End-to-End Dexterous Manipulation with Deliberate Interactive Estimation

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The DARPA ARM-S Program

Six Teams:
- Carnegie Mellon University
- HRL Laboratories
- iRobot
- Jet Propulsion Laboratory
- SRI International
- University of Southern California

All teams provided same GFE: identical robots and test objects

Each team creates and refines algorithms at its own facility

Teams send code to DARPA’s test facility for evaluation

youtube.com: “DARPA Autonomous Robotic Manipulation”
http://thearmrobot.com/
“Traditional” Sense-Plan-Act
Interactive Manipulation

DARPA ARM-S Experiments
Unlocking a Door

Jet Propulsion Laboratory
California Institute of Technology

September 22, 2011
2x Real-Time
Team Approach / Philosophy

**Sense**: Non-Contact Map building and initial object classification and localization

**Plan** (with best model)
Into contact with environment

**Estimation**
(conditioned on model)
Update object, robot, environment, contact states

**Act/Control**: (feed-forward model)
Merge with feedback behaviors

- Minimal calibration: assume there are errors, and estimate online.
- Model Based: continual model refinement & use all aproi knowledge
- By the final DARPA test we had enforced touching (table or object), updating, and *then* grasping or manipulating, *for everything*
1. Table plane estimation (RANSAC)

2. 2.5 D map generation with clustering of elevated cells

3. Object Segmentation:
   a) Geometric/Volume Based
   b) Contour Based
   c) Color Based

   Iterative Closed Point (ICP) pose refinement
   Contour and RGB space template matching

6 DOF Pose
Estimation: Objects and Arm in Visual Frame

- Unscented Kalman Filter
- Measurement Fusion:
  - Visual (3D points, features, shape, silhouette)
  - Tactile (contact points)
  - Force Torque (object mass)
- State \( X = \{G_{KV}, G_{PO}\} \)

\( G_{KV} \): Kinematic wrist to wrist in visual frame

\( G_{PO} \): Palm to Object

P. Hebert. Combined Shape, Appearance and Silhouette for Simultaneous Manipulator and Object Tracking. ICRA 2012
TODAY 11:45-12:00 Room 3
• World modeling (robot + objects), using Spatial Operator Algebra (SOA) models
  A. Jain, et al. *Minimal Coordinate Formulation of Contact Dynamics in Operational Space*. RSS 2012 (To Appear).

• Real-time estimation of object & arm pose conditioned on object models.

• Model-predictive trajectory planner for a 15-DOF robotic torso
  • Sampling in a lower DOF space of synchronized parameterized actions with bounded velocity constraints
  • Resulting motions are naturally continuous in velocity and do not require post-processing (smoothing).
  • Computationally efficient, parallelizable sampling methods.
Model-Predictive Trajectory Planner

**Grasping:** free-space or behavior-based for fully and partially known geometry

**View planning:** minimize occlusions for arm tracking

**Interaction:** sequences of deliberate motion into objects and environment for localization
Behavior Based Grasping (90+% of grasps)

“grounding grasp”

“table grasp”
Generalized Compliant Motion (GCM)

4 Task Frame Feedback Behaviors (Concurrent, Super-positioning) for all actions:
- Force-Torque Regularization
- Estimated Kinematic Wrist to Visual Wrist Feedback / Visual Tracking
- Dither additive disturbance
- Kinematic limit avoidance

2 Finger Behaviors
- Strain Regularization
- Pause on contact
System / Control Framework

Pickup Ball → \{Move above ball, touch table, touch ball, close fingers\}

Touch Table→ \{Cartesian trajectory + force control behavior\}
ARM-S Phase 1: Grasping Tasks

- Ball
- Shovel
- Novel Hammer
- Maglite
- Novel Rock
- Hammer
- Floodlight
- Rock
- Case
- Screwdriver
- Radio
- Novel Screwdriver
ARM-S Phase 1: Manipulation Tasks

- Open Door
- Staple
- Flashlight
- Unlock Door
- Hang Up Phone
- Drill
<table>
<thead>
<tr>
<th></th>
<th>Successes (out of 72)</th>
<th>Grasping (out of 48)</th>
<th>Manipulation (out of 24)</th>
<th>Average Time (seconds)</th>
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<tbody>
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<td>67</td>
<td>47</td>
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<tr>
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<td>151.8</td>
</tr>
</tbody>
</table>

JPL is “Team A”

Achieved with: Estimator/Model Based interactive manipulation
Questions?

For more info:

P. Hebert. *Combined Shape, Appearance and Silhouette for Simultaneous Manipulator and Object Tracking*. ICRA 2012

**TODAY 11:45-12:00 Room 3**

T. Allen. *Two-Fingered Caging of Polygons Via Contact-Space Graph Search*. ICRA 2012

**Thursday 11:30-11:45 Room 2**

ICRA May 16th 2012