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Preoperative trajectory planning for percutaneous procedures in deformable environments

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ABSTRACT

In image-guided percutaneous interventions, a precise planning of the needle path is a key factor to a successful intervention. In this paper we propose a novel method for computing a patient-specific optimal path for such interventions, accounting for both the deformation of the needle and soft tissues due to the insertion of the needle in the body. To achieve this objective, we propose an optimization method for estimating preoperatively a curved trajectory allowing to reach a target even in the case of tissue motion and needle bending. Needle insertions are simulated and regarded as evaluations of the objective function by the iterative planning process. In order to test the planning algorithm, it is coupled with a fast needle insertion simulation involving a flexible needle model and soft tissue finite element modeling, and experimented on the use-case of thermal ablation of liver tumors. Our algorithm has been successfully tested on twelve datasets of patient-specific geometries. Fast convergence to the actual optimal solution has been shown. This method is designed to be adapted to a wide range of percutaneous interventions.

1. Introduction

Today, percutaneous procedures have become a common alternative to open surgery, particularly for the treatment of abdominal tumors. However, the preoperative planning, that aims at determining a secure and efficient needle path before the intervention, remains one of the main challenges of this therapy.

Computer assistance for the preoperative planning of this kind of surgery remains limited. Even if nowadays the visualization can be enhanced by volume rendering or 3D reconstruction based on CT (Computerized Tomography) or MRI (Magnetic Resonance Imaging) data acquired preoperatively, the surgeon still has to choose a needle path by mentally assessing possible trajectories inside the anatomy.

Nonetheless, the planning based on the static preoperative data does not take into account the deformations of the tissue which can significantly impact the accuracy and relevance of the planned trajectory, since both the target lesions and the obstacles such as vessels can move (see Fig. 1). In the case of the abdominal organs, there are two sources of deformations: the interaction between the needle and the tissue and the respiratory motion.

In Section 2, we present the motivations for this work as well as modeling hypotheses. After presenting the related works in Section 3, we detail in Section 4 the new algorithm *Haystack* (HST) that we propose to include a simulation of the deformations due to needle insertion within the automatic trajectory planning process, and the deformable models we used. In Section 5, we report the evaluation of *Haystack* in the context of hepatic radiofrequency ablation, with an assessment using 12 datasets of patient-specific geometries. We present a comparison between our algorithm and two reference algorithms (exhaustive method and Nelder-Mead downhill simplex method) to evaluate the efficiency and accuracy of *Haystack*. The paper ends with a discussion on the results and the benefit of considering the possible deformations preoperatively, and a conclusion.

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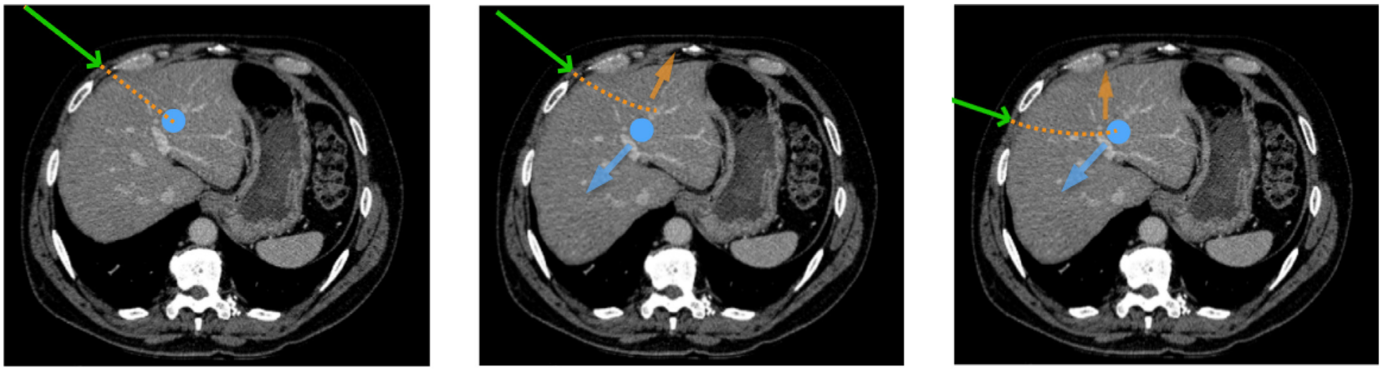

Fig. 1. (a) Trajectory (insertion point and angle, represented by the green arrow) planned within a static scene may actually lead to a deformed needle path (dotted line) that deviates from its ideal straight path because of the deformability of the tissues and needle itself. It can hit an obstacle or even (b) miss the target. (c) Insertion point and angle able to anticipate the deformations of the needle and organs, to reach the target in optimal conditions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

2. Motivations and problem statement

In [1], the survey of the experiments aiming at quantifying phenomena related to the needle–tissue interaction reports that forces applied to the tissue due to the interaction with the needle can exceed 1 N. For example, Hing et al. [2] present force profiles observed during 45 insertions of a brachytherapy needle into a porcine liver: cutting and friction forces of 1.5 N have been measured. At the same time, the liver is a highly deformable object with low stiffness as shown by [3,4]. Therefore, the forces applied due to the interaction with the needle result in important deformations, mainly in the areas close to the needle trajectory. While these deformations are ignored by previous planning algorithms [5–7], they are usually considered an important issue that must be addressed directly during the intraoperative needle control and navigation. Some works describe different techniques to mitigate the impact of the needle interaction: for example Mahvash et al. propose increasing the insertion velocity to minimize the tissue deformation mainly during the puncture of the organ surface [8], while Kobayashi introduces an intelligent robotic manipulator driven by an imaging modality capturing the actual deformation of the tissue [9].

As for the deformations due to the respiratory motion, Rohlfing et al. quantify the motion of liver due to breathing [10]: after removing the rigid-motion component, a mean residual deformation of 10 mm has been reported. Nevertheless, in clinical routine, the needle insertion is done under shallow (i.e. quiet) breathing; in this case, Korin reports deformations which do not exceed 3 mm [11]. Similar observations are reported in [12] where gating techniques are considered. Finally, it can also be supposed that the inserted needle plays a role of an additional mechanical constraint further reducing the respiration-induced displacement of the internal structures of the organ.

In this work, we do not consider any deformation due to the breathing for two reasons: first, as described in the literature dealing with experimental assessment, the "periodical" component of the respiratory motion can be significantly reduced. Second, the "irregular" motions for example due to coughing cannot be taken into account preoperatively and must be addressed intraoperatively. In the general case, optimal needle placement can be achieved by a combination of accurate preoperative planning and intraoperative control. While there is still need for advanced intraoperative navigation and control, we show that by modeling the needle–tissue interactions and deformation we can improve the preoperative planning, thus reducing requirements for intraoperative control.

The objective is to demonstrate the feasibility of including simulations of deformations in an automatic preoperative planning algorithm in a reasonable time and with an acceptable accuracy.

We emphasize that an important aspect of this work is that it is generic. Firstly, the planning method we present here can be applied to an arbitrary percutaneous procedure involving deformable tissues such as liver, spleen, or kidney tissues. Secondly, we employ a simulation engine to demonstrate the robustness of the planning algorithm, but it could be replaced with any other similar simulator.

3. Related works and contributions

Much significant work has been performed in both fields: that of the preoperative planning of needle path (more particularly for percutaneous thermal ablations), and the flexible needle insertion in soft tissues.

As for the preoperative trajectory planning, most of the works in the literature relate to percutaneous thermal ablations and address the issue of optimizing the volume of the ablated tissue, i.e. destroying all the tumor while preserving most of the healthy tissue. Some authors approximate the ablation volume by ellipsoids: Butz [13] uses Powell's optimization algorithm to improve the placement of a manually positioned needle. Other works focus on the accurate estimation of the ablation volume: Altrogge [14], Chen [15], and Haase [16] simulate heat propagation in the tissues using finite element methods but without considering the feasibility and safety of the path itself. Wang [17] proposes a mathematical model based on geometric optimization to optimize the needle puncture placements and the ablation frequencies for treating large liver tumors with multiple needles. However, none of these methods accounts for any other surgical constraint in their path planning. For instance, the avoidance of certain surrounding anatomical structures that must not be damaged by the needle during the insertion, or the inclusion of a portion of healthy liver in the trajectory for a better cauterization are also important aspects of the planning to ensure the safety of the procedure. These aspects have been less studied in terms of computer-assisted path planning. The automatic method proposed by Seitel et al. [18] is capable of finding the best compromise between multiple clinical criteria. The optimization is computed on polygonal surfaces of patient models. In a similar way, Schumann [19] has investigated a fast automatic path proposal directly based on segmentation masks. Other works propose non-automatic (interactive) path planning: a user interface that helps the surgeon to define his intervention path manually has been introduced by März [20], and Seitel et al. [18] from the same group