Guided Brachytherapy, pp. 319–344. Springer (2017)
2. Keyes, M., et al.: Canadian prostate brachytherapy in 2012. Can. Urol. Assoc. J 7(1-2), 51 (2013). https://doi.org/10.5489/cuaj.218
3. Stone, N.N., et al.: Prostate gland motion and deformation caused by needle placement during brachytherapy. Brachytherapy 1(3), 154–160 (2002). https://doi.org/10.1016/s1538-4721(02)00058-2
4. Harris, S., et al.: The probot—an active robot for prostate resection. Proc. IME H J. Eng. Med. 211(4), 317–325 (1997). https://doi.org/10.1243/0954411971534449
5. Bassan, H.S., Patel, R.V., Moallem, M.: A novel manipulator for percutaneous needle insertion: design and experimentation. IEEE/ASME Trans. Mechatron 14(6), 746–761 (2009). https://doi.org/10.1109/tmech.2009.2011357

6. Long, J.-A., et al.: Development of a novel robot for transperineal needle based interventions: focal therapy, brachytherapy and prostate biopsies. J. Urol. 188(4), 1369–1374 (2012). https://doi.org/10.1016/j.juro.2012.06.003
7. Hungr, N., et al.: A 3-d ultrasound robotic prostate brachytherapy system with prostate motion tracking. IEEE Trans. Robot 28(6), 1382–1397 (2012). https://doi.org/10.1109/tro.2012.2203051
8. Yu, Y., et al.: Robot-assisted prostate brachytherapy. In: International Conference on Medical Image Computing and Computer-Assisted Intervention, pp. 41–49 (2006)
9. Kobayashi, Y., et al.: Development of an integrated needle insertion system with image guidance and deformation simulation. Comput. Med. Imag. Graph. 34(1), 9–18 (2010). https://doi.org/10.1016/j.compmedimag.2009.08.008
10. Neubach, Z., Shoham, M.: Ultrasound-guided robot for flexible needle steering. IEEE (Inst. Electr. Electron. Eng.) Trans. Biomed. Eng. 57(4), 799–805 (2009). https://doi.org/10.1109/tbme.2009.2030169
11. Adebar, T., et al.: A robotic system for intra-operative trans-rectal ultrasound and ultrasound elastography in radical prostatectomy. In: International Conference on Information Processing in Computer-Assisted Interventions, pp. 79–89 (2011)
12. Perez-Calatayud, J., et al.: I-125 seed calibration using the seedselectron® afterloader: a practical solution to fulfill aapm-estro recommendations. J. Contemp. Brachytherapy 4(1), 21–28 (2012). https://doi.org/10.5114/jcb.2012.27948
13. Patriciu, A., et al.: Automatic brachytherapy seed placement under mri guidance. IEEE (Inst. Electr. Electron. Eng.) Trans. Biomed. Eng. 54(8), 1499–1506 (2007). https://doi.org/10.1109/tbme.2007.900816
14. Okamura, A.M., Simone, C., O'leary, M.D.: Force modeling for needle insertion into soft tissue. IEEE Trans. Biomed. Eng. 51(10), 1707–1716 (2004). https://doi.org/10.1109/tbme.2004.831542
15. Dattoli, M., Waller, K.: A simple method to stabilize the prostate during transperineal prostate brachytherapy. Int. J. Radiat. Oncol. Biol. Phys. 38(2), 341–342 (1997). https://doi.org/10.1016/s0360-3016(96)00581-0
16. Podder, T., et al.: In vivo motion and force measurement of surgical needle intervention during prostate brachytherapy. Med. Phys 33(8), 2915–2922 (2006). https://doi.org/10.1118/1.2218061
17. Podder, T., et al.: Effects of velocity modulation during surgical needle insertion. In: 2005 Ieee Engineering in Medicine and Biology 27th Annual Conference, pp. 5766–5770 (2006)
18. Webster, R.J., III, et al.: Nonholonomic modeling of needle steering. Int. J. Robot Res. 25(5-6), 509–525 (2006). https://doi.org/10.1177/0278364906065388
19. DiMaio, S.P., Salcudean, S.E.: Needle steering and motion planning in soft tissues. IEEE (Inst. Electr. Electron. Eng.) Trans. Biomed. Eng. 52(6), 965–974 (2005). https://doi.org/10.1109/tbme.2005.846734
20. Glozman, D., Shoham, M.: Image-guided robotic flexible needle steering. IEEE Trans. Robot 23(3), 459–467 (2007). https://doi.org/10.1109/tro.2007.898972
21. Reed, K.B., et al.: Integrated planning and image-guided control for planar needle steering. In: 2008 2nd Ieee Ras & Embs International Conference on Biomedical Robotics and Biomechatronics, pp. 819–824 (2008)
22. Konh, B., Honarvar, M., Hutapea, P.: Application of sma wire for an active steerable cannula. Smart Mater. Adapt. Struct. Intell. Syst 56048, V002T02A008 (2013)
23. Ebrahimi, R., et al.: Hand-held steerable needle device. In: International Conference on Medical Image Computing and Computer-Assisted Intervention, pp. 223–230 (2003)
24. Dupont, P.E., et al.: Design and control of concentric-tube robots. IEEE Trans. Robot 26(2), 209–225 (2009). https://doi.org/10.1109/tro.2009.2035740
25. Rucker, D.C., et al.: Sliding mode control of steerable needles. IEEE Trans. Robot 29(5), 1289–1299 (2013). https://doi.org/10.1109/tro.2013.2271098
26. Engh, J.A., et al.: Percutaneous intracerebral navigation by duty-cycled spinning of flexible bevel-tipped needles. Neurosurgery 67(4), 1117–1123 (2010). https://doi.org/10.1227/neu.0b013e3181ec1551
27. Carriere, J., et al.: Surgeon-in-the-loop 3-d needle steering through ultrasound-guided feedback control. IEEE Rob. Autom. Lett. 3(1), 469–476 (2017). https://doi.org/10.1109/lra.2017.2768122
28. Majewicz, A., Okamura, A.M.: Cartesian and joint space teleoperation for nonholonomic steerable needles. In: 2013 World Haptics Conference (Whc), pp. 395–400 (2013)
29. Abolhassani, N., Patel, R.: Deflection of a flexible needle during insertion into soft tissue. In: 2006 International Conference of the Ieee Engineering in Medicine and Biology Society, pp. 3858–3861 (2006)
30. Abolhassani, N., Patel, R.V., Ayazi, F.: Minimization of needle deflection in robot-assisted percutaneous therapy. Int. J. Med. Robot. Comput. Assist. Surg. 3(2), 140–148 (2007). https://doi.org/10.1002/rcs.136
31. Lehmann, T., et al.: A virtual sensor for needle deflection estimation during soft-tissue needle insertion. In: 2015 Ieee International Conference on Robotics and Automation (Icra), pp. 1217–1222 (2015)
32. Barbé, L., et al.: Needle insertions modeling: identifiability and limitations. Biomed. Signal Process Control 2(3), 191–198 (2007). https://doi.org/10.1016/j.bspc.2007.06.003
33. Yan, K.G., et al.: An improved needle steering model with online parameter estimator. Int. J. Comput. Assist. Radiol. Surg. 1(4), 205–212 (2006). https://doi.org/10.1007/s11548-006-0058-0
34. Carriere, J., et al.: Real-time needle shape prediction in soft-tissue based on image segmentation and particle filtering. In: 2016 Ieee International Conference on Advanced Intelligent Mechatronics (Aim), pp. 1204–1209 (2016)
35. Moreira, P., Misra, S.: Biomechanics-based curvature estimation for ultrasound-guided flexible needle steering in biological tissues. Ann. Biomed. Eng. 43(8), 1716–1726 (2015). https://doi.org/10.1007/s10439-014-1203-5
36. Rossa, C., et al.: Adaptive quasi-static modelling of needle deflection during steering in soft tissue. IEEE Rob. Autom. Lett. 1(2), 916–923 (2016). https://doi.org/10.1109/lra.2016.2527065
37. Wood, N.A., et al.: Needle steering system using duty-cycled rotation for percutaneous kidney access. In: 2010 Annual International Conference of the Ieee Engineering in Medicine and Biology, pp. 5432–5435 (2010)
38. Majewicz, A., et al.: Design and evaluation of duty-cycling steering algorithms for robotically-driven steerable needles. In: 2014 Ieee International Conference on Robotics and Automation (Icra), pp. 5883–5888 (2014)
39. Maghsoudi, A., Jahed, M.: Inverse dynamics control of needle in prostate brachytherapy. In: 2012 Ieee International Conference on Industrial Technology, pp. 510–515 (2012)
40. Khadem, M., et al.: A mechanics-based model for simulation and control of flexible needle insertion in soft tissue. In: 2015 Ieee International Conference on Robotics and Automation (Icra), pp. 2264–2269 (2015)
41. Khadem, M., et al.: A two-body rigid/flexible model of needle steering dynamics in soft tissue. IEEE ASME Trans. Mechatron. 21(5), 2352–2364 (2016). https://doi.org/10.1109/tmech.2016.2549505
42. Fallahi, B., et al.: Sliding-based switching control for image-guided needle steering in soft tissue. IEEE Rob. Autom. Lett. 1(2), 860–867 (2016). https://doi.org/10.1109/lra.2016.2528293
43. Zhang, Y., Qi, Z., Zhang, H.: An improved rrt* algorithm combining motion constraint and artificial potential field for robot-assisted flexible needle insertion in 3d environment. In: 2021 3rd International Conference on Industrial Artificial Intelligence (Iai), pp. 1–6 (2021)
44. Moreira, P., et al.: Needle steering in biological tissue using ultrasound-based online curvature estimation. In: 2014 Ieee International Conference on Robotics and Automation (Icra), pp. 4368–4373 (2014)
45. Li, F., Huang, Z., Xu, L.: Path planning of 6-dof venipuncture robot arm based on improved a-star and collision detection algorithms. In: 2019 Ieee International Conference on Robotics and Biomimetics (Robio), pp. 2971–2976 (2019)
46. Li, P., Yang, Z., Jiang, S.: Needle-tissue interactive mechanism and steering control in image-guided robot-assisted minimally invasive surgery: a review. Med. Biol. Eng. Comput. 56(6), 931–949 (2018). https://doi.org/10.1007/s11517-018-1825-0

47. Huang, C., Lei, Y.: A novel model-based path planning method for robot-assisted flexible needle insertion. In: 2017 13th Ieee Conference on Automation Science and Engineering (Case), pp. 1414–1419 (2017)
48. Lehmann, T., et al.: Needle path control during insertion in soft tissue using a force-sensor-based deflection estimator. In: 2016 Ieee International Conference on Advanced Intelligent Mechatronics (Aim), pp. 1174–1179 (2016)
49. Vrooijink, G.J., et al.: Needle path planning and steering in a three-dimensional non-static environment using two-dimensional ultrasound images. Int. J. Robot Res. 33(10), 1361–1374 (2014). https://doi.org/10.1177/0278364914526627
50. Khadem, M., et al.: Semi-automated needle steering in biological tissue using an ultrasound-based deflection predictor. Ann. Biomed. Eng. 45(4), 924–938 (2017). https://doi.org/10.1007/s10439-016-1736-x
51. Alterovitz, R., Goldberg, K., Okamura, A.: Planning for steerable bevel-tip needle insertion through 2d soft tissue with obstacles. In: Proceedings of the 2005 Ieee International Conference on Robotics and Automation, pp. 1640–1645 (2005)
52. Alterovitz, R., et al.: Steering flexible needles under markov motion uncertainty. In: 2005 Ieee/rsj International Conference on Intelligent Robots and Systems, pp. 1570–1575 (2005)
53. Alterovitz, R., Branicky, M., Goldberg, K.: Motion planning under uncertainty for image-guided medical needle steering. Int. J. Robot Res. 27(11-12), 1361–1374 (2008). https://doi.org/10.1177/0278364908097661
54. Patil, S., et al.: Needle steering in 3-d via rapid replanning. IEEE Trans. Robot 30(4), 853–864 (2014). https://doi.org/10.1109/tro.2014.2307633
55. Sutherland, G.R., et al.: An image-guided magnetic resonance-compatible surgical robot. Neurosurgery 62(2), 286–293 (2008). https://doi.org/10.1227/01.neu.0000315996.73269.18
56. Cole, G., Pilitsis, J., Fischer, G.S.: Design of a robotic system for mri-guided deep brain stimulation electrode placement. In: 2009 Ieee International Conference on Robotics and Automation, pp. 4450–4456 (2009)
57. Mehrtash, A., et al.: Automatic needle segmentation and localization in mri with 3-d convolutional neural networks: application to mri-targeted prostate biopsy. IEEE Trans. Med. Imag. 38(4), 1026–1036 (2018). https://doi.org/10.1109/tmi.2018.2876796
58. Chinzei, K., et al.: Mr compatible surgical assist robot: system integration and preliminary feasibility study. In: International Conference on Medical Image Computing and Computer-Assisted Intervention, pp. 921–930 (2000)
59. Dai, X., et al.: Automatic multi-catheter detection using deeply supervised convolutional neural network in mri-guided hdr prostate brachytherapy. Med. Phys. 47(9), 4115–4124 (2020). https://doi.org/10.1002/mp.14307
60. Tadakuma, K., et al.: The experimental study of a precision parallel manipulator with binary actuation: with application to mri cancer treatment. In: 2008 Ieee International Conference on Robotics and Automation, pp. 2503–2508 (2008)
61. Goldenberg, A.A., et al.: Robot-assisted mri-guided prostatic interventions. Robotica 28(2), 215–234 (2010). https://doi.org/10.1017/s026357470999066x
62. Van den Bosch, M.R., et al.: Mri-guided robotic system for transperineal prostate interventions: proof of principle. Phys. Med. Biol. 55(5), N133–N140 (2010). https://doi.org/10.1088/0031-9155/55/5/n02
63. Chentanez, N., et al.: Interactive simulation of surgical needle insertion and steering. In: Acm Siggraph 2009 Papers, pp. 1–10 (2009)
64. Bui, H.P., et al.: Real-time error control for surgical simulation. IEEE (Inst. Electr. Electron. Eng.) Trans. Biomed. Eng. 65(3), 596–607 (2017). https://doi.org/10.1109/tbme.2017.2695587
65. Bui, H.P., et al.: Controlling the error on target motion through real-time mesh adaptation: applications to deep brain stimulation. Inter. J. Numer. Meth. Biomed. Eng 34(5), e2958 (2018). https://doi.org/10.1002/cnm.2958
66. Courtecuisse, H., et al.: Real-time simulation of contact and cutting of heterogeneous soft-tissues. Med. Image Anal. 18(2), 394–410 (2014). https://doi.org/10.1016/j.media.2013.11.001
67. Rappel, H., et al.: A tutorial on bayesian inference to identify material parameters in solid mechanics. Arch. Comput. Methods Eng. 27(2), 361–385 (2020). https://doi.org/10.1007/s11831-018-09311-x
68. Mohamedou, M., et al.: Bayesian identification of mean-field homogenization model parameters and uncertain matrix behavior in non-aligned short fiber composites. Compos. Struct. 220, 64–80 (2019). https://doi.org/10.1016/j.compstruct.2019.03.066
69. Dhaliwal, S.S., et al.: Review of clinical and technological consideration for mri-guided robotic prostate brachytherapy. IEEE Trans. Med. Robot. Bionics 3(3), 583–605 (2021). https://doi.org/10.1109/tmrb.2021.3097127
70. Krieger, A., et al.: Design of a novel mri compatible manipulator for image guided prostate interventions. IEEE (Inst. Electr. Electron. Eng.) Trans. Biomed. Eng. 52(2), 306–313 (2005). https://doi.org/10.1109/tbme.2004.840497
71. Song, S.-E., et al.: Development and preliminary evaluation of a motorized needle guide template for mri-guided targeted prostate biopsy. IEEE (Inst. Electr. Electron. Eng.) Trans. Biomed. Eng. 60(11), 3019–3027 (2013). https://doi.org/10.1109/tbme.2013.2240301
72. Fischer, G.S., et al.: Mri-compatible pneumatic robot for transperineal prostate needle placement. IEEE/ASME Trans. Mechatron 13(3), 295–305 (2008). https://doi.org/10.1109/tmech.2008.924044
73. Li, G., et al.: A fully actuated robotic assistant for mri-guided prostate biopsy and brachytherapy. In: Medical Imaging 2013: Image-Guided Procedures, Robotic Interventions, and Modeling, vol. 8671 (2013). 867117
74. Blackwell, M., et al.: An image overlay system for medical data visualization. Med. Image Anal. 4(1), 67–72 (2000). https://doi.org/10.1016/s1361-8415(00)00007-4
75. Weiss, C.R., et al.: Augmented reality visualization using image-overlay for mr-guided interventions: system description, feasibility, and initial evaluation in a spine phantom. Am. J. Roentgenol. 196(3), W305–W307 (2011). https://doi.org/10.2214/ajr.10.5038
76. Magee, D., et al.: An augmented reality simulator for ultrasound guided needle placement training. Med. Biol. Eng. Comput. 45(10), 957–967 (2007). https://doi.org/10.1007/s11517-007-0231-9
77. Basu, S., Tsai, J., Majewicz, A.: Evaluation of tactile guidance cue mappings for emergency percutaneous needle insertion. In: 2016 Ieee Haptics Symposium (Haptics), pp. 106–112 (2016)
78. Rossa, C., et al.: Multiactuator haptic feedback on the wrist for needle steering guidance in brachytherapy. IEEE Rob. Autom. Lett. 1(2), 852–859 (2016). https://doi.org/10.1109/lra.2016.2528295
79. Abayazid, M., Shahriari, N., Misra, S.: Three-dimensional needle steering towards a localized target in a prostate phantom. In: 5th Ieee Ras/embs International Conference on Biomedical Robotics and Biomechatronics, pp. 7–12 (2014)
80. Su, H., et al.: An mri-guided telesurgery system using a fabry-perot interferometry force sensor and a pneumatic haptic device. Ann. Biomed. Eng. 45(8), 1917–1928 (2017). https://doi.org/10.1007/s10439-017-1839-z
81. Salcudean, S.E., et al.: A robotic needle guide for prostate brachytherapy. In: 2008 Ieee International Conference on Robotics and Automation, pp. 2975–2981 (2008)
82. Schneider, C.M., Okamura, A.M., Fichtinger, G.: A robotic system for transrectal needle insertion into the prostate with integrated ultrasound. In: Ieee International Conference on Robotics and Automation, 2004. Proceedings. Icra'04. 2004, vol. 1, pp. 365–370 (2004)
83. Bebek, Ö., Hwang, M.J., Cavusoglu, M.C.: Design of a parallel robot for needle-based interventions on small animals. IEEE ASME Trans. Mechatron. 18(1), 62–73 (2011). https://doi.org/10.1109/tmech.2011.2162427
84. Wartenberg, M., et al.: Closed-loop active compensation for needle deflection and target shift during cooperatively controlled robotic needle insertion. Ann. Biomed. Eng. 46(10), 1582–1594 (2018). https://doi.org/10.1007/s10439-018-2070-2
85. Moreira, P., et al.: Tele-operated mri-guided needle insertion for prostate interventions. J. Med. Robot. Res 4(01), 1842003 (2019). https://doi.org/10.1142/s2424905x18420035

86. Wartenberg, M., et al.: Towards synergistic control of hands-on needle insertion with automated needle steering for mri-guided prostate interventions. In: 2016 38th Annual International Conference of the Ieee Engineering in Medicine and Biology Society, pp. 5116–5119. (2016)
87. de Battisti, M.B., et al.: A novel adaptive needle insertion sequencing for robotic, single needle mr-guided high-dose-rate prostate brachytherapy. Phys. Med. Biol. 62(10), 4031–4045 (2017). https://doi.org/10.1088/1361-6560/aa664b
88. Seifabadi, R., et al.: Robotic system for mri-guided prostate biopsy: feasibility of teleoperated needle insertion and ex vivo phantom study. Int. J. Comput. Assist. Radiol. Surg. 7(2), 181–190 (2012). https://doi.org/10.1007/s11548-011-0598-9
89. Poquet, C., et al.: A novel comanipulation device for assisting needle placement in ultrasound guided prostate biopsies. In: 2013 Ieee/rsj International Conference on Intelligent Robots and Systems, pp. 4084–4091 (2013)
90. Rossa, C., et al.: A hand-held assistant for semiautomated percutaneous needle steering. IEEE (Inst. Electr. Electron. Eng.) Trans. Biomed. Eng. 64(3), 637–648 (2016). https://doi.org/10.1109/tbme.2016.2565690

How to cite this article: Li, Y., et al.: A review on the techniques used in prostate brachytherapy. Cogn. Comput. Syst. 4(4), 317–328 (2022). https://doi.org/10.1049/ccs2.12067