Data-Driven Grasping and Manipulation

Nancy S. Pollard
Carnegie Mellon University

with Lillian Chang, Lily Fu, and Ying Li
Motivation

Why do people choose to grasp and manipulate objects in the way that they do, rather than some other way?

How can we teach similar skills to robots or animated characters?
Motivation

rotation not permitted

rotation permitted
Motivation

Why do people choose to grasp and manipulate objects in the way that they do, rather than some other way?

How can we teach similar skills to robots or animated characters?
Motivation

where should the hands be placed to mimic the example?
Motivation

Why do people choose to grasp and manipulate objects in the way that they do, rather than some other way?

How can we teach similar skills to robots or animated characters?

Problem of overimitation

Different perspectives
- Optimal grasps
- Natural appearance
- Practical or minimal strategies
Outline

Example based grasp synthesis
  • transfer forces
  • transfer shape
  • combine force and shape

Prerotation strategies in human subjects

Collecting high quality human hand motion

Revisit motivating questions
  - Why do people choose to grasp and manipulate objects as they do?
  - How can we teach similar skills to robots / animated characters?

Ongoing and future work
Outline

Example based grasp synthesis
  • transfer forces
  • transfer shape
  • combine force and shape

Prerotation strategies in human subjects

Collecting high quality human hand motion

Revisit motivating questions
  - Why do people choose to grasp and manipulate objects as they do?
  - How can we teach similar skills to robots / animated characters?

Ongoing and future work
Grasps as Contacts and Forces
## Grasps as Contacts and Forces – Related Work

### Grasp synthesis
- Li and Sastry ’87
- Nguyen ‘88
- Mirtich and Canny ’94
- Ponce and colleagues ‘93, ‘95, ‘97
- Burdick and colleagues ‘93, ’00
- van der Stappen and colleagues ‘00
- Zhu and colleagues ‘01, ’03

### Caging / Capture
- Trinkle, Abel, and Paul ’88
- Harada and Kaneko ‘98
- Rimon and Blake ‘99
- Gopalakrishnan and Goldberg ’02

### Non-prehensile manipulation
- Mason ’86
- Peshkin and Sanderson ‘88
- Trinkle and Paul ‘90
- Donald, Jennings, and Rus ‘97
- Erdmann ’98
- Lynch and Mason ’99
- Zhang and Goldberg ’02

### Grasp analysis
- Mishra, Schwartz, and Sharir, ’87
- Markenscoff, Ni, and Papadimitriou ’90
- Bicchi ‘95
- Rimon and Burdick ’98

### Survey
- Bicchi ‘00
### Grasps as Contacts and Forces – Related Work

#### Grasp synthesis
- Li and Sastry ’87
- Nguyen ‘88
- Mirtich and Canny ’94
- Ponce and colleagues ‘93, ‘95, ‘97
- Burdick and colleagues ’93, ’00
- van der Stappen and colleagues ‘00
- Zhu and colleagues ‘01, ’03

#### Caging / Capture
- Trinkle, Abel, and Paul ’88
- Harada and Kaneko ‘98
- Rimon and Blake ‘99
- Gopalakrishnan and Goldberg ’02

#### Non-prehensile manipulation
- Mason ’86
- Peshkin and Sanderson ’88
- Trinkle and Paul ’90
- Donald, Jennings, and Rus ‘97
- Erdmann ’98
- Lynch and Mason ’99
- Zhang and Goldberg ‘02

#### Grasp analysis
- Mishra, Schwartz, and Sharir, ’87
- Markenscoff, Ni, and Papadimitriou ’90
- Bicchi ‘95
- Rimon and Burdick ’98

#### Survey
- Bicchi ‘00

*There has been very little research on example based grasp synthesis from this perspective*
Grasps as Contacts and Forces

How should we grasp this object?

Give me a collection of good grasps that match this example

Pollard, PhD thesis, 1994
Quality as “Safety Margin”

Suppose:

- each contact can apply 5 units of force
- 1 unit of force is required to support the object

Example

Safety margin of 10
Q = 10

Alternate grasp

Safety margin of 7
Q = 7

This grasp is 70% as good as the example
One contact in each region

Grasp is at least 90% as good as the example

Computation time: $O(N)$

$N = \#contacts$

Pollard, PhD thesis, 1994

Grasps as Contacts and Forces

50% as good as the example

Grasps as Contacts and Forces
Highlights

We developed a very fast O(N) algorithm for computing contact regions on the surface of an object.

We can make guarantees about the “safety margin” of the resulting grasps.

Resulting grasps tend to look similar to the original example.

Pollard, PhD thesis, 1994
Outline

Example based grasp synthesis
  • transfer forces
  • transfer shape
  • combine force and shape

Prerotation strategies in human subjects

Collecting high quality human hand motion

Revisit motivating questions
  - Why do people choose to grasp and manipulate objects as they do?
  - How can we teach similar skills to robots / animated characters?

Ongoing and future work
Grasps as Hand Shape

Shape is also important
Grasps as Hand Shape

Query Object

Shape Matching

Matches

Hand Pose Database
Grasps as Hand Shape – Related Work

Primitive shapes for procedural grasping / classification
- Napier ‘80
- Cutkosky and Howe ’90
- Rijpkema and Girard ‘91
- Bekey et al. ’93
- Mas Sanso and Thalmann ’94
- Kang and Ikeuchi ‘94, ’95
- Douville, Levison, and Badler ‘96
- Iberall ’97

3D object recognition / model matching
- Prokop and Reeves ’92
- Dorai and Jain ‘97
- Johnson and Hebert ’99
- Mori, Belongie, and Malik ‘01
- Funkhouser and colleagues ’02
- Tangelder and Veltkamp ‘04
- Frome et al. ’04

Linking primitive shape to hand shape and grasp quality
- Miller et al. ‘05
Grasps as Hand Shape – Related Work

Primitive shapes for procedural grasping / classification
- Napier ‘80
- Cutkosky and Howe ‘90
- Rijpkema and Girard ‘91
- Bekey et al. ’93
- Mas Sanso and Thalmann ’94
- Kang and Ikeuchi ‘94, ’95
- Douville, Levison, and Badler ‘96
- Iberall ‘97

Linking primitive shape to hand shape and grasp quality
- Miller et al. ‘05

3D object recognition / model matching
- Prokop and Reeves ’92
- Dorai and Jain ‘97
- Johnson and Hebert ’99
- Mori, Belongie, and Malik ‘01
- Funkhouser and colleagues ’02
- Tangelder and Veltkamp ’04
- Frome et al. ‘04

We use a feature set designed with the knowledge that the configuration of contact forces is very important for grasping.
Results

coke bottle pose:
4 clusters

Highlights

We developed a fast feature matching algorithm to identify possible grasps of an object based on hand shape

Resulting grasps have a natural hand shape

Outline

Example based grasp synthesis
  • transfer forces
  • transfer shape
  • combine force and shape

Prerotation strategies in human subjects

Collecting high quality human hand motion

Revisit motivating questions
  - Why do people choose to grasp and manipulate objects as they do?
  - How can we teach similar skills to robots / animated characters?

Ongoing and future work
Combining Force and Shape

How good is this grasp?

A safety margin computed with an abstract view of forces is not adequate.

Example
Safety margin of 10
Q = 10

Alternate grasp
Safety margin of 7
Q = 7
Combining Force and Shape

Consider maximum muscle forces and tendon moment arms

Compute a safety margin

Results can be used to iteratively optimize grasps, compare grasps against one another, and provide guidance for an interactive grasping system.

Future Plans for this Project

Contact regions w/ safety margin as before

But now accounting for object shape *and hand anatomy*

Regions updated interactively as information is acquired
Example based Grasp Synthesis – Conclusions

A grasp shapes the hand around the object to “comfortably” perform the desired task.

Within this framework, we can “teach” robots or animated characters to grasp and manipulate objects using similar forces and hand shape.
Outline

Example based grasp synthesis
  • transfer forces
  • transfer shape
  • combine force and shape

Prerotation strategies in human subjects

Collecting high quality human hand motion

Revisit motivating questions
  - Why do people choose to grasp and manipulate objects as they do?
  - How can we teach similar skills to robots / animated characters?

Ongoing and future work
A Broader View of Grasping

Grasping is a process
• Small adjustments near and following contact
• Large scale preparation of the object for grasping
Prerotation Strategies
Preparatory Manipulation – Related Work

Characterize grasping process and variation with task
- Jeannerod '81
- Stelmach et al. '94
- Desmurget et al. '96
- Johansson '96
- Li et al. ‘98
- Latash et al. ‘98
- Bongers et al. ‘04
- Rand and Stelmach ‘05

Optimization criteria for static lift
- Dysart and Woldstad ‘96
- Engelbrecht ’97

End grasp comfort
- Fischman ‘98
- Rosenbaum et al. ‘92
Preparatory Manipulation – Related Work

Characterize grasping process and variation with task

Jeannerod ‘81
Stelmach et al. ‘94
Desmurget et al. ‘96
Johansson ‘96
Li et al. ‘98
Latash et al. ‘98
Bongers et al. ‘04
Rand and Stelmach ‘05

Optimization criteria for static lift

Dysart and Woldstad ‘96
Engelbrecht ‘97

End grasp comfort

Fischman ‘98
Rosenbaum et al. ‘92

We have found very little research on strategies for moving the object to adjust it prior to grasping
Experimental Setup

Chang and Pollard, in preparation
Experimental Protocol

Phase I:
8 trials in orientations 1 through 8 – pan
8 trials in orientations 1 through 8 – water jug
instructions: move object from start to goal without spilling any water

Phase II:
2 x 8 trials for the pan, followed by 2 x 8 trials for water jug
instructions: use the right hand only

Phase III:
8 trials for the pan, followed by 8 trials for the water jug
instructions: use the right hand and avoid any sliding of the object

At the end of each Phase, subjects rated all trials for comfort and naturalness

Chang and Pollard, in preparation
Results – Consistent Prerotation

Chang and Pollard, in preparation
Results – Consistent Prerotation

Chang and Pollard, in preparation
Why Prerotate?

Chang and Pollard, in preparation
Poses with Prerotation have Lower Joint Torques

Chang and Pollard, in preparation
Poses with no Prerotation show Variability

Chang and Pollard, in preparation
Poses with no Prerotation show Variability

Chang and Pollard, in preparation
Highlights

We showed that:

• The strategy of prerotation is consistent across subjects and across a certain class of objects

• Prerotation reduces overall joint torque

• Prohibiting prerotation changes the grasp
  ○ a subject’s preferred grasp may be difficult to reach

Chang and Pollard, in preparation
Future Plans for this Project

Use prerotation in robotic manipulation

- to reduce joint torques (and increase loads that can be managed)
- to produce more natural results
- to overcome kinematic limitations
# Outline

**Example based grasp synthesis**
- transfer forces
- transfer shape
- combine force and shape

**Prerotation strategies in human subjects**

**Collecting high quality human hand motion**

**Revisit motivating questions**
- Why do people choose to grasp and manipulate objects as they do?
- How can we teach similar skills to robots / animated characters?

**Ongoing and future work**
Capturing Accurate Hand Motion

Problem: Captured hand motions often do not look realistic

- Extra joint freedoms appearance of “broken joints”
- Fewer joint freedoms difficulty fitting observed data

Substantial manual effort to set up joint parameters (hand skeletal structure) for each new subject
Skeleton Identification from Motion Data

Existing solutions did not handle
- low range of motion
- high noise (e.g., skin slip)
## Skeleton Identification from Motion Data

New algorithms for:

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>- constrained least squares</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>- improved circle fitting</td>
<td></td>
</tr>
</tbody>
</table>

|-----------------|---------------------------------------------------------------------------------------------------------------------------------------------------|
The Thumb Carpometacarpal (CMC) Joint

- 3 joints connect the 4 bones
- 2 main directions of motion

Adduction-Abduction (AA)

Flexion-Extension (FE)

[Netter, 2nd edition, 2001]
The Thumb Carpometacarpal (CMC) Joint

Adduction-Abduction (AA)

Flexion-Extension (FE)
Motion Capture Setup

Problem: Find a model for the thumb CMC joint to best match observed marker motion.

Measure T1, T2, and T3 in the hand frame.

Hand frame H1, H2, H3.
Related Work

Joint modeling
- Cooney et al. ‘81
- Hollister et al. ‘92
- Santos and Valero-Cuevas ‘06

Estimation from isolated thumb movements
- Cheze et al. ‘01
- Cerveri et al. ‘06

Optimization minimizing marker reconstruction error
- Sommer and Miller ‘80
- van den Bogert, Smith, and Nigg ‘94
- Reinbolt et al. ‘05
Related Work

Joint modeling
Cooney et al. ‘81
Hollister et al. ‘92
Santos and Valero-Cuevas ‘06

Estimation from isolated thumb movements
Cheze et al. ‘01
Cerveri et al. ‘06

Optimization minimizing marker reconstruction error
Sommer and Miller ‘80
van den Bogert, Smith, and Nigg ‘94
Reinbolt et al. ‘05

We found the cost functions used in previous work to be inadequate

We also found the optimization routines to have unnecessary complexity
Thumb Carpometacarpal Joint – Parameters

Axis orientations
zh (2D)
zt (2D)

Joint positions
ph (3D)
pt (3D)

Axis separation distance
d (1D)
Thumb Carpometacarpal Joint – Parameters

Free variables (4D)

Axis orientations
zh (2D)
zt (2D)

Joint positions
ph (3D)
pt (3D)

Least squares estimate

Axis separation distance
d (1D)
Thumb Carpometacarpal Joint – Search Problem

**CHOSE** zh, zt

**ESTIMATE** remaining parms

**EVALUATE** cost function

Free variables (4D)

Least squares estimate

Axis orientations
- zh (2D)
- zt (2D)

Joint positions
- ph (3D)
- pt (3D)

Axis separation distance
d (1D)

**CHOOSE** zh, zt

**ESTIMATE** remaining parms

**EVALUATE** cost function
What should we optimize?

Find best joint axes to minimize marker reconstruction error??
An Anatomically Motivated Cost Function

\[ f = \sum_{k=1}^{N} \frac{(\theta_2(k) - \mu_2)^2}{2N \sigma_2^2} + \frac{\text{range}(\theta_3)}{\text{range}(\theta_1)} + \frac{(d - \mu_d)^2}{2\sigma_d^2} \]

minimize twist

maximize ratio of flex/ext to abd/add

reward separation dist. close to expected value
Results

Mean and standard deviation axes for 48 hands (24 subjects)

Compared to a cost function that is not anatomically motivated, we have:

- Lower standard deviation across subjects
- Higher repeatability across trials for the same subject
- A better fit to the subject’s motion (e.g., less twist)
Highlights

We developed an anatomy based cost function that produces highly repeatable reconstructions of a subject’s thumb CMC joint.

Our cost function outperforms current state of the art.

The search space for this optimization is four-dimensional.
Motivation

Why do people choose to grasp and manipulate objects in the way that they do, rather than some other way?

How can we teach similar skills to robots or animated characters?
Conclusions

A grasp is a set of strategies to shape the hand around the object to “comfortably” perform a task.

Within this framework, we can “teach” robots or animated characters to grasp and manipulate objects.
- Using similar forces and hand shape
- Using pre-manipulation strategies to reduce effort or achieve a preferred grasp

We have much to do to understand why people choose to grasp and manipulate objects in the way they do:
- Minimize effort
- Achieve a preferred grasp
- Many other issues will go into answering this question
Ongoing and Future Work

Dynamics and deformation

Sensing

Evaluation and perception
Dynamics and Deformation

Optimization of dynamic motion


Data-driven dynamic grasp controllers

Dynamics and Deformation

Efficient dynamics computation for interactive control of hand motion

Role of hand deformation in grasping

Kim and Pollard, “Interactive User Control of Skeleton Driven Deformable Body Simulation,” in preparation
Evaluation and Perception

Human perception of errors in motion


Evaluation of character capabilities

Naturalness of robot handover behavior
User Perception of Robot-Human Handover

Grasps as Contacts and Forces

We can form an abstract representation of a grasp as a set of contacts and associated forces.
Grasps as Hand Shape

Our features consider distribution of contact normal vectors

Pair-wise distance is not adequate for grasping