Physics-Based Manipulation under Uncertainty

Michael Koval
mkoval@cs.cmu.edu

February 9, 2016
Hands: Design and Control for Dexterous Manipulation
What caused these failures?
motion planning problem
object pose uncertainty
object pose uncertainty
motion planning problem
proprioceptive uncertainty
8 PLACEMENT HEADS - SPEED UP TO 20,000 cph

Source: https://youtu.be/S8qkaTsr2_o - ESSEMTEC pick and place machine
Source: https://youtu.be/yygM-MSxvw - ELCON part feeder machine
How can we manipulate under uncertainty?
Closed-loop or open-loop?
Non-deterministic or probabilistic uncertainty?
Closed-form or sample-based representation?
Estimate, react, or plan?
Visual Feedback

Tactile Feedback

No Feedback
Image-space visual servoing

Markerless real-time articulated tracking

realtime tracking of articulated objects

dark grey: depth measurements
colored: tracked model

Visual Feedback

Tactile Feedback

No Feedback
Visual Feedback

Tactile Feedback

No Feedback
Use “guarded moves” to reduce uncertainty
Plan a sequence that maximizes information gain

Estimate the pose of the object using tactile sensing

Closed-loop grasping using contact sensing

Learn feedback policies that use sensor feedback

Learn feedback policies that use sensor feedback

Visual Feedback

Tactile Feedback

No Feedback
Visual Feedback

Tactile Feedback

No Feedback
Open-loop robotic part alignment

Push Grasping


Rearrangement Planning
Robust Trajectory Selection

Convergent Planning

A brief introduction to POMDPs.
state
\[ s = (q, x) \]

action
\[ a = (\dot{q}, \Delta t) \]
\[ T = p(s'|s, a) \]

observation
\[ o = (o_q, o_c) \]
\[ \Omega = p(o|s, a) \]
state space

$\dim(S) = n$

Planning in Belief Space
Planning in Belief Space

state space
\[ \dim(S) = n \]

belief space
\[ \dim(\Delta) = \infty \]
Offline Planning
Point-Based Methods

Online Planning
Offline Planning
Point-Based Methods

Online Planning
Point-based solvers

\[ V^\pi = \sum_{t=1}^{\infty} \gamma^t R(s_t, a_t) \]

$V^\pi = \sum_{t=1}^{\infty} \gamma^t R(s_t, a_t)$

Point-based solvers

Point-based solvers

\[ V^\pi = \sum_{t=1}^{\infty} \gamma^t R(s_t, a_t) \]

\[ V^\pi = \sum_{t=1}^{\infty} \gamma^t R(s_t, a_t) \]

Point-based solvers

Point-based solvers

\[ V^\pi = \sum_{t=1}^{\infty} \gamma^t R(s_t, a_t) \]

\[ \pi^* = \arg \max_{\pi} V^\pi [b(s_0)] \]


Point-based solvers
Offline Planning
Point-Based Methods

Online Planning
**Offline Planning**  
*Point-Based Methods*

**Online Planning**
\[ a \sim \pi_{\text{explore}}(b_0) \]
\[ s' \sim T(s, a, s') \]
\[ a \sim \pi_{\text{explore}}(b_0) \]

\[ s' \sim T(s, a, s') \]

\[ o \sim p(o|s,a) \]

\[ a^* = \arg \max_i Q(b_0, a_i) \]
Offline Planning

Point-Based Methods

Online Planning
Heuristics / Bounds

Combine online and offline planning.
The post-contact belief space is small
The post-contact belief space is small
The post-contact belief space is small

The post-contact belief space is small
Decompose into pre- and post-contact policies

- **pre-contact policy**
  - Computed online
  - Move-until-touch
  - Once per problem

- **post-contact policy**
  - Computed offline
  - Closed-loop
  - Once per object

Physics-Based Manipulation under Uncertainty

Michael Koval
mkoval@cs.cmu.edu

February 9, 2016
Hands: Design and Control for Dexterous Manipulation