Integrating Motion Planning and Control of Steerable Needles: Real-time Re-planning vs. Deformation-aware LQG control

Sachin Patil and Ron Alterovitz

Department of Computer Science, University of North Carolina at Chapel Hill

- Executing steerable needle procedures is challenging for a human operator due to nonholonomic motion in 6-D space, considerable tissue deformation, anatomical obstacles, and limited sensor feedback.
- Objective: Enable accurate, autonomous needle steering by computing and executing safe motion plans that maximize probability of success under deformations and uncertainty.

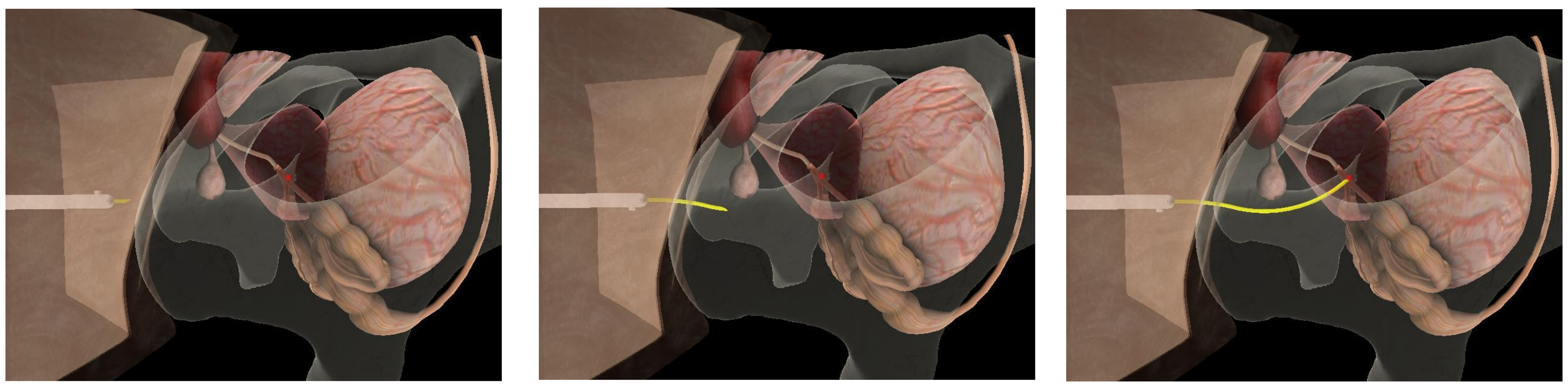
Real-time Re-planning

Interleave planning and execution using a fast Rapidly Exploring Random Trees (RRT) planner augmented with:

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

Choose an optimal plan from multiple candidate plans at each time-step based on user-supplied criterion (such as insertion distance or obstacle clearance).

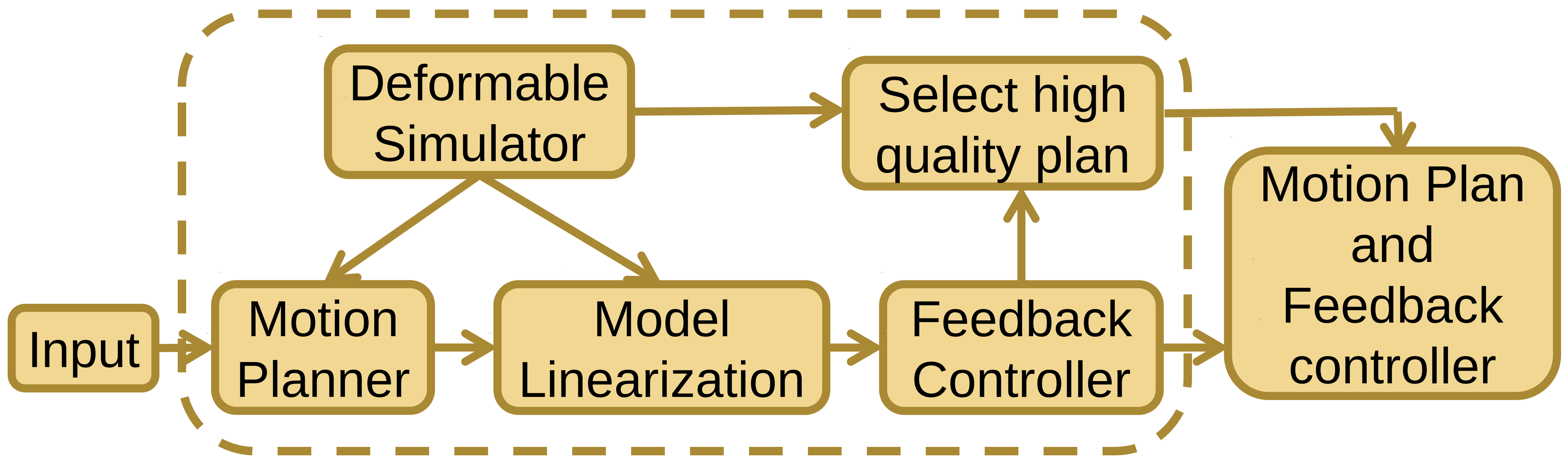
Simulation of needle insertion procedure with artificial actuation noise using control by re-planning in a 3D anatomical environment modeling the prostate and surrounding tissues.

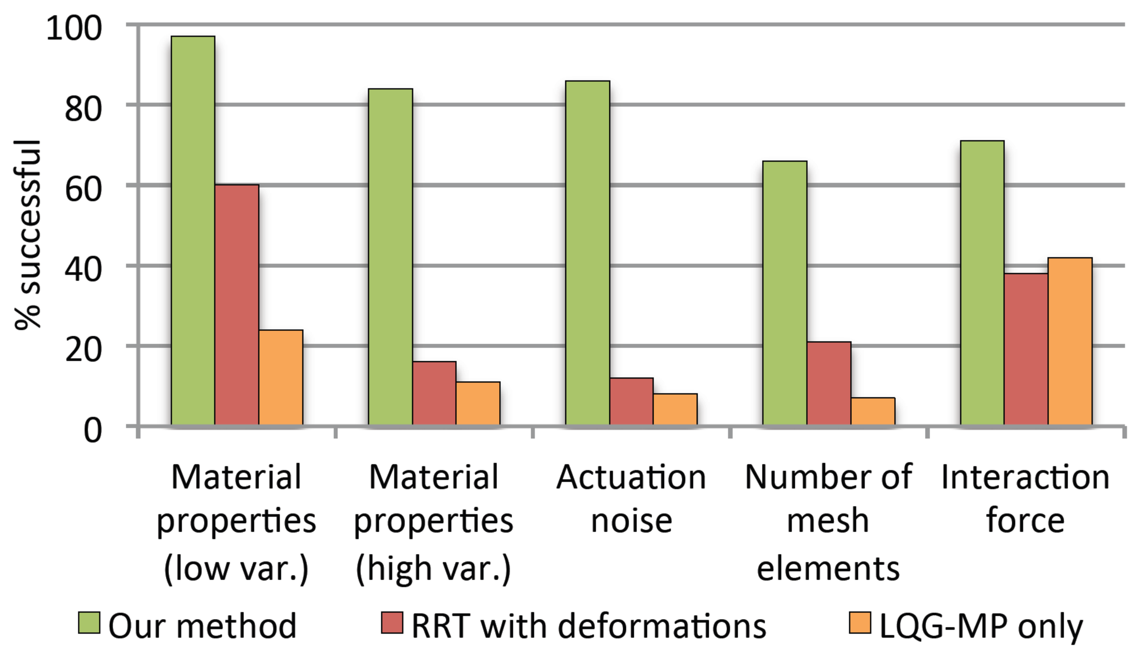


S. Patil and R. Alterovitz. "Interactive Motion Planning For Steerable Needles In 3D Environments With Obstacles". In *Proc. IEEE Int. Conference on Biomedical Robotics and Biomechatronics (BioRob)*, 2010, pp 893-889.

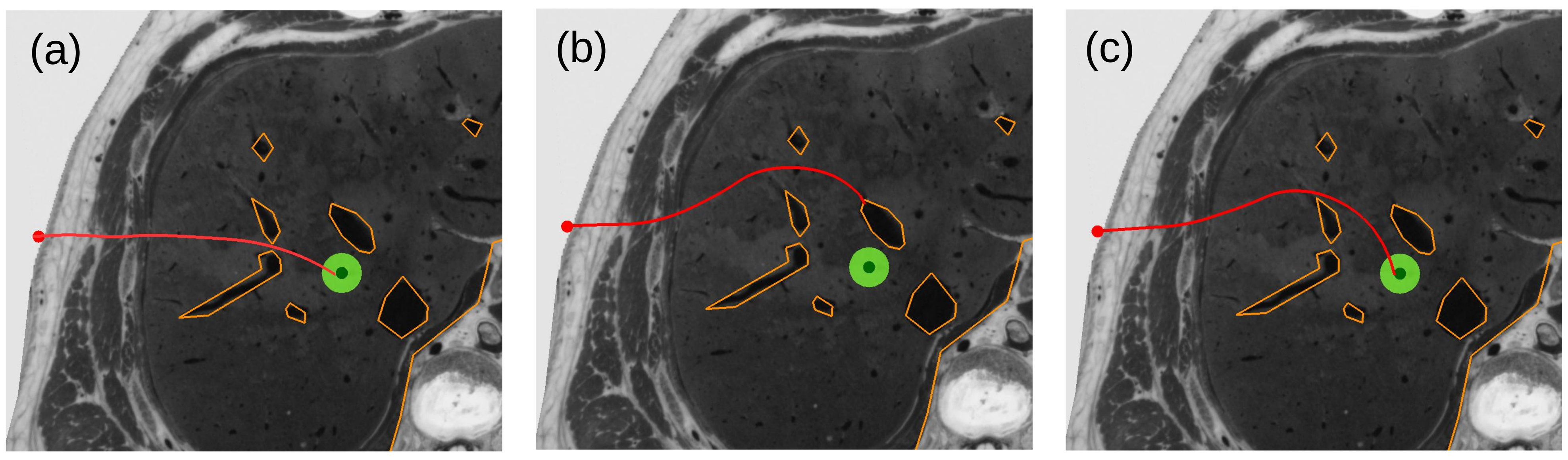
Deformation-Aware Planning and Control under Uncertainty

Compute a priori a set of motion plans and corresponding optimal controllers that consider both deformations and uncertainty. Choose a high quality plan that maximizes probability of success and use feedback controller for closed-loop error correction during execution.





Our method outperforms methods that consider only deformations or uncertainty individually as measured by probability of success.



Simulations of planar needle insertion in the liver:
(a) A plan with low probability of success.
(b) Perturbations during open-loop execution of a high-quality plan causes the needle to hit a vessel.
(c) Our deformation-aware LQG controller compensates for uncertainty and guides the needle to the target region.

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.

Real-time Re-planning

\+ Fast, reactive planner
\+ Handles large disturbances during execution
\+ Ability to evaluate multiple plans at runtime

– Does not consider uncertainty during planning
– Does not reuse information from prior planning steps

Deformation-aware LQG Control

\+ Explicitly handles both deformations and uncertainty
\+ Directly incorporates sensing

– Requires physically-based simulator; difficult
– Cannot handle large departures from chosen plan
– Control policy can exceed control input limits

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