Motion Planning Under Uncertainty for Steerable Needles

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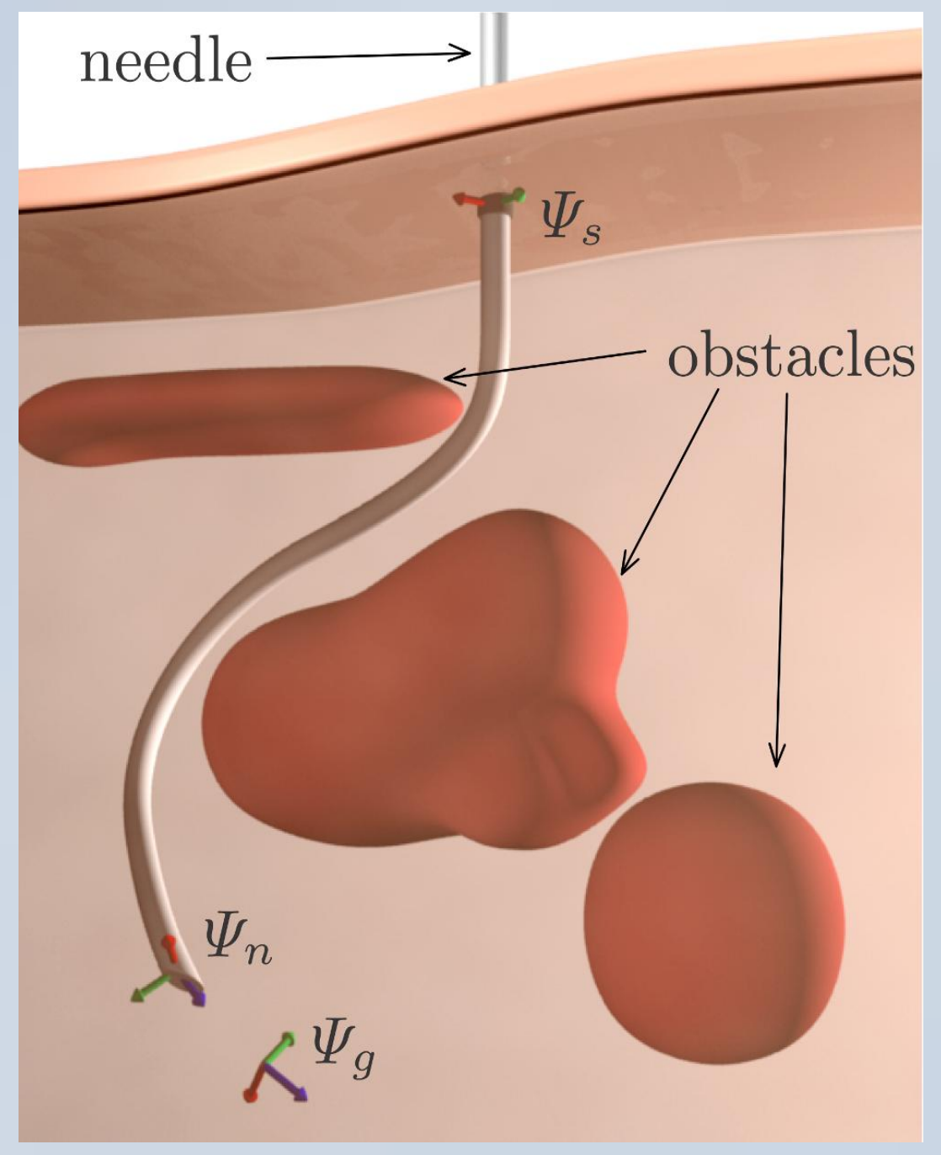
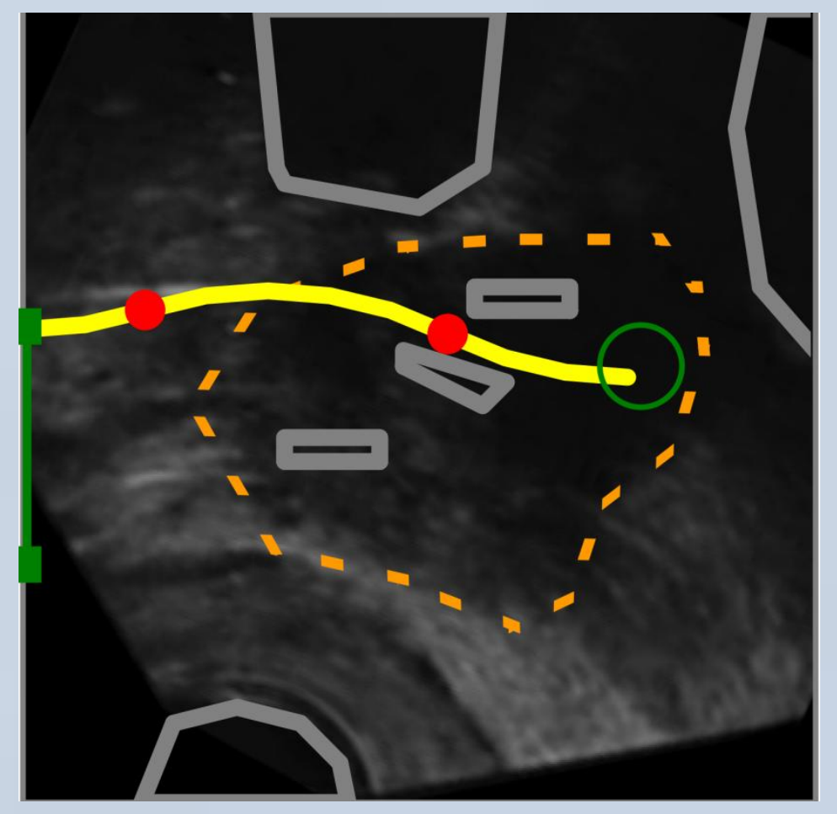
Motivation



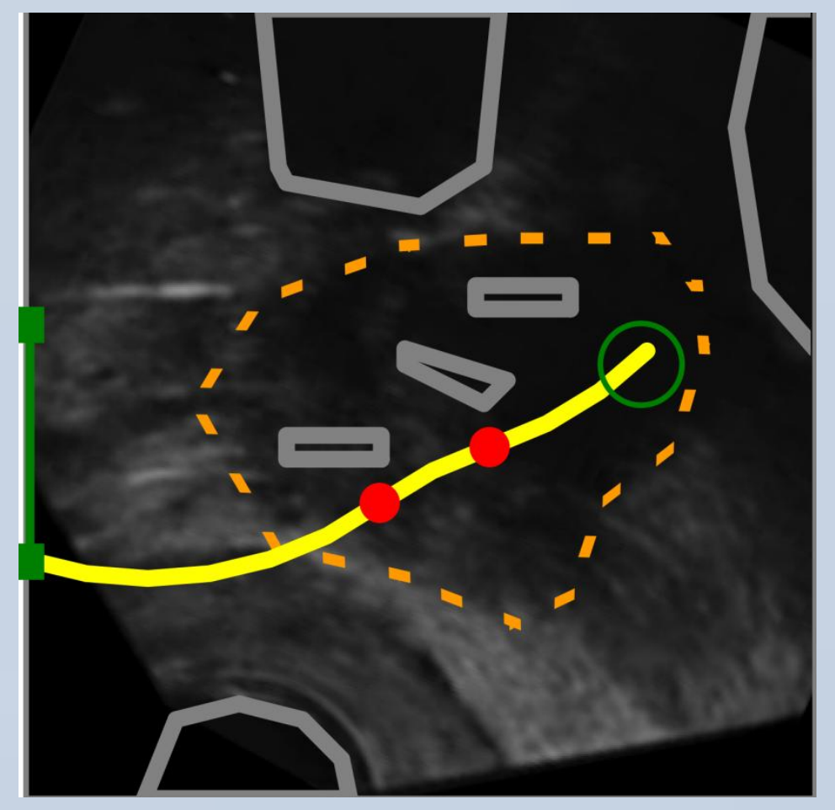
- Steerable needles are controlled within deformable tissue by inserting and twisting the needle externally at its base.
- Guiding the needle to a desired target is challenging for a human operator due to anatomical obstacles, nonholonomic motion, and limited sensor feedback.
- Motion planning algorithms can assist physicians by automatically computing safe motion plans.
- Modeling errors and uncertainty introduced by: (i) noisy actuation, (ii) noisy sensing, and (iii) disturbances due to tissue deformations. These must be accounted for during planning.

Objective: Compute safe motion plans for autonomous needle steering in deformable tissue that maximizes the probability of successfully avoiding obstacles and reaching the target.

Needle Steering in Planar Tissue Slices

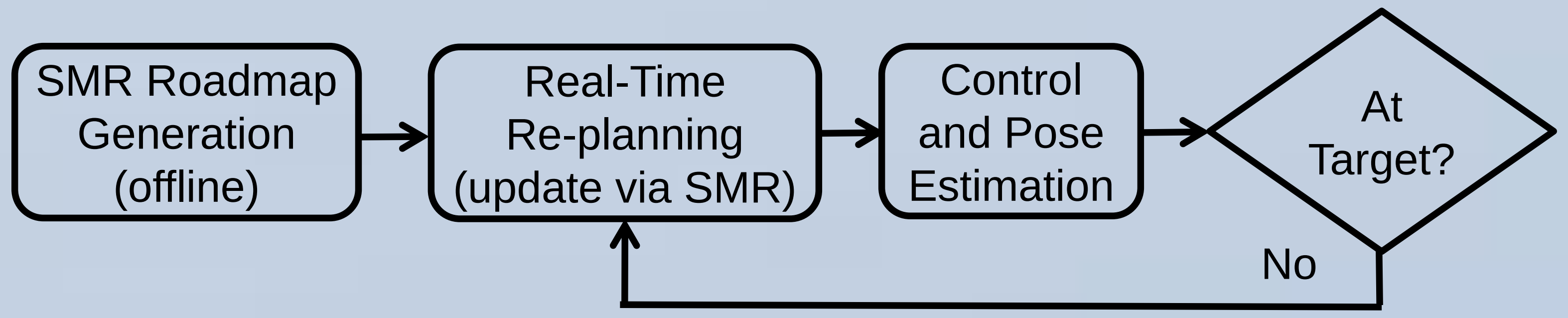


Shortest path, probability of success: 36.7%



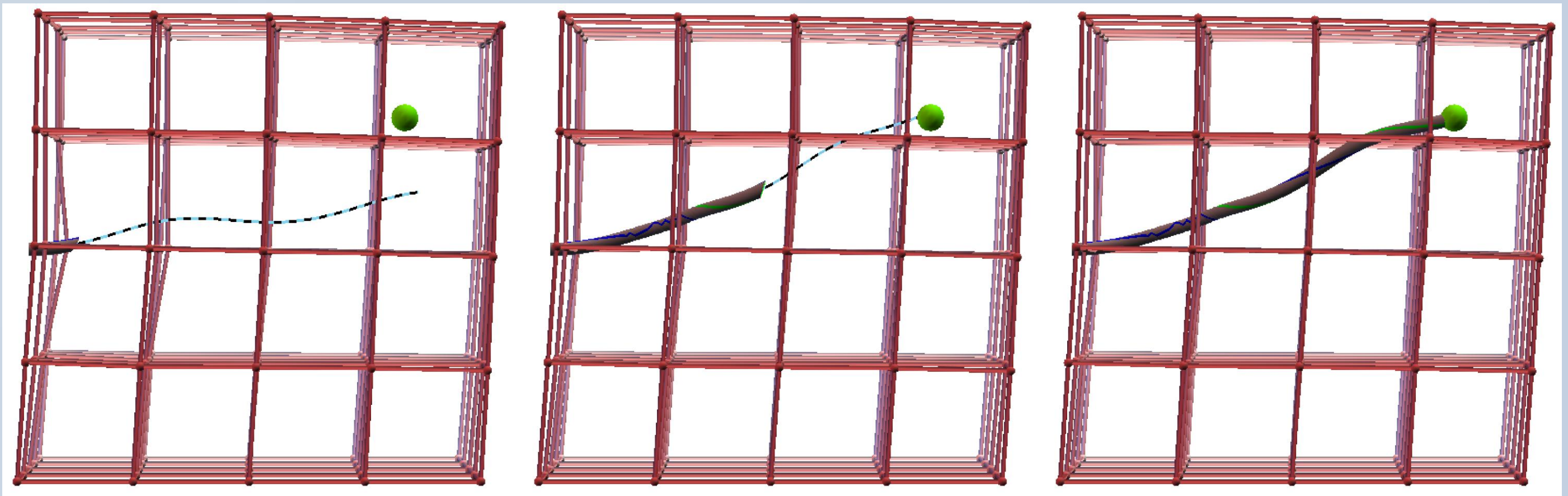
SMR plan, probability of success: 73.7%

The Stochastic Motion Roadmap (SMR) planner combines sampling-based motion planning with the well-established theory of Markov Decision Processes (MDP). It considers the effects of uncertainty and maximizes the probability of successfully avoiding obstacles and reaching the target.



R. Alterovitz, T. Simeon, and K. Goldberg. "The Stochastic Motion Roadmap: A Sampling Framework For Planning With Motion Uncertainty". In *Proc. Robotics: Science and Systems (RSS)*, 2007, MIT Press, pp. 233-241.

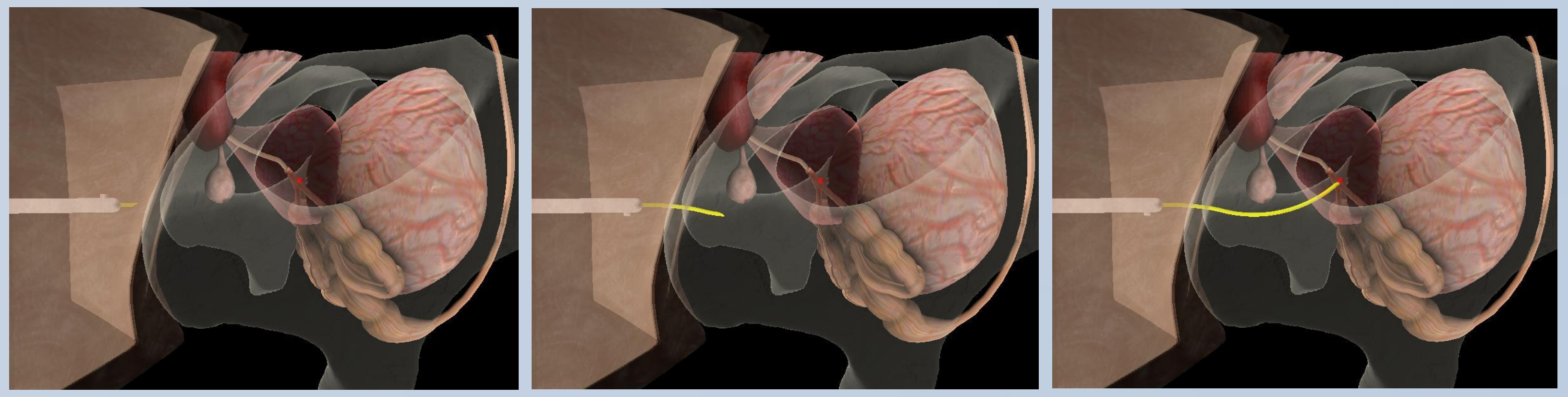
Real-time Control



We perform real-time control for the steerable needle in 3D deformable tissue using a model-predictive controller (MPC), which steers the needle along 3D helical trajectories, and varies the helix radius to correct for perturbations.

K. Hauser, R. Alterovitz, N. Chentanez, A. Okamura, and K. Goldberg. "Feedback Control For Steering Need Through 3D Deformable Tissue Using Helical Paths". In *Proc. Robotics: Science and Systems (RSS)*, 2009.

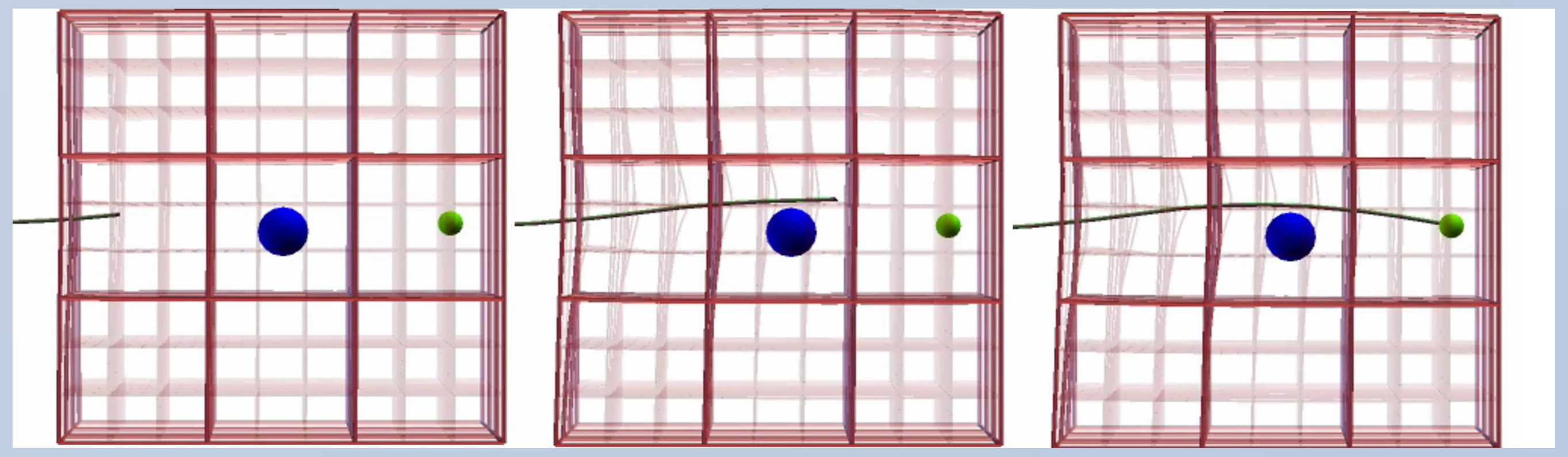
Real-Time Re-planning



We perform real-time re-planning for the steerable needle in 3D environments with obstacles, using a Rapidly Exploring Random Tree (RRT) planner with the following key features:

- Reachability-guided sampling
- Duty-cycling to plan bounded curvature needle trajectories

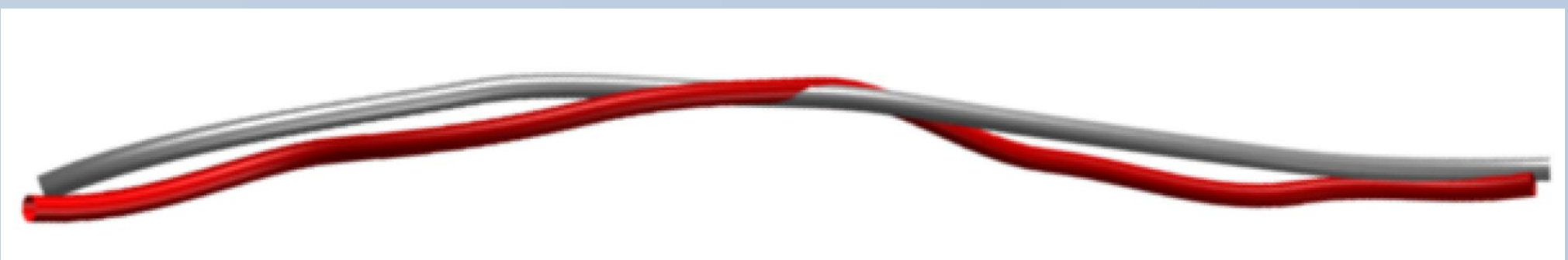
This allows us to generate several candidate plans in real-time of which an optimal plan can then be chosen based on a user-supplied optimality criterion (such as distance or clearance).



We apply our interactive planner for real-time re-planning in 3D deformable tissue with obstacles.

S. Patil and R. Alterovitz. "Interactive Motion Planning For Steerable Needles In 3D Environments With Obstacles". In *Proc. IEEE Int. Conference on Biomedical Robotics and Biomechatronics (BioRob)*, 2010, pp 893-889.

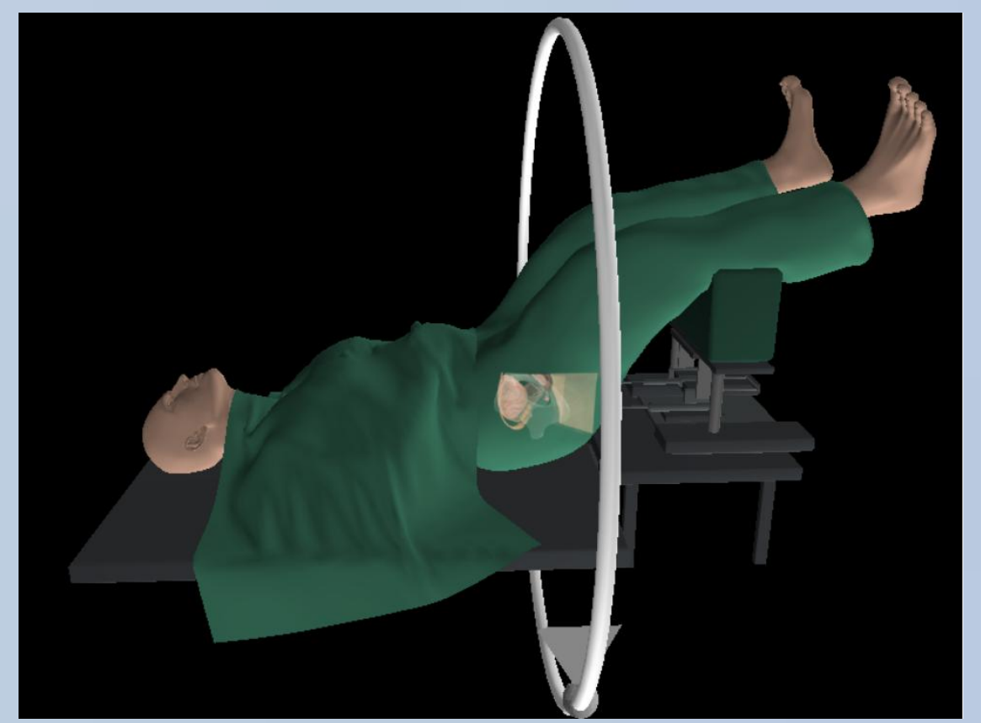
LQG-based Planning and Control



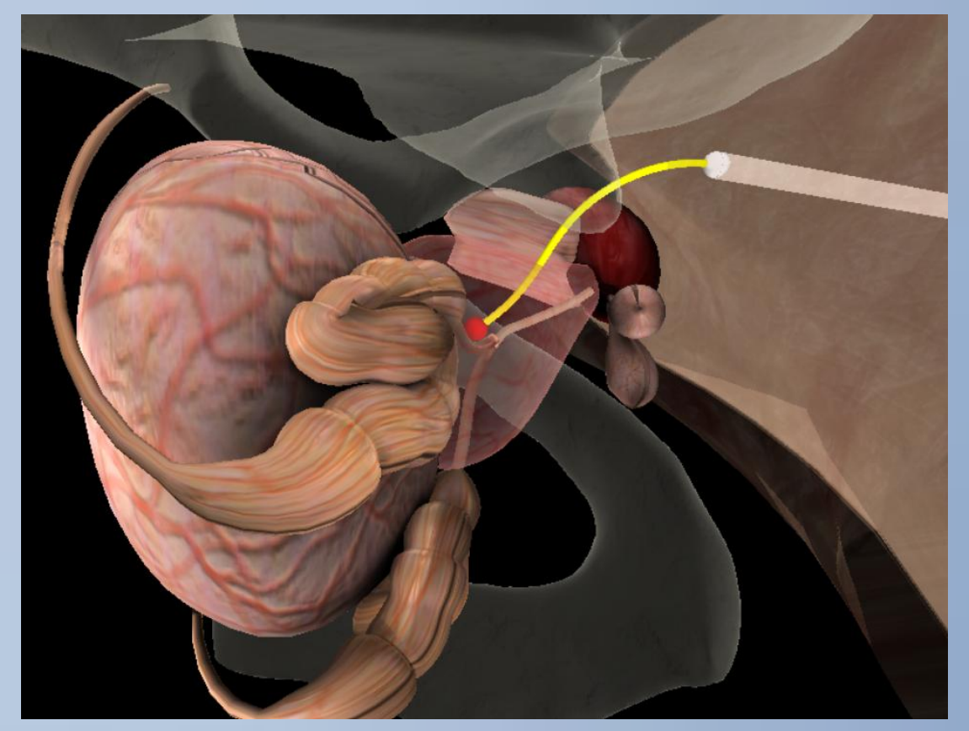
Planned trajectory (gray) and actual trajectory using LQG controller (red).

We derive a Linear Quadratic Gaussian (LQG) controller that keeps the steerable needle close to the planned trajectory when subject to actuation noise and only partial, noisy sensor feedback.

Optimizing Sensor Placement



Prostate brachytherapy with steerable needles and X-ray imager on C-arm.

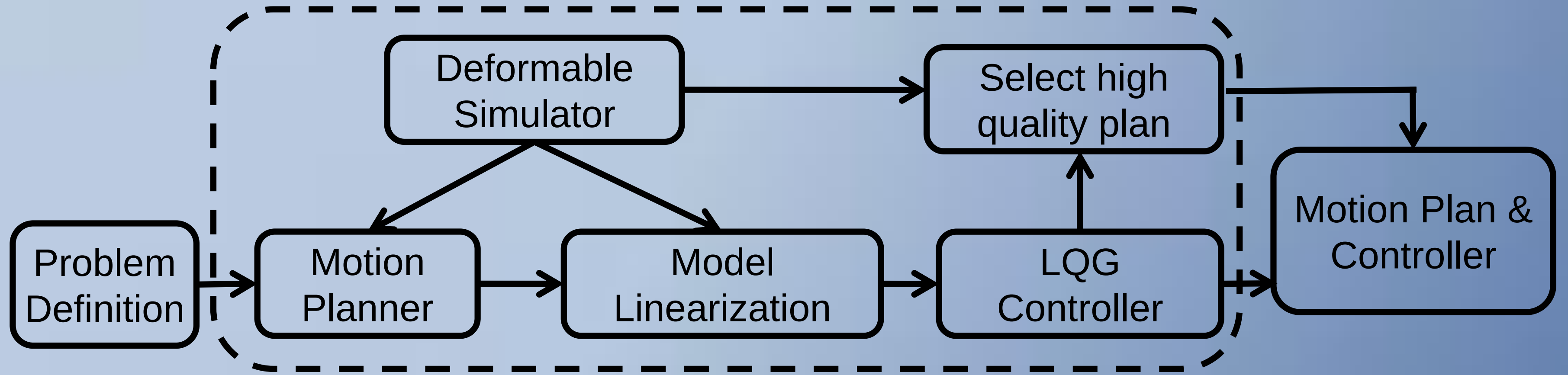


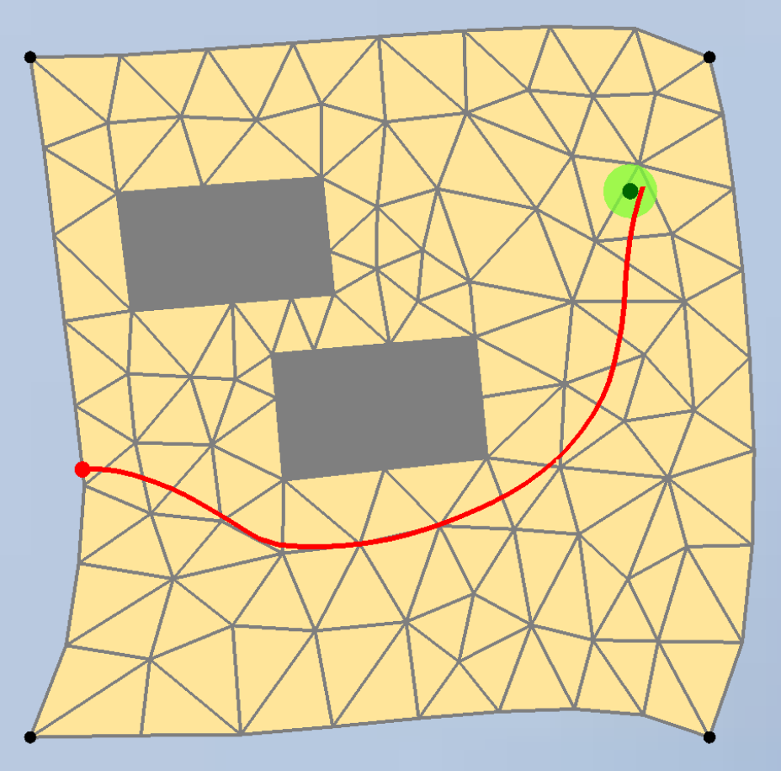
Optimal motion plan and corresponding C-arm placement

We characterize a priori probability distributions of the needle-tip states for a steerable needle operating under LQG control. We then use this to select optimal motion plans and corresponding sensor placements.

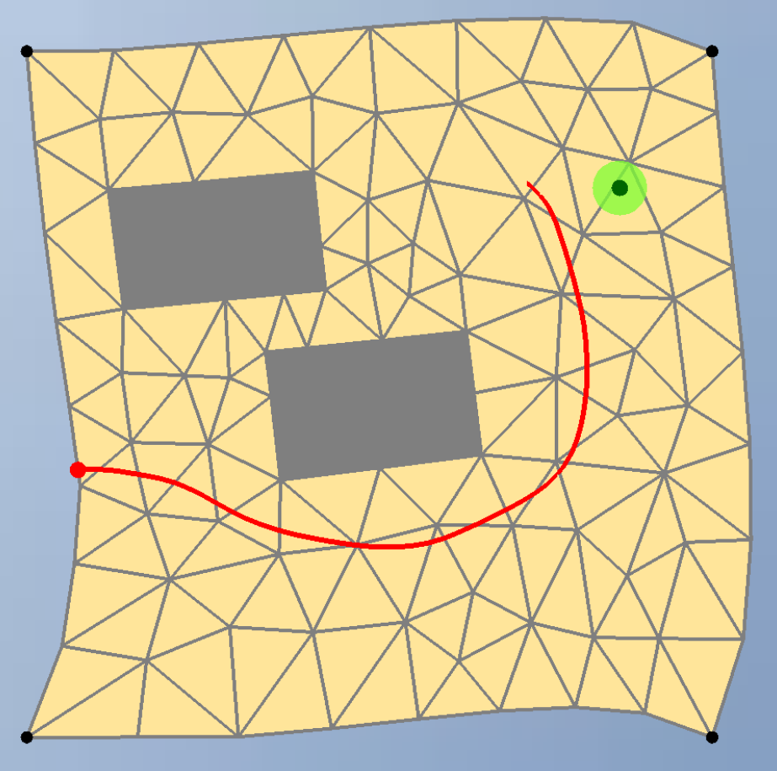
J. van den Berg, S. Patil, R. Alterovitz, P. Abbeel, and K. Goldberg. "LQG-Based Planning and Control of Steerable Needles". In *Workshop on Algorithmic Foundations of Robotics (WAFR)*, 2010, pp. 373-389.

Deformation-Aware Planning Under Uncertainty

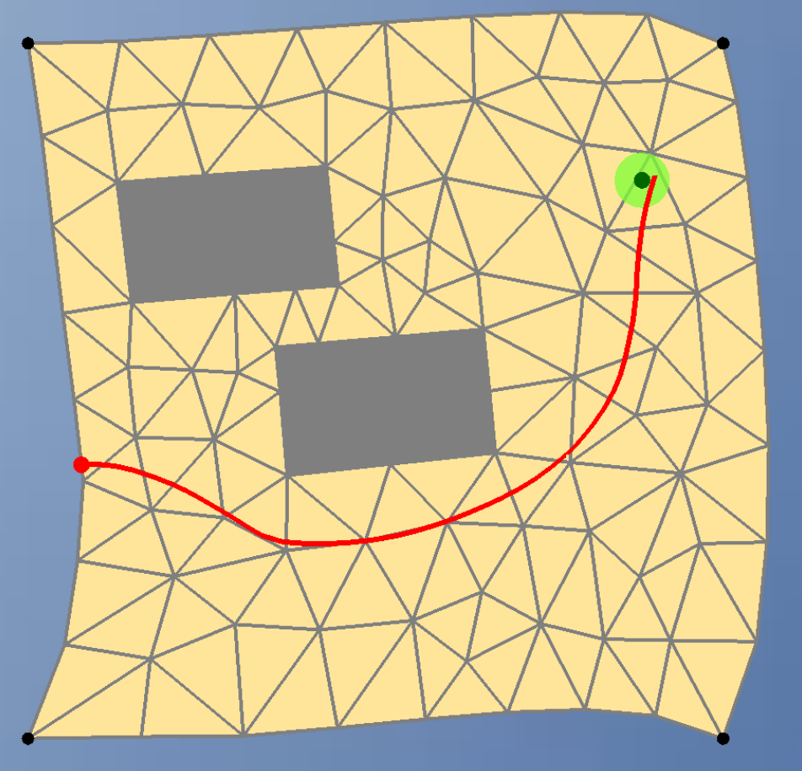




We plan in a simulated deformable environment and select a high quality plan that maximizes the probability of success.



Perturbations during open-loop execution of the selected plan cause the needle-tip to deviate from the intended trajectory.



Our deformation-aware LQG controller compensates for uncertainty and has considerably higher rates of success as compared to prior methods.

S. Patil, J, van den Berg, and R. Alterovitz. "Motion Planning Under Uncertainty In Highly Deformable Environments". In *Proc. Robotics: Science and Systems (RSS)*, 2011.