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Path planning for steerable needles using duty-cycled spinning

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Abstract

This paper presents an adaptive approach for 2D path planning of steerable needles. It combines duty-cycled rotation of the needle with the classic Rapidly-Exploring Random Tree (RRT) algorithm and it is used intraoperatively to compensate for system uncertainties and perturbations. Simulation results demonstrate the performance of the proposed motion planner on a workspace based in ultrasound images.

1 Introduction

Percutaneous medical procedures usually involve the insertion of a needle deep into soft tissue and depend on precise tip positioning for effectiveness. Needle deflection and tissue deformation are the most important factors that affect needle insertion accuracy and require great expertise from the surgeon to compensate for their effects. In addition, the procedure target may be located in a region of difficult access, which cannot be reached by conventional rigid needles without causing excessive, injurious pressure on tissue. This situation is critical in the presence of obstacles in the needle path, such as important organs or vessels.

Special needles capable of active steering during its insertion have been designed to overcome such problems and also expand the applicability of percutaneous procedures [1]. These needles use their great flexibility and beveled tips to enhance and magnify the needle deflection effect, allowing curved trajectories that could be used to avoid sensitive or impenetrable areas inaccessible with the traditional technique.

When inserted into tissue, a steerable needle follows a curved path that is prescribed by the geometry of its beveled tip, its relative stiffness with respect to the tissue and the insertion and twist velocities at the needle entry point. As a consequence, motion planning is a complex task and its difficulty increases as we consider the presence of uncertainties due to errors in tip positioning, needle modeling, tissue inhomogeneity and deformation. Thus, the need of developing a robotic steering system capable of compensating for such effects.

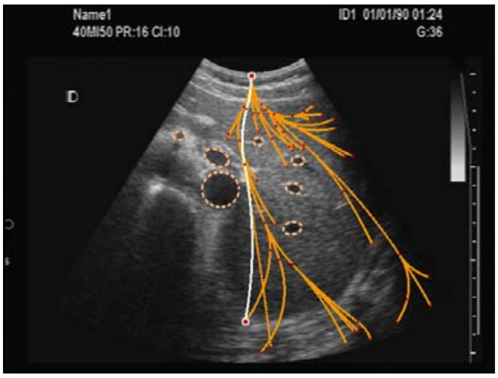


Figure 1: A typical tree built by the Arc-based RRT to search for a feasible path and its corresponding solution.

Medical imaging can be used not only for the planning but also for the control of robot-assisted medical procedures. The use of 2D ultrasound imaging is specially attractive because it is safe, affordable and provides information related to tissue properties, target displacement and tool position [2]. For using such type of medical imaging in robotic needle steering, it is desirable to have a fast method for 2D path planning that respects the needle movement constraints.

The main contribution of this work is the proposal of a path planner that uses duty-cycled rotation of the needle combined with the classic Rapidly-Exploring Random Tree (RRT) algorithm [3] to obtain fast calculation of feasible trajectories (Fig. 1). Also, we developed an adaptive strategy that applies fast replanning during the insertion procedure to compensate for system uncertainties, like tissue deformation, tissue inhomogeneity, positioning errors and other modeling approximations.

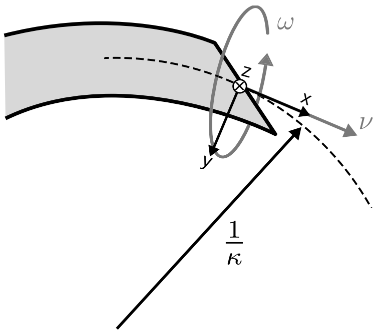


Figure 2: Flexible needle steering via duty-cycled spinning.

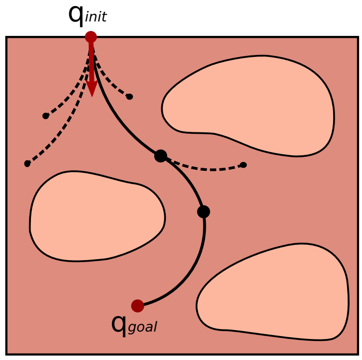


Figure 3: Arc-based RRT path planner.

2 Needle steering with duty-cycled spinning

When pushed forward, the natural behaviour of a steerable needle is to bend in the direction of its sharpened tip, following an arc of approximately constant curvature κ as depicted in Fig. 2. The arc direction can be controlled by twisting the base of the needle to change its bevel orientation. The usual technique for needle steering in a 2D plan [4], called stop-and-turn, explores such idea by alternating pure insertion of the needle with occasional 180° rotations to reorient the needle whenever there is a curvature inversion. In consequence, the needle can only reach points that belong to arcs of constant curvature, what limits path possibilities and makes the planning slow and not suitable for online replanning.

An alternative is to make use of a duty-cycle strategy [5] that explores needle twisting to achieve different curvature values. This method works by combining periods of pure insertion with periods of simultaneous insertion and rotation so that any curvature ranging from the natural curvature to a pure straight trajectory can be achieved. When considering the duty-cycle strategy to insert the needle along a 2D plan, we simplify the path planning problem to that of a a car-like mobile robot that is subjected to two constraints: it can only move with continuous tangent direction and its turning radius is lower bounded.

3 Arc-based RRT path planner

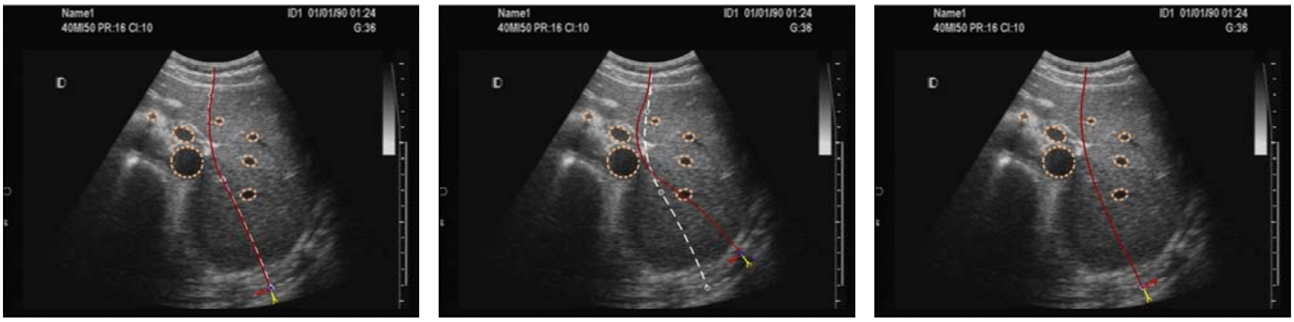
Let the configuration q of a needle be defined by its tip cartesian coordinates and orientation angle. The objective of the planner is to find a combination of circular arcs capable of taking the needle from its initial configuration q_{init} to a final configuration q_{goal} while respecting the system constraints. An arc is defined by its curvature and its two extremity configurations. The final extremity of each arc should correspond to the next arc's initial extremity, not only in position but also in orientation, so we have C^1 continuity. The goal orientation is not considered as a problem requirement since in a percutaneous procedure the final needle orientation is usually irrelevant. Thus, it is used as an extra degree of freedom to obtain such orientation continuity. The workspace is a 2D plane with boundaries defined to be the ultrasound image area, and the locations of the targets and obstacles are considered known and defined by the surgeon.

We construct a tree based in the classical RRT by randomly sampling points from the free space and trying to connect them to a tree rooted in q_{init}. To respect the needle constraints, we propose a geometric-based Arc Local Planner that calculates the only arc capable of connecting two points given that the initial point is associated to a given orientation. If the obtained arc respects the curvature range and does not intersect any obstacle, it is added to the tree. The tree is expanded until it can be connected to the target and then a graph search is conducted to return the trajectory (Fig. 3). More details of the algorithm are provided in [6].

For our adaptive replanning, we suppose that 2D information about the actual needle position is available and provided by an ultrasound tracking system out of the scope of this paper. This visual feedback is used as the needle's new initial configuration and the curvatures of all arcs previously calculated are adjusted to fit it. If a collision is detected or if the new curvature does not respect the maximum limit, then the RRT planner is run again to find a new trajectory.

4 Results

We tested the proposed Arc-Based RRT planner for needle steering in the 2D environment with obstacles depicted in Fig. 1. The workspace is based on an



(a) Final error = 0.83 mm

(b) Final error = 33.41 mm

(c) Final error = 0.20 mm

Figure 4: Simulated trajectories of the needle tip in simulations of (a) an ideal situation, (b) under disturbances and (c) with adaptive replanning for noise compensation. Planned path (dashed) and simulated needle trajectory (solid).

Table 1: Arc-Based RRT performance in Simulation 1.

Number of trials	10000
Number of successes	10000
Average number of nodes	114
Average CPU time (ms)	3.05

abdominal ultrasound image obtained with a General Electric Diasonics Synergy equipment and is defined to be the area covered by the ultrasound transducer and the obstacles are seven round structures distinguishable in the image. For the kinematic model of the needle, we specified a needle radius of curvature of 6.01 cm. Simulations are run in a PC with Intel Core 2 Duo 3.00 GHz, 3.2 GB memory and Ubuntu 10.04 operational system. To validate the proposed planner, we performed three different simulations.

Simulation 1

The first simulation evaluates the capability of the proposed algorithm to find a solution. For each trial, an initial configuration and a goal point are randomly picked from an uniform distribution. The maximum number of nodes for the RRT is 2500. Table 1 presents the results of Simulation 1 for 10000 trials. Feasible paths were found in all cases, with an average of 114 nodes, which corresponds to an average of 3.05 milliseconds of CPU time used.

Simulation 2

The second simulation evaluates if the system constraints are respected and if the needle is capable of following the expected trajectory during an open-loop insertion procedure. For this, the needle tip was computationally simulated using the model proposed in [7]. The workspace is the same used in previous simulations.

We used the Arc-based RRT to obtain a feasible path and the correspondent sequence of duty-cycles parametrized in path length. The sequence of inputs was then applied to the simulated needle and it resulted in the trajectory depicted in Fig. 4a. It can be observed that in the case of an ideal situation, the needle was able to follow the path almost exactly, with a small final error of 0.83 mm due to curvature discontinuity combined with discretization.

However, if we consider the presence of system uncertainties and perturbations such as positioning errors, tissue deformation and inhomogeneity, the result can greatly deviate from the expected. In simulation, these perturbations were modeled as white noises added to the measured tip configuration and to the actual natural curvature. The consequence of the addition of such noises can be seen in Fig. 4b, where the needle failed to avoid the obstacles and finished the insertion with 33.41 mm of error.

Simulation 3

The adaptive replanning strategy was evaluated at the same workspace and perturbation conditions as Simulation 2. In this last simulation, instead of applying the control inputs in open-loop, we used our adaptive strategy to systematically replan the trajectory along the insertion procedure. Fig. 4c illustrates how the online update of the path was able to compensate for the uncertainties, with a final error of only 0.20 mm.

5 Conclusions

In this paper we proposed a closed-loop strategy for motion planning of steerable needles using duty-cycling and a new Arc-based RRT planner. The use of the duty-cycle technique instead of the usual stop-and-turn gave the system more trajectory possibilities. This multiplicity of solutions is specially necessary for the case of steering around obstacles during insertion procedures restricted to a 2D working space.

The Arc-based RRT proved to respect the system constraints while being fast enough to be used in an intraoperative system. We think it could be easily adapted to a preoperative planner by adding some new features, such as the calculation of initial orientation and insertion point and the possibility for the surgeon of choosing image regions as passage points for the needle.

The proposed replanning strategy made the insertion procedure more robust to system uncertainties such as tissue deformation, errors in position, inhomogeneity and modeling approximations. The simulation results showed that even under perturbations, the needle was able to reach the target with satisfactory precision while an open-loop strategy would fail to avoid the obstacles and to arrive at the desired position. Preliminary work suggests that the replanning could also be used to compensate for small magnitude physiological movement if the tissue-needle combination presents good steerability. However, this possibility needs to be further investigated.

The next step is to evaluate the proposal on tissue phantoms and robotic hardware. We also plan to extend this method to 3D motion planning using the duty-cycle strategy for different planes in a tridimensional workspace. Possible future works include the investigation of motion planners that combine the duty-cycling strategy with smoother trajectories such as splines curves.

Acknowledgments

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