



Apprenticeship Learning for Robotic Control

Pieter Abbeel
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Final Report

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Report Type: Final Report

Primary Contact Email: pabbeel@cs.berkeley.edu

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Organization / Institution name: UC Berkeley

Contract/Grant Title: (YIP-12) Apprenticeship Learning for Robotic Control

Contract/Grant #: FA9550-12-1-0345

PI Name: Pieter Abbeel

Program Manager: James Lawton

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Abstract:

Our research had three main thrusts: (i) Optimization-based motion planning: Traditional approaches to motion planning tend to slow down in high-dimensional spaces and for curvature constrained problems. We developed an optimization-based approach that can efficiently solve such problems. (ii) Belief space planning: To account for uncertainty about the environment and robot belief space planning tries to find a plan that optimizes (on expectation) the sequence of probability distributions that would result from that plan. As a consequence belief space planning anticipates (and accounts for) sensory information, the expected magnitude of perturbations, and controllability. We made contributions in handling collisions, handling occlusions, scaling up belief space planning, going beyond unimodal beliefs, and hierarchical belief space planning. (iii) Learning from demonstrations: We developed an approach to generalize demonstrated motion in training scenarios to test scenarios. At the core of our approach is non-rigid registration to warp the training scene onto the test scene. While registration is only concerned with the objects and their environment, we show that it is possible to meaningfully extrapolate the registration and to also warp the robot gripper trajectories from training scene to test scene. Our approach is particularly appealing for the manipulation of deformable objects, which present the robot with a very high-dimensional state space and large amounts of variability, making them particularly challenging for robots to manipulate. It has enabled autonomous knot tying for a wide range of knot-types and automation of some simplified suturing tasks.

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Annual Accomplishments:

Our research had three main thrusts: (i) Optimization-based motion planning, (ii) Belief space planning, (iii) Learning from demonstrations.

(i) Optimization-based motion planning

Traditional approaches to motion planning tend to slow down in high-dimensional spaces and for curvature constrained problems (such as needle steering and ribbon routing). We developed an optimization-based approach that can efficiently solve such problems [58, 68, 74]. In this work we introduced a new optimization-based approach for robotic motion planning among obstacles. Like CHOMP (Covariant Hamiltonian Optimization for Motion Planning), our algorithm can be used to find collision-free trajectories from naïve, straight-line initializations that might be in collision. At the core of our approach are (a) a sequential convex optimization procedure, which penalizes collisions with a hinge loss and increases the penalty coefficients in an outer loop as necessary, and (b) an efficient formulation of the no-collisions constraint that directly considers continuous-time safety. Our algorithm is implemented in a software package called TrajOpt. We validated our approach through a series of experiments comparing TrajOpt with CHOMP and randomized planners from OMPL, with regard to planning time and path quality. We considered motion planning for 7 DOF robot arms, 18 DOF full-body robots, statically stable walking motion for the 34 DOF Atlas humanoid robot, and physical experiments with the 18 DOF PR2. We also applied TrajOpt to plan curvature-constrained steerable needle trajectories in the $SE(3)$ configuration space and multiple non-intersecting curved channels within 3D-printed implants for intracavitary brachytherapy.

(ii) Belief space planning

Uncertainty about the environment is unavoidable in unstructured settings. Uncertainty about the robot itself can also be a factor, especially as robots become cheaper and cheaper. Belief space planning algorithms try to find a plan that optimizes (on expectation) the sequence of probability distributions that would result from that plan. As a consequence belief space planning anticipates (and accounts for) sensory information, the expected magnitude of perturbations, and controllability.

Building on advances in sequential convex optimization our most recent work is able to find (locally) optimal paths in Gaussian belief spaces. Our key contributions have been in handling probabilistic collision checking for articulated robots [62], in handling sensors with a limited field of view and occlusions [69], and in exploiting the structure of Gaussian belief space planning problems to enable scaling up to significantly higher dimensional problems (i.e., higher number of degrees of

freedom of the robot, higher number of objects, and higher number of landmarks) than was possible before [75].

Gaussian belief space planning, while surprisingly effective, nevertheless has significant limitations as it is only able to reason about unimodal beliefs. In [C89] we have started to investigate multimodal belief representations in the context of grasping occluded objects.

Recent work has made headway on integration of task and motion planning in state space. We developed Interfaced Belief Space Planning (IBSP): a modular approach to task and motion planning in belief space. We use a task-independent interface layer to combine an off-the-shelf classical planner with motion planning and inference. We determinize the problem under the maximum likelihood observation assumption to obtain a deterministic representation where successful plans generate goal-directed observations. We leverage properties of maximum likelihood observation determinizations to obtain a simple representation of (optimistic) belief space dynamics that is well suited to planning. Our interface is implemented with standard belief state queries, requiring only the ability to sample, compute unnormalized likelihoods, and compute maximum likelihood states. Our contribution is a novel algorithm for task and motion planning in belief space that has minimal dependence on the details of the inference engine used. IBSP can work with a broad class of black box state estimators, with zero changes to the algorithm. We validate our approach in simulated tasks for the PR2 that account for continuous state, different types of initial state distributions, and negative observations.

(iii) Learning from demonstrations

In [C64] we have started to develop the beginnings of a theory that allows for generalization from training scenarios to test scenarios. At the core of our approach is non-rigid registration to warp the training scene (where the demonstration happens) onto the test scene (which is a previously unseen situation where the robot has to autonomously succeed). While registration is only concerned with the objects and their environment, we show that it is possible to meaningfully extrapolate the registration and to also warp the robot gripper trajectories from training scene to test scene. Our approach is particularly appealing for the manipulation of deformable objects, which present the robot with a very high-dimensional state space and large amounts of variability, making them particularly challenging for robots to manipulate. Our approach has enabled autonomous knot tying for a wide range of knot-types and starting configurations. It has enabled automation of some simplified suturing tasks. Figure 1 illustrates some of our experiments.



Figure 1: Autonomous knot-tying, suturing, and folding of a t-shirt. Key insight in this project was how to build on existing techniques for non-rigid registration to enable generalization of motions by warping them appropriately from training scene to test scene.

Our approach as discussed thus far only considers robot gripper pose trajectories, but often what matters forces and torques the robot applies. For instance, tightening a knot requires pulling the ends, flattening an article of clothing requires smoothing out wrinkles, and erasing a whiteboard requires applying downward pressure. In [C92] we show how the variation between multiple demonstrations of variants of the same task can be used to determine when, and to which extent, forces than well pose matter. This results in a learned variable impedance control strategy that trades off force and position errors, providing the right level of compliance for each motion.

Improved registration [C87]: The first step in our approach is a non-rigid registration between training scene and test scene. The current registration only considers a geometric representation of train and test scenes and it considers all parts of the scenes equally important. In [C87] we show how to incorporate surface normals. Future work will study how to incorporate visual (in addition to geometric) features.

Archival Publications (published) during Reporting Period:

Numbering matches number on my webpage: www.cs.berkeley.edu/~pabbeel

[106] Modular Task and Motion Planning in Belief Space,

Dylan Hadfield-Menell, Edward Groshev, Rohan Chitnis, Pieter Abbeel.
In the proceedings of the *28th IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Hamburg, Germany, September 2015. ([pdf](#))

[92] Learning Force-Based Manipulation of Deformable Objects from Multiple Demonstrations,

Alex Lee, Henry Lu, Abhishek Gupta, Sergey Levine, Pieter Abbeel.

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[87] A Non-Rigid Point and Normal Registration Algorithm with Applications to Learning from Demonstrations,

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[89] Active Exploration using Trajectory Optimization for Robotic Grasping in the Presence of Occlusions,

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[75] Scaling up Gaussian Belief Space Planning through Covariance-Free Trajectory Optimization and Automatic Differentiation,

Sachin Patil, Greg Kahn, Michael Laskey, John Schulman, Ken Goldberg, Pieter Abbeel.

In the proceedings of the *11th International Workshop on the Algorithmic Foundations of Robotics (WAFR)*, Aug. 2014. ([pdf](#))

[72] Motion Planning with Sequential Convex Optimization and Convex Collision Checking,

John Schulman, Yan Duan, Jonathan Ho, Alex Lee, Ibrahim Awwal, Henry Bradlow, Jia Pan, Sachin Patil, Ken Goldberg, Pieter Abbeel.

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[69] Gaussian Belief Space Planning with Discontinuities in Sensing Domains,

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[68] Planning Locally Optimal, Curvature-Constrained Trajectories in 3D using Sequential Convex Optimization,

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[64] Learning from Demonstrations through the Use of Non-Rigid Registration,

John Schulman, Jonathan Ho, Cameron Lee, Pieter Abbeel.

In the proceedings of the *16th International Symposium on Robotics Research (ISRR)*, Dec 2013. ([pdf](#))

[63] A Case Study of Trajectory Transfer through Non-Rigid Registration for a Simplified Suturing Scenario,

John Schulman, Ankush Gupta, Sibi Venkatesan, Mallory Tayson-Frederick, Pieter Abbeel.

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In the proceedings of *Robotics: Science and Systems (RSS)*, Jul 2013. ([pdf](#), [videos](#), [code](#))

Changes in Research Objective, if any:

None

Change in AFOSR program manager, if any:

Dr. Jay Myung left as of 2012/5/31. When starting off the AFOSR was working to bring in a new program officer to manage Dr. Jay Myung's portfolio. In the interim, Dr. Robert Bonneau (robert.bonneau@afosr.af.mil; 703-696-9545), with the help of Ms. Stephanie Bruce (stephanie.bruce@afosr.af.mil; 703-588-0664), oversaw the portfolio. Ultimately Dr. James Lawton became the new program officer, and still currently is.

Extensions Granted or Milestones Slipped, if any:

None

Include any new discoveries, inventions, or patent disclosures during this reporting period (if none, report none)

None

1.

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Principal Investigator Name

The full name of the principal investigator on the grant or contract.

Pieter Abbeel

Program Manager

The AFOSR Program Manager currently assigned to the award

James Lawton

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Abstract

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Changes in research objectives (if any):

n/a

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Extensions granted or milestones slipped, if any:

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AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, \$K)

	Starting FY	FY+1	FY+2
Salary			
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