Grasping

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Recap

- We’ve talked about how to move robots so they don’t collide
- But how do we get robots to move objects in the world?
  - *Grasping* studies how to stably make contact with objects and move them
- Now we want to collide! (i.e. make contact with objects)
  - But how do we know if a given grasp is *stable* or not?
Outline

- Model & Definitions
- Form Closure
- Force Closure
- Current methods for grasp planning
Towards Dexterous Manipulation

- First robotic hand for dexterous manipulation

  Salisbury hand 1982

- Software for grasp modeling & analysis

  - Models for several robot hands
  - Tools for grasp selection
  - Matlab toolbox
  - Grasp analysis with fully/under-actuated hands
Mathematical Model

- **Model**
  - Predict the behavior of the hand and object under various loading conditions that may arise during grasping
- **Disturbance**
  - Inertia force – e.g. fast motion
  - Applied force – e.g. Gravity
- **Grasp maintenance**
  - No contact separation
  - No unwanted contact sliding
- **Closure grasp**
  - The special class of grasps that can be maintained for every possible disturbing load
Model Simplification

**Real World**
- Complex mechanism
- Soft contacts
- Soft objects
- Bounded force
- Object is free-floating

**Simplified Problem**
- Ignore hand mechanism
- Assume $n$ point contacts
- Assume rigid object
- Assume unlimited force
- Assume object is fixed
Definition

- **Finger** – A point contact
- **Twist**
  - A combination of translational and rotational velocity of the object
    \[ \mathbf{v} = [\mathbf{v}^T \, \mathbf{\omega}^T]^T \]
- **Wrench**
  - A combination of the force and torque applied to the object (at object origin)
    \[ \mathbf{g} = [\mathbf{f}^T \, \mathbf{m}^T]^T \]
- **Wrench space**
  - Space of wrenches applied to the object
    - 3D: 6 dimensional wrench space (3 force, 3 torque)
    - 2D: 3 dimensional wrench space (2 force, 1 torque)
Grasp Kinematics

- Partial Grasp Matrix

- Object twist in world frame \( \{N\} \) $\rightarrow$ Object twist in the contact frame \( \{C\} \)

\[
v_{i,\text{obj}} = \tilde{G}_i^T v_i
\]

where

\[
\tilde{G}_i^T = \overline{R}_i^T P_i^T
\]
Grasp Kinematics

- Partial Hand Jacobian

- Map joint velocities of hand $\Rightarrow$ twist of the hand in $\{N\} \Rightarrow$ twist of hand in $\{C\}$

$$v_{i,hnd} = \tilde{J}_i \dot{q}$$

where

$$\tilde{J}_i = R_i^T Z_i.$$
Definition

- Kinematics

\[ \nu_{c,\text{obj}} = \tilde{G}^T \nu , \quad \text{where} \quad \tilde{G}^T = \begin{pmatrix} \tilde{G}_1^T \\ \vdots \\ \tilde{G}_{nc}^T \end{pmatrix} , \quad \tilde{J} = \begin{pmatrix} \tilde{J}_1 \\ \vdots \\ \tilde{J}_{nc} \end{pmatrix} \]

\[ \nu_{c,\text{hnd}} = \tilde{J}q , \]

- Contact

  - Two coincident points – one on the hand, one on the object

\[ H_i(\nu_{i,\text{hnd}} - \nu_{i,\text{obj}}) = 0 . \]

\[ H_i = \begin{bmatrix} H_{iF} & 0 \\ 0 & H_{iM} \end{bmatrix} . \]

- Immobilization

  - A grasp can counter any wrench applied to the object

  - Guarantees the stability of the grasp
Contact Modeling

- Point contact without friction
- Hard-finger
- Soft-finger
Contact Modeling

• Point contact without friction (PwoF)
  • Contact properties
    • Contact patch is small
    • Contact surface is slippery $\rightarrow$ no surface friction
  • Transmitted to the object
    • Normal component of the translational velocity
    • Normal component of the contact force
Contact Modeling

• Hard Finger (HF)

  • Contact properties
    • Small contact patch
    • Large enough surface friction
    { friction force, but no appreciable friction moment }

  • Transmitted to the object
    • All three components of the translational velocity
    • All three components of the contact force
    • No angular velocity or moment
Contact Modeling

- Soft Finger (SF)
  - Contact properties
    - Large enough contact patch
    - Large enough surface friction
    - appreciable friction moment
  - Transmitted to the object
    - All three components of the translational velocity
    - All three components of the contact force
    - Normal component of contact moment
Contact Modeling

• Relative twist at each contact point

\[
\begin{pmatrix}
\tilde{J}_i \\
-\tilde{G}_i^T
\end{pmatrix}
\begin{pmatrix}
\dot{q} \\
v
\end{pmatrix}
= v_{i,\text{hnd}} - v_{i,\text{obj}}
\]

• When object is stably grasped

  • \(H_i(v_{i,\text{hnd}} - v_{i,\text{obj}}) = 0\). where \(H_i = \begin{bmatrix} H_{iF} & 0 \\ 0 & H_{iM} \end{bmatrix}\)

• Kinematic contact constraint equation

  \[
  H(v_{c,\text{hnd}} - v_{c,\text{obj}}) = 0
  \]
  which is

  \[
  (J - G^T) \begin{pmatrix}
  \dot{q} \\
v
  \end{pmatrix} = 0
  \]
  where \(G^T = H\tilde{G}^T \in \mathbb{R}^{n_\lambda \times 6}\)
  \(J = H\tilde{J} \in \mathbb{R}^{n_\lambda \times n_q}\).
Contact Modeling

- **Friction cone**
  - The set of forces that can be applied at a contact point without sliding on the object
  - Friction cone for $i$th contact point is the set
    \[ \mathcal{F}_i = \left\{ (f_{in}, f_{it}, f_{io}) | \sqrt{f_{it}^2 + f_{io}^2} \leq \mu_i f_{in} \right\} \]
    - $f_{in}$ is the force applied normal to the surface
    - $f_{io}$ and $f_{it}$ are the forces applied along the surface

- **Notes**
  - Coulomb friction
  - Depends on coefficient of friction between hand and object ($\mu$)
  - Bigger $\mu$ implies wider friction cone
Grasp Restraint

- Form closure
- Force closure
Form Closure

- Form closure grasp
  - The object cannot move regardless of surface friction

- What does this imply?
  - If the grasping hand has its joints locked, it is impossible to move the object, even infinitesimally
Form closure

- Which of these is in form closure?

- Example – power (enveloping) grasp
  - Palm and finger wrap around the object
You need \textit{at least} $N+1$ contacts to achieve first-order form closure, where $N$ is the number of DOF of the object.

<table>
<thead>
<tr>
<th>Dimension of Object</th>
<th>Minimum Number of Contacts for First-Order Form Closure</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D (3 DOF)</td>
<td>4</td>
</tr>
<tr>
<td>3D (6 DOF)</td>
<td>7</td>
</tr>
</tbody>
</table>

Force Closure

• Definition

  • **Frictional properties** of the object can be used to immobilize the object

• What does it imply?

  • If the grasping hand has its joints locked, stability of this grasp depends on friction between contacts and object ($\mu$)
Form closure VS Force closure

- If a grasp achieves form closure, does it also achieve force closure?
  - First order form closure $\Rightarrow$ form closure
  - Frictionless force closure $\Rightarrow$ force closure
  - First order form closure $=$ Frictionless force closure

- All first-order form closure grasps are also force closure
  - How about second-order form closure?
Force Closure

\[ \mu = 0 \]

Form closure \( \not\rightarrow \) force closure.

\[ \mu > 0 \]

Force closure \( \not\rightarrow \) form closure.
Testing of Force Closure

- Many algorithms exist to test for force closure, here is one:

**Input**: Contact locations

**Output**: Is the grasp in Force-Closure? (Yes or No)

1. Approximate the friction cone at each contact with a set of wrenches
2. Combine wrenches from all cones into a set of points $S$ in wrench space
3. Compute the convex hull of $S$
4. If the origin is inside the convex hull, return YES. If not, return NO.
Testing for Force Closure

- Why does this algorithm work?
  - Hint: the convex hull represents the positive linear combination of all the wrenches
Force Closure

• Which grasp do you think is more sensitive to error in contact position?

![Wrench space](image1)
![Wrench space](image2)

Note: wrench space is 6-dimensional, these are only cartoons

• Yes or no answer isn’t enough to choose between grasps
Force Closure Metrics

- A popular metric
  - Radius of largest hyper-sphere you can fit in convex hull (centered at origin)

- Task-specific metric of Li and Sastry
  - Use task-specific ellipsoid instead of hyper-sphere
Force Closure

- For a 3D object
  - Minimum number of contacts to achieve force closure is 3 (compare to 7 for form closure)
  - Not surprisingly, 3-finger grippers are very popular

Stanford/JPL Hand  Barrett Hand  Robotiq Hand  Schunk SDH Hand
Searching for Force Closure Grasps

- In the 90s
  - Search for a set of $n$ point contacts on the surface of an object, where $n$ is the number of fingers of your hand
- Search is in $2n$ dimensional space (since surface of object is 2-dimensional)
- Disadvantage
  - Ignores hand kinematics $\implies$ probability that these contacts are reachable while obeying hand kinematics is low
  - Search space scales poorly with number of fingers
Searching for Force Closure Grasps

• In the 2000s (Peter Allen et al.):
  • Sample pose of hand relative to object with fingers in a pre-shape
  • Approach object until contact and close the fingers
  • Get contact points between fingers and object
  • Test these contact points for force closure

• Advantages
  • **Search space** is only 6-dimensional (pose of hand) + set of pre-shapes
  • Search can be arranged so hand always approaches parallel to surface of object
Pre-computing Grasp Sets

- Searching for grasps is slow!
  - Especially with dynamics
    (i.e. if you don’t assume object is fixed)

- But, we can **pre-compute** a set of stable grasps for a given object
Pre-computing grasp sets is not new!

5.1 Choosing a grasp

Before attempting a detailed plan of the grasp, Handey examines different classes of candidate grasps and evaluates their feasibility both at the pickup point and the putdown point. A grasp class is characterized by a choice of object surfaces. Within a

Columbia Grasp Database


- Reuse the 3D models from the Princeton Shape Benchmark (PSB)
  - Well known academic dataset of 1,814 models
  - All models resized to “graspable” sizes
  - PSB models were not originally selected with an eye towards robotic grasping
    - Some of the models are not obvious choices for grasping experiments.

- Provide grasps at 4 scales
  - …because grasping is scale dependent
  - .75, 1.0, 1.25 and 1.5 times the size of each model
  - 7,256 3D models in all

*Shilane et al., SMI 2004*
Columbia Grasp Database

- How to compute a grasp given the database?
  - Shape matching, collocating and grasp computing

- Performance
  - 20 seconds, from shape matching to final output
Integrating Grasping and Manipulation Planning

- So far …
  - We only test for collision with obstacles online (ignore them when computing grasp set)
  - We wanted to integrate grasp planning with motion planning (consider obstacles and reachability, too)

Integrating Grasping and Manipulation Planning

- Grasping + Manipulation planning
  - Valid grasp – Grasp quality metric
  - Local information – object, robot kinematics, etc.

- Approach
  1. Pre-compute grasp set offline, get force-closure score
  2. Online, compute 2 scores for each grasp
     - Environment Clearance Score
     - Reachability Score

Integrating Grasping and Manipulation Planning

Grasp Planning Framework

**Precomputation**

1. Parameter Sampling
2. Grasp Policy
3. Force Closure
4. Grasp-scoring Function
5. Validation
   - Collision Checking
   - Inverse Kinematics
6. Planning

**Online Computation**

Manipulator and Object parameters

Grasp Policy

manipulator poses

grasp F-C scores

Grasp Set

ordered grasps

try next grasp if failed

first valid grasp

Arm and Manipulator Trajectory
Computing Environment Clearance Score

- Compute **clearance** from points on object to nearest obstacle
Integrating Grasping and Manipulation Planning

- Combine scores to create grasp ranking

Environment Clearance \* Grasp Quality \* Reachability = Total Score

- Test grasps in order of ranking
  - We showed this is much faster than testing in random order

Integrating Grasping and Manipulation Planning
Grasp Planning in Complex Scenes

- Motivation
  - Integration of grasp and manipulation planning is still limited to a fixed set of grasps
  - Next, we tried searching for grasps online using similar scoring
Grasp Planning in Complex Scenes

- Cost function for optimization

\[ C(HPO, O, E) = \frac{F(HPO, O) + \zeta S(HPO, O)}{X(HPO, E)} \]

- Approximate Collision – \( F(HPO, O) \)
  - Whether the fixed part of the hand will be in collision

- Fit Cost – \( S(HPO, O) \)
  - The error of the fit between the preshape and the object at this HPO

- Contact Safety Cost – \( X(HPO, E) \)
  - The likelihood of the fingers being able to reach the desired contact points without collision – how?
Grasp Planning in Complex Scenes

- Conical Clearance Map (ConCM)
  - To evaluate the cost of contacting the object
Grasp Planning in Complex Scenes

Grasp refinement to avoid interpenetration of the palm


Barrett Hand (7DOF)
Grasp–RRT planner

• Motivation
  • What if the object model is incomplete and/or inaccurate?
    • The pre-computed grasps may not fit well
  • No pre-calculated grasping data → pure online search

• Grasp–RRT planner
  • Build a feasible grasp +
  • Solving IK +
  • Search a collision-free trajectory to the grasping pose
Comparison

Classical approach to planning grasping motions

- Object definition
- Grasp planner
- Grasp selection
- Object position $p_o$
- Object localization
- Robot
- IK-algorithm
- Motion planning (e.g. RRT)
  - Collision-free grasping motion

Grasp-RRT

- Integrated grasp and motion planning
- Object definition
- Robot
- Object localization
- Start $q_{start}$
- Goal $q_{goal}$
- Grasp hypotheses
- Grasp selection
- IK-solving
- Collision-free grasping motion
Grasp–RRT planner

- Grasp-RRT

Grasp–RRT planner

- Determine the approach direction
  - Approach sphere
  - Sampling distribution
Grasp–RRT planner

- Based on the approach direction
  - Compute a virtual target pose
  - Resolve IK and move towards the target pose as far as possible
  - Validate the grasping pose
    - Closing the fingers, determining the contacts and performing grasp wrench space analysis
Grasp–RRT planner

- Compute a target pose