Evaluating Grasping Performance in “Unstructured” Tasks

Aaron M. Dollar
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Performance Evaluation of Hands

• Oliver: “Need to get the human out of the loop in evaluation”

• One step further: Need to decouple as many subsystems as possible in evaluation
  – E.g. sensing/perception and control schemes (and human) don’t affect results
  – Easier to do in analysis/simulation, harder to do in experimental evaluation
Performance Evaluation of Hands

• Some high-level (experimental) approaches:
  – “open loop” testing scenarios
    • Can do this with adaptive hands!
  – Use robot arm where possible
    • Make scenario more like the real thing rather than benchtop testing
  – Wide variation of object and hand/object interaction properties
Performance Evaluation of Hands

• Object properties
  – What range of size, shape, weight, etc. can be accommodated?
Performance Evaluation of Hands

• Hand-object interaction properties
  – Position/orientation of the object relative to the hand
  – Force applied to the object
    • During reaching/hand closing
    • After grasp
Overview

• Ways that we’ve examined performance
  – Simulated Error
  – Contact/Disturbance Force
  – Pullout Force
  – Standard Objects and Tasks
  – Comparison to Human Performance
Overview

• Ways that we’ve examined performance
  – Simulated Error
  – Contact/Disturbance Force
  – Pullout Force
  – Standard Objects and Tasks
  – Comparison to Human Performance

• Many of these have been used before/frequently by others.
  - Apologies in advance for the lack of “thoroughness”, especially in terms of citations
Evaluation Approach 1: Simulated Error
Simulated Error

- Basic idea:
  - Arrange object in a known position/orientation that would generally not be attempted under no error
  - E.g. place off-center

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Grasp Space

Robot
Simulated Error

• Basic idea:
  – Arrange object in a known position/orientation that would generally not be attempted under no error
    • E.g. place off-center
  – Examine range of positions/orientations over which the object can be successfully grasped
  – Do with a wide range of objects
Simulation Results

Object location (distance from hand center)

Torque Ratio $\frac{\tau}{k_r}$

Small Object $r/l=0.1$

Grasp fails

Large Object $r/l=0.9$

Contact Force $F_{ru}/k_l$

Dollar and Howe, IJRR 2010
Simulated Error - Experimental

• For experiments: decouple subsystems:
  – Get the human out of the loop
    • No teleop, placing objects in the hand, etc.
  – Do “open loop” testing
    • Place the object in a known location/orientation
    • Command the arm to go to a “wrong” position/orientation
    • Actuate/control hand open-loop
  – Examine range of success (objects, positions, etc.)
SDM Hand Performance Results

- Experimental testing of SDM hand:
  - Range of objects that could be grasped (O.C.)
  - How far from “center” could they be grasped (E.C.)
  - How much disturbance force applied during reach and grasp (O.C.+E.C.)
Analysis of Results

• Assume a normal distribution \( z \) of object position from expected position
  
  – Low \( \sigma \) for good sensing
  – High \( \sigma \) for poor sensing

\[
z(x, x_t, \sigma) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(x-x_t)^2}{2\sigma^2}}
\]

\[
p(x, x_t, \sigma) = \int_{-\infty}^{x} z(x')dx'
\]

Dollar and Howe, IJRR 2010
Evaluation Approach 2: Contact/Disturbance Force
Experiments

- Objects mounted to force/torque sensor
- Measure net contact force on object
  - Would tend to disturb objects
SDM Hand Performance Results

- Experimental testing of SDM hand:
  - Range of objects that could be grasped (O.C.)
  - How far from “center” could they be grasped (E.C.)
  - How much disturbance force applied during reach and grasp (O.C.+E.C.)
## “Objects of Daily Living”

### TABLE III

<table>
<thead>
<tr>
<th>Object</th>
<th>Categories</th>
<th>Source(s)</th>
<th>Mass (g)</th>
<th>Dims. (cm)</th>
<th>Veneer</th>
<th>Granite</th>
<th>Linoleum</th>
</tr>
</thead>
<tbody>
<tr>
<td>bag of coffee beans, paper</td>
<td>D1, P1</td>
<td>[36]</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>baking pan (non-stick metal)</td>
<td>D1, P1, D2</td>
<td>[34]</td>
<td>351.9</td>
<td>21x11x8</td>
<td>0.105±0.006</td>
<td>0.139±0.013</td>
<td>0.069±0.007</td>
</tr>
<tr>
<td>bottle cap, metal</td>
<td>D1, P1, D2</td>
<td>[24, 31]</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>bowl, glass</td>
<td>D1, P1, D2</td>
<td>[28, 31]</td>
<td>545.1</td>
<td>18x8</td>
<td>0.223±0.009</td>
<td>0.124±0.006</td>
<td>0.163±0.003</td>
</tr>
<tr>
<td>box of crackers, cardboard</td>
<td>D1, P1</td>
<td>[37]</td>
<td>194.6</td>
<td>6x13x20</td>
<td>0.536±0.015</td>
<td>0.702±0.015</td>
<td>0.514±0.005</td>
</tr>
<tr>
<td>eating utensil, stainless steel</td>
<td>D1, P1, D2</td>
<td>*most sources</td>
<td>47.6</td>
<td>18x4x1</td>
<td>0.206±0.023</td>
<td>0.124±0.006</td>
<td>0.134±0.007</td>
</tr>
<tr>
<td>can of preserved food, steel</td>
<td>D1, P1</td>
<td></td>
<td>473.9</td>
<td>7x11</td>
<td>0.363±0.005</td>
<td>0.219±0.012</td>
<td>0.207±0.010</td>
</tr>
<tr>
<td>bowl, ceramic</td>
<td>D1, P1, D2</td>
<td>[28, 31]</td>
<td>479.3</td>
<td>13x8</td>
<td>0.236±0.006</td>
<td>0.111±0.009</td>
<td>0.266±0.011</td>
</tr>
<tr>
<td>juice carton (empty), paper</td>
<td>D1, P1, D2</td>
<td>[34]</td>
<td>74.5</td>
<td>10x10x24</td>
<td>0.257±0.011</td>
<td>0.303±0.040</td>
<td>0.252±0.013</td>
</tr>
<tr>
<td>coffee can (full), tin</td>
<td>D1, P1</td>
<td>[24]</td>
<td>397.4</td>
<td>10x18</td>
<td>0.329±0.016</td>
<td>0.163±0.008</td>
<td>0.219±0.016</td>
</tr>
<tr>
<td>dinner plate, ceramic</td>
<td>D1, P1, D2</td>
<td>[28]</td>
<td>798</td>
<td>27x3</td>
<td>0.350±0.011</td>
<td>0.222±0.004</td>
<td>0.349±0.011</td>
</tr>
<tr>
<td>drinking straw, plastic</td>
<td>D1, P1</td>
<td>[28]</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>beverage bottle, glass (empty)</td>
<td>D1, P1</td>
<td>[31, 32, 36]</td>
<td>213.7</td>
<td>6x24</td>
<td>0.325±0.030</td>
<td>0.171±0.020</td>
<td>0.168±0.018</td>
</tr>
<tr>
<td>beverage bottle, glass (full)</td>
<td>D1, P1</td>
<td>[31, 32, 36]</td>
<td>597.1</td>
<td>6x24</td>
<td>0.307±0.008</td>
<td>0.182±0.010</td>
<td>0.150±0.009</td>
</tr>
<tr>
<td>jar, glass</td>
<td>D1, P1, D2</td>
<td>[25, 34]</td>
<td>289</td>
<td>7x16</td>
<td>0.173±0.010</td>
<td>0.113±0.008</td>
<td>0.184±0.012</td>
</tr>
<tr>
<td>jar lid, steel</td>
<td>D1, P1, D2</td>
<td>[25, 30, 34]</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>
Properties of ODLs

• For frictional properties, need to specify both object and surface properties

• Tested objects on common household surfaces
  – wood veneer, granite, polished metal, linoleum, unfinished wood, glass
Frictional properties test setup
Frictional properties results

![Bar graph showing instances of coefficient of static friction]

- X-axis: Coefficient of Static Friction
- Y-axis: Instances
SDM Hand Performance Results

• Experimental testing of SDM hand:
  – Range of objects that could be grasped (O.C.)
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  – How much disturbance force applied during reach and grasp (O.C.+E.C.)

How much disturbance force is too much?
Frictional properties results

- 50% of objects \( \rightarrow \) 0.463 N or less
- 75% of objects \( \rightarrow \) 0.116 N or less
- 90% of objects \( \rightarrow \) 0.051 N or less
Frictional properties results

- 50% of objects → 0.463 N or less
- 75% of objects → 0.116 N or less
- 90% of objects → 0.051 N or less

During reach/grasp, ~0.05N of contact force will move 90% of common objects, potentially causing grasp to fail.
Evaluation Approach 3: Pullout Force

(see Joe Falco’s talk)
Evaluation Approach 4: Standard Objects and Tasks
YCB
Object and Model Set
Benchmarking in Manipulation Research

Prof. Aaron Dollar
Dr. Berk Calli
Yale University

Prof. Sidd Srinivasa
Aaron Walsman
Carnegie Mellon Univ.

Prof. Pieter Abbeel
Arjun Singh
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Arjun Singh
Univ. of California, Berkeley

Kurt Konolige, James Bruce, Naresh Rajkumar
Project Overview

• Set of Real Physical Objects distributed to large number of research groups (~100 so far)
• Hi-Res RGBD scans and geometric models
• Task and Benchmark Protocols for standardized procedures
How can we quantitatively compare approaches in manipulation research?

- Simulation (good start, but finite value due to lack of realism)
- Experiment

Experimental validation is generally done in an *ad hoc* way

- Objects and tasks are not standard
- Incomplete detail (for replicability) is generally given
- Procedures are not generalizable across platforms

→ Very few accepted benchmarking procedures
Our Approach

• Physical objects widely distributed/available
  – *has been a hurdle limiting previous attempts
  – Available for purchase at cost
    • Free distribution of initial 50 kits
• Sufficient data provided for using the objects
  – Physical properties, RGBD scans, and geometric models
• Detailed task protocols and benchmarking procedures
  – Allow replicable procedures and quantification of performance
  – Give framework and samples, have community contribute/update

*much of this will be an evolving effort with community feedback and interaction
YCB Object Selection Priorities

• Variety:
  – Physical properties: shape, size, deformability, and texture.
  – Grasping and manipulation difficulty: simple geometric shapes (e.g. boxes and spheres) vs. higher shape complexity (e.g. spring clamps, spatula, banana, toys)

• Use: Range of manipulation tasks
  – Simple grasping
  – Common tasks (e.g. pitcher/cup, hammer/nails)
  – Complex assemblies (e.g. toy airplane)
  – Standardized tests (e.g. box and blocks, 9-hole peg)
YCB Object Selection Priorities

• Durability:
  – Avoid objects that are fragile or perishable.
  – To increase longevity, choose objects that are likely to remain in circulation and change little over time.

• Cost:
  – Keep as low as possible to broaden accessibility
    • Commercial items only (i.e. no custom fabrication)

• Portability:
  – Fit in single box within airline size/weight limits
Food Items
Kitchen Items
Tool Items
Shape Items
Manipulation Tests
Assembly objects
Other YCB Features

• (very) Hi-Res RGB-D scans of the objects
  – Meshes and mesh code available
• Object size/mass properties
• Templates/Instructions for developing detailed task and reporting specifications
  – *Really* need more community involvement in this aspect
How to get it

• www.ycbbenchmarks.org
• Purchase orders via website
  – Object cost + shipping for research labs (~$500)
• Data files (very large) through Amazon
Evaluation Approach 5: Comparison to Human Capabilities
Comparison to Human Performance

• Basic Idea: *Quantify* human hand usage and function
• Compare robot performance to it
The Yale Human Grasping Dataset

Ian M. Bullock, Thomas Feix, and Aaron M. Dollar
Project Overview

• Subjects wore head-mounted camera
• Recorded and analyzed ~8 hours of dense grasping using per subject
• 4 subjects: 2 Housekeepers, 2 Machinists
Project Overview

• ~32,000 (?) unique grasps total analyzed
  – Coded manually by trained raters
  – Took a few years ;)
• Recorded:
  – Grasp type
  – Object properties
  – Task type
  – Time duration
Project Overview

• Dataset includes:
  – Video files
  – Video stills for each grasp
  – Lots of coded data for each:
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Video</td>
<td>Number of the video file</td>
<td>Video number from 1-179</td>
</tr>
<tr>
<td>Time Stamp</td>
<td>Time stamp of the grasp in the video file</td>
<td>Video timestamp in hh:mm:ss format</td>
</tr>
<tr>
<td>Duration</td>
<td>Length of the grasp instance</td>
<td>Duration in seconds</td>
</tr>
<tr>
<td>Subject</td>
<td>Participant profession and number</td>
<td>Machinist 1/2, Housekeeper 1/2</td>
</tr>
<tr>
<td>BlackRatio</td>
<td>Proportion of instance blacked out for privacy</td>
<td>Ratio between 0 (all visible) and 1 (all black)</td>
</tr>
<tr>
<td>Grasp</td>
<td>The grasp type according to (Feix et al. 2009)</td>
<td>no grasp, one of 33 grasp types</td>
</tr>
<tr>
<td>OppType</td>
<td>Opposition type of the grasp (Mackenzie &amp; Iberall 1994)</td>
<td>Pad, Palm, Side, NG</td>
</tr>
<tr>
<td>PIP</td>
<td>Power, intermediate or precision grasp</td>
<td>Power, Intermediate, Precision, NG</td>
</tr>
<tr>
<td>Object</td>
<td>High level object name</td>
<td>no object, object name</td>
</tr>
<tr>
<td>A</td>
<td>Longest object dimension</td>
<td>Length in cm</td>
</tr>
<tr>
<td>B</td>
<td>Intermediate object dimension</td>
<td>Length in cm</td>
</tr>
<tr>
<td>C</td>
<td>Shortest object dimension</td>
<td>Length in cm</td>
</tr>
<tr>
<td>Grasped Dimension</td>
<td>Dimension along which object is grasped</td>
<td>a/b, a/b/c, b, c, b/c, floppy, CCObj, NG</td>
</tr>
<tr>
<td>Rigidity</td>
<td>Rigidity of the object</td>
<td>rigid, fragile, squeezable, floppy, CCObj, NG</td>
</tr>
<tr>
<td>Roundness</td>
<td>Dimensions along which object is round</td>
<td>a, c, non-round, floppy, CCObj, NG</td>
</tr>
<tr>
<td>Mass</td>
<td>Mass of the object</td>
<td>Value in g</td>
</tr>
<tr>
<td>CCObj</td>
<td>True (1) if Cannot Classify Object (see Section 3)</td>
<td>0, 1, NG</td>
</tr>
<tr>
<td>Shape</td>
<td>Basic shape class, according to (Zingg 1935)</td>
<td>equant, oblate, prolate, bladed, CCObj, NG</td>
</tr>
<tr>
<td>Type</td>
<td>Object type, as defined in (Feix et al. 2013b)</td>
<td>11 object types, CCObj, NG</td>
</tr>
<tr>
<td>Task</td>
<td>High level task name</td>
<td>no task, brief task description</td>
</tr>
<tr>
<td>Force</td>
<td>Type of forces required for task</td>
<td>weight, interaction, CCTask, NG</td>
</tr>
<tr>
<td>Constraint</td>
<td>Constraints of the task</td>
<td>11 constraint types, CCTask, NG</td>
</tr>
<tr>
<td>Class</td>
<td>Function class of the task</td>
<td>hold, feel, use, CCTask, NG</td>
</tr>
<tr>
<td>CCTask</td>
<td>True (1) if Cannot Classify Task (see Section 3)</td>
<td>0, 1, NG</td>
</tr>
</tbody>
</table>

NG = No Grasp, CCTask/CCObj = Cannot Classify
URL

https://www.eng.yale.edu/grablab/humangrasping/
Human Precision Manipulation

• Examine human subjects’ ability to manipulate an object grasped in the fingertips
  – Various sizes of objects
  – 2-5 fingers in contact with the object

• Record position and orientation workspace of the object
  – Trakstar sensors
  – Screen-based feedback
Human Precision Manipulation

• Measuring workspace of fingertip-based manipulation
Human Precision Manipulation

• Workspace volume is one possible quantification for comparing performance
  – 2-finger case:
    • 68% of points within 1.05 cm of the centroid and 95% within 2.31 cm
  – 3-finger case:
    • 68% of points within 0.94 cm of the centroid and 95% of points within 2.19 cm
Human Precision Manipulation

- PCA to find major axis
- Major axis direction is significant, others not
  - ~axisymmetric

Bullock et. Al, TOH 2015
Questions/Comments?