8 Conclusion

This monograph introduces a set of algorithms that computationally plan and optimize image-guided medical procedures based on imaging data and physician-specified clinical criteria. These computational methods bridge the gap between medical imaging, where emerging advancements are enabling clinicians to non-invasively examine anatomy and metabolic processes in detail, and medical robotics, which is rapidly gaining acceptance in clinical practice.

The monograph focuses on three motion planning problems that arise in image-guided medical procedures: motion planning for rigid needles, motion planning for steerable needles , and motion planning for radiation sources for cancer treatment. Each of these motion planning problems introduces new computational challenges and is subject to unique planning and optimization constraints imposed by the physician's treatment requirements, the patient's anatomy, and the physical limitations of medical equipment and devices. We present planning and optimization algorithms for each of these general problems, and then customize the solutions to the specific application of prostate brachytherapy.

8.1 Contributions

Motion planning for image-guided medical procedures presents three major algorithmic challenges: deformations, uncertainty, and optimality.

8.1.1 Deformations

When surgical devices such as needles contact soft tissue, the soft tissue may deform. Clinicians must compensate for these deformations to successfully guide a surgical device to a clinical target. To facilitate this, we propose optimization-based motion planning. The "cost" of a candidate plan is a function of the resulting placement error, obstacle collisions, and path length. This function can be evaluated by executing a physically-based simulation for a candidate plan. We can compute the optimal plan by using the physically-based simulation as a function in an optimization algorithm that minimizes cost.

R. Alterovitz and K. Goldberg: Motion Planning in Medicine, STAR 50, pp. 107–113, 2008.
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An essential component of this approach is a simulation of tissue deformations that occur when surgical devices such as needles contact soft tissue. We identified and implemented appropriate models and algorithms to interactively estimate soft tissue deformations due to forces applied during surgical and interventional medical procedures. The software tools integrate methods from real-time physically-based simulation in computer graphics and classical finite element methods.

8.1.2 Uncertainty

The motion response of surgical devices to commanded actions cannot be predicted with absolute certainty. Errors arise due to patient variability as well as limitations inherent to the surgical device (for example, a "rigid" needle flexing due to contact with tissue). Clinicians can take this uncertainty into account to guide surgical devices to a clinical target with a high probability of success.

This monograph presents the Stochastic Motion Roadmap (SMR), a new general motion planning framework that explicitly considers motion uncertainty during planning by combining motion sampling with Markov Decision Processes and Dynamic Programming. We applied the SMR framework to needle steering and showed that accounting for needle motion uncertainty during planning can significantly increase the probability of reaching targets without colliding with obstacles.

8.1.3 Optimality

Throughout this book, we focused on optimization-based motion planning. For needle insertion and needle steering, we minimized costs due to obstacle collisions, path length, and placement error. For needle steering with motion uncertainty, we maximized the probability of success. For radiation source motion planning, we minimized the deviation from physician-specified dose requirements. Optimization is a powerful framework for formulating and computing motion plans that maximize the probability of successfully achieving clinical goals while minimizing tissue damage and other negative side effects.

8.2 Future Directions

Advances in imaging and robotic surgical devices continue to introduce challenges and offer new opportunities for future research. In this section we outline some of these, including approaches for extending these results from 2-D planes to 3-D tissue volumes and new optimization-based planning approaches that can explicitly consider uncertainty in tool/tissue interaction.

8.2.1 Realistic Simulation of Image-Guided Medical Procedures

In chapters 2, 3, and 4, we focused on motion planning problems for image-guided medical procedures that consider tissue deformations on a 2-D imaging plane. Due to constraints of many imaging modalities such as ultrasound imaging, often only 2-D anatomical and tissue deformation information is available. However, the improving performance and increasing availability of full 3-D imaging modalities such as CT scans and MRI is introducing the ability to acquire 3-D patient-specific information pre- and intra-operatively. The 2-D simulations described in this book can serve as a foundation on which to develop accurate and efficient 3-D FEM simulations of tissue deformations.

The first challenge in simulating 3-D deformations is to define meshes of appropriate complexity to represent heterogeneous tissue volumes. For many image-guided procedures, the input for meshing will be a 3-D image volume and segmentation information. The segmentation information generally includes anatomical structures and regions of interest specified using polygonal outlines on multiple slices of the 3-D volume. From these outlines, it is possible to generate surface meshes for each tissue type using methods such as Marching Cubes [149]. Open source software tools such as NETGEN and TetGen [187, 193] can then be used to automatically generate a 3-D tetrahedral mesh from the tissue type surface meshes. Mesh decimation and smoothing may be required to reduce the number of elements; the goal is to generate a mesh that is sufficiently sparse to support fast FEM simulation while having sufficient density in key regions to realistically model the tissue. We illustrate 3-D surface meshes for the prostate and several surrounding tissues in figure 8.1.

The next challenge is representing forces exerted by the needle on the soft tissue. In 2-D, we modified the mesh as the needle was being inserted, maintaining mesh nodes along the needle shaft so that we could apply cutting and frictional forces as FEM boundary conditions. In 3-D, there are three approaches that should be considered: mesh modification, mesh refinement, and meshless methods. Although mesh modification worked well in our 2-D simulation in chapter 2, it is unclear whether modification of the 3-D mesh can be performed without resulting in degenerate elements (elements that invert and have "negative" area). With mesh refinement, new nodes are created in the vicinity of the needle path, which has been successfully applied to needle insertion in with regular meshes [165], but will require significant improvements in algorithmic computational complexity to be appropriate for real-time interactive simulation. Another potentially promising approach to explore is meshless methods, a relatively new approach based on clouds of linked nodes [148].

There is an inherent trade-off between the accuracy and speed of physically-based simulation algorithms for medical procedures involving soft tissue deformations. Methods like mass-spring systems introduced in chapter 2 achieve high speed (as measured by the frame rate of the simulation) while finite element methods used in chapters 3 and 4 achieve higher accuracy but are slower. This trade-off becomes more pronounced when transitioning from 2-D simulations to 3-D simulations due to the added computational complexity of computing deformations for 3-D models. As illustrated in figure 8.2, the appropriate method to select depends on the application; while simulation for physician training is subject to strict real-time performance requirements, accuracy is more critical for patient-specific procedure planning. The development of new physically-based

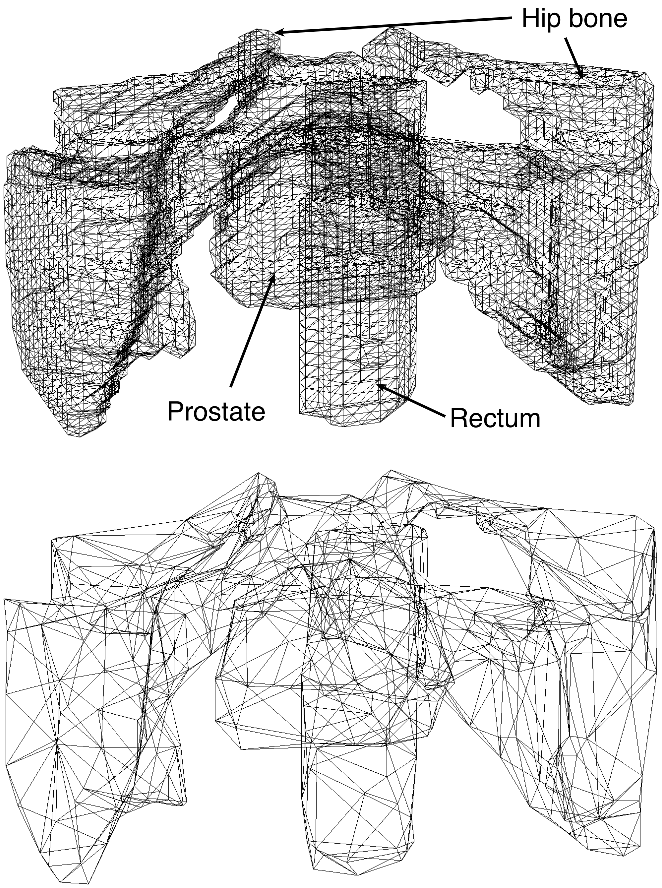

Fig. 8.1. We illustrate 3-D meshes generated from segmented slices from an MRI scan. The mesh on the top encodes the tissue geometry with high accuracy while the sparser mesh on the bottom is more suitable for real-time physically-based simulation.

simulation algorithms can push the trade-off frontier outwards, enabling faster, more accurate simulations of medical procedures.

For many types of soft tissue, the relationship between stress and strain is highly nonlinear [86]. Fast and accurate simulation of 3-D deformable soft tissues with nonlinear behavior has not yet been integrated into a practical surgery simulator. An interesting avenue for research is to explore computationally efficient methods to simulate realistic tissue mechanics and dynamics due to forces applied by surgical instruments or devices. In chapter 2, we focused on linearly elastic models of soft tissue. Future work should incorporate nonlinear tissue behavior, including both nonlinear geometry and nonlinear soft tissue material properties, to accurately simulate large deformations. To more realistically

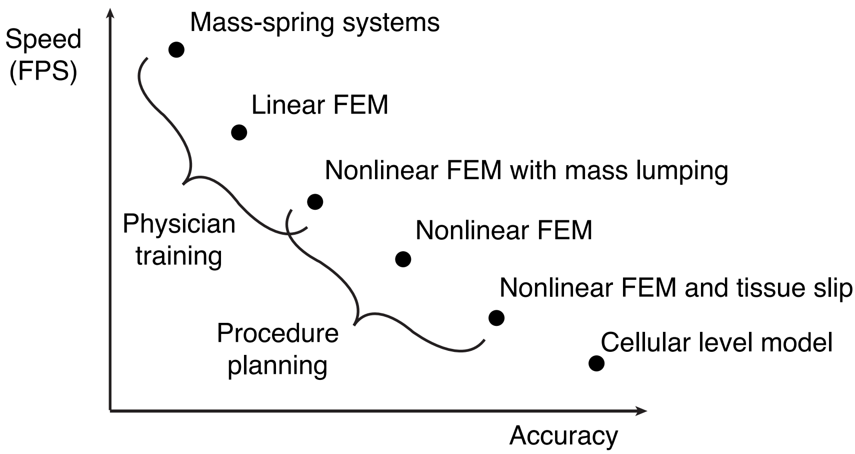

Fig. 8.2. There is an inherent trade-off between the accuracy and speed (as measured in frames-per-second) of physically-based simulation algorithms for medical procedures involving soft tissue deformations. While simulation for physician training is subject to strict real-time performance requirements, accuracy is more critical for patient-specific procedure planning. New algorithms can push the trade-off frontier outwards, enabling faster, more accurate simulations.

model tissue dynamics, another important aspect is to explicitly model slip between tissue types. Rather than considering the mesh of heterogeneous tissue to be connected, the simulation should allow each independently meshed tissue type to deform and move independently and affect neighboring tissues through collision and frictional forces. For computational efficiency, constructing oct-trees and related data structures may accelerate collision detection of deformable objects [99].

Finally, it is crucial to validate these new simulation and planning algorithms using data from physical experiments. Testbeds using artificial tissue phantoms can provide detailed information about deformations, including the precise displacements of points inside deforming tissues [119] and the forces that occur during needle insertion [70]. The needle steering testbed being developed at Johns Hopkins University, shown in figure 8.3, provides an ideal platform for obtaining precise deformation and force measurements for steerable needles in deforming tissue [208, 209]. Ultimately, simulations will also need to be validated using medical images from animal studies or patient cases.

8.2.2 Planning Algorithms for Image-Guided Medical Procedures

New treatment technologies also introduce new computational planning challenges. In this book, we discussed motion planning for steerable needles, a new treatment approach which was submitted in 2006 for a United States Patent [211].

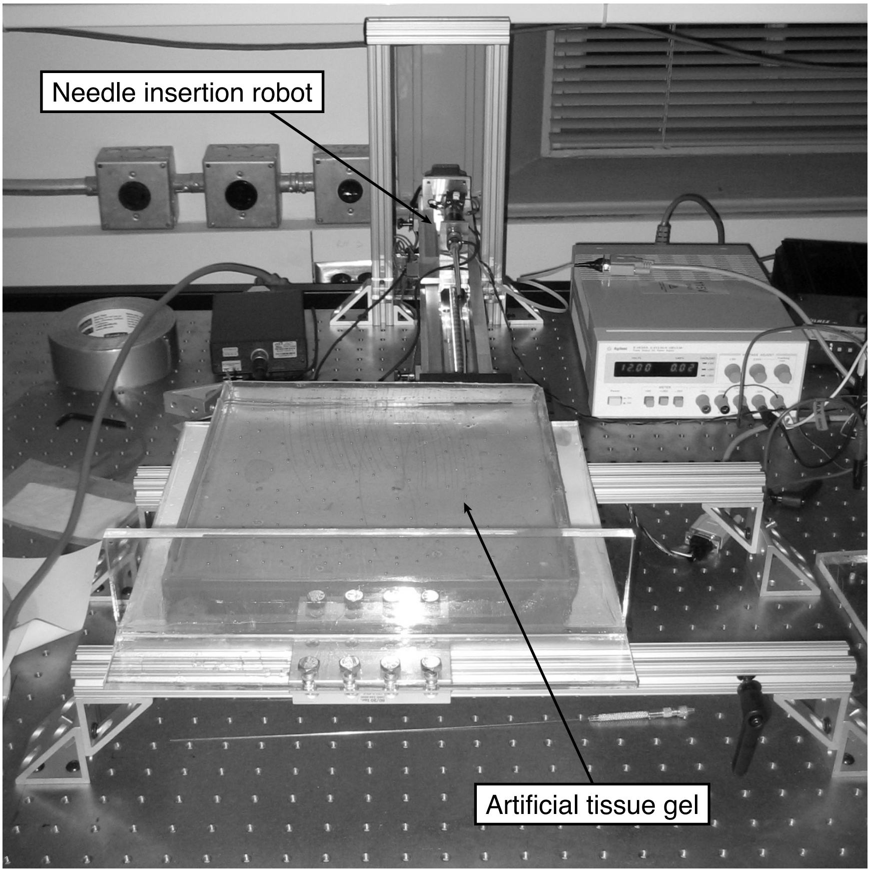

Fig. 8.3. The needle steering testbed at Johns Hopkins University [208, 209] includes a robotic device that can insert and steer a needle in a semi-transparent artificial tissue gel. Optical cameras mounted above the testbed (not shown) can precisely track the motion of the needle and deformations of the artificial tissue gel, enabling physical validation of computational simulations and motion planning algorithms for steerable needles.

New extensions to needle steering are already being proposed that change the dynamic behavior of the needle, including a flattened and expanded bevel tip [76]. In future work, we will explore motion planning for steerable needles in 3-D volumes, where needles nominally follow helical trajectories.

Recently there has been a renaissance in research on thermal therapy for cancer treatment, where directional beams of heat are used to kill cancer cells. This type of therapy raises dose planning problems mathematically similar to HDR brachytherapy dose optimization but can offer a new capability: directional beams [66]. This treatment approach also introduces new challenges for planning since the plan must be updated in real-time during treatment to override the natural tendency of living tissues to compensate for temperature changes via blood flow.

Another open area for research is combining motion planning with uncertainty and deformations. Because patient-specific tissue parameters generally cannot be known exactly, we would like to develop probabilistic models to compute and display uncertainty in tissue deformations. Developing new classes of motion planners that explicitly consider motion uncertainty and deformations and their combined effect on the planning objective will improve the effectiveness of operating inside the highly variable environment of living tissue.

8.2.3 New Clinical Applications

Although this monograph focuses on the specific application of prostate brachytherapy, we believe these motion planning algorithms can be applied to many other medical procedures, including anesthesia injections, biopsies, and cryotherapy. Needle steering could be performed in a variety of soft tissue types, such as inside the liver or brain. Future work is needed to expand the applicability of the methods presented in this monograph; this will require physician feedback and adaptation for the nuances of each procedure and tissue type.

8.3 Conclusion

In medicine, improvements in imaging, combined with new devices to reach what is revealed, can lead to improved treatment and patient health. Innovations in medical imaging are constantly introducing new and improved imaging modalities. Mega-voltage Cone-beam Computed Tomography (MVCBCT) is a new imaging modality that uses the same linac as Intensity Modulated Radiation Therapy (IMRT), allowing physicians to image and treat the patient using the same device without moving and re-aligning the patient [159, 175]. Optical coherence tomography (OCT) is an optical *in vivo* imaging method with micron-scale resolution that can be used to visualize the tiny intra-retinal and intra-corneal anatomy [73]. Molecular imaging techniques are enabling radiologists to visualize *in vivo* intracellular biochemical pathways, introducing the potential to identify pathways involved in disease before traditional symptoms appear [212]. Each new imaging modality introduces a wealth of new digital information, which introduces new computational challenges. In parallel, new robotic medical devices are being introduced, from needle insertion robots [83, 169, 172, 209] to active cannulas capable of following curved paths in soft tissue as well as open cavities [210] to magnetically controlled micro-robots operating in the eye [78]. By bridging the gap between medical imaging and robotic surgical devices with motion planning algorithms, our aim is to assist physicians and thus improve patient care.