Principles of Robot Autonomy II

Fundamentals of Manipulation – Jeannette Bohg
Today’s itinerary

• Recap
  • Modeling a Grasp
  • Form/Force Closure?
  • Grasp Pipeline

• Grasp Force Optimization

• Manipulation Case Study - Planar Pushing
  • Modeling
  • Model Verification
What is a grasp?

• Restraining an object’s motion through application of forces and torques at a set of contact points
What are good grasp characteristics?

**Grasp Maintenance:**
contact forces applied by the hand are such that they prevent contact separation and unwanted contact sliding

**Closure:**
Grasps that can be maintained for every possible disturbance load
What’s a grasp?

• = set of wrenches that can be achieved

\[ F_o = G_1 f_{c_1} + \cdots + G_k f_{c_k} = \begin{bmatrix} G_1 & \cdots & G_k \end{bmatrix} \begin{bmatrix} f_{c_1} \\ \vdots \\ f_{c_k} \end{bmatrix} \]

\( f_c \in FC \).

• \( G_i = \) wrench basis vectors transformed into single reference coordinate frame

• \( G=[G_1 \ldots G_k] = \) grasp map
  • Transforming all applied forces and torques to achievable wrenches
Grasp Wrench Space

• Convex hull of all the wrenches from the contact points -- total possible range of wrenches that can be applied

• For 3D objects, wrench space is 6D
  • 3D for force, 3D for torque
  • For 2D objects, it’s 3D

\[ \begin{align*} f_x & \quad c_1 \\
\tau_z & \quad c_2 \\
f_y & \quad \text{COM} \end{align*} \]
Form Closure

- Joint angles locked
- Palm fixed in space
- Impossible to move the object even infinitesimally under arbitrary external wrenches
- No wiggle room
- Power grasps, enveloping grasps
Force Closure

Force Closure:
- Grasp can be maintained under any object wrench
- Forces can be applied at the contact points to withstand the external wrench
- Friction forces help balance the wrench
- Fewer contacts needed compared to Form Closure
Both grasps are stable. Which one is better?
Worst Case Scenario

• The point on the wrench hull that is closest to the origin is the weakest point
• Disturbances in the opposite direction are hardest to resist
• Metric $\varepsilon = \text{The radius of the largest ball that can be enclosed in the wrench hull}$
  • Varies from 0 to 1 due to normalization of wrenches
Are these grasps equally good?
How do we generate a grasp?
Grasp Force Optimization

• In force closure, you can **theoretically** resist any wrench

• But what forces do you need to apply at each contact to generate the desired wrench?
Motivating Example

Figure adapted from A Grasping Force Optimization Algorithm for Multiarm Robots With Multifingered Hands. Lipiello et al. Transactions on Robotics. 2013

Fig. 3. Sequence of significant configurations of the bottle and of the forces during task execution with $n = 10$. 
Formalizing the problem

- M contact points at $p^{(i)}$
- $f^{(i)}$ is the contact force applied at contact point
- Local coordinate system where $x, y$ are tangent to surface and $z$ is aligned with surface normal pointing inward

$$\sqrt{f_x^{(i)} f_x^{(i)}} + f_y^{(i)2} \leq \mu_i f_z^{(i)}$$

- or in planar case: $f_x^{(i)} \leq \mu_i f_y^{(i)}$
Friction Cone Constraints

\[
\sqrt{f_x(i)^2 + f_y(i)^2} \leq \mu_i f_z(i)
\]

- or in planar case:  
  \[f_x(i) \leq \mu_i f_y(i)\]

- Second-order cone constraints
  \[
  K_i = \left\{ x \in \mathbb{R}^3 \mid \sqrt{x_1^2 + x_2^2} \leq \mu_i x_3 \right\}, \quad i = 1, \ldots, M
  \]

- Compact notation \( f(i) \in K_i \), \( i = 1, \ldots, M \).
Equilibrium Constraints

Applied forces need to generate a wrench that compensates external wrench.

\[
\sum_{i=1}^{M} T^{(i)} f^{(i)} + f^{\text{ext}} = 0
\]

\[
\sum_{i=1}^{M} P^{(i)} T^{(i)} f^{(i)} + \tau^{\text{ext}} = 0
\]
Other Constraints Constraints

Hardware constraints (max torque, kinematic limits).

\[ f \in C_{\text{other}} \]
Convex Optimization Problem

Second-order cone program because friction cones are quadratic.

Objective function:

\[ F_{\text{max}} = \max \{ \| f^{(1)} \|, \ldots, \| f^{(M)} \| \} \]
\[ = \max_{i=1,\ldots,M} \sqrt{f_x^{(i)^2} + f_y^{(i)^2} + f_z^{(i)^2}} \]

Optimization problem:

\[
\begin{align*}
\text{minimize} & \quad F_{\text{max}} \\
\text{subject to} & \quad f^{(i)} \in K_i, \quad i = 1, \ldots, M \\
& \quad \Phi f + \omega^{\text{ext}} = 0
\end{align*}
\]
Motivating Example

Figure adapted from A Grasping Force Optimization Algorithm for Multiarm Robots With Multifingered Hands. Lipiello et al. Transactions on Robotics. 2013
Manipulation through Contact

Learning Hierarchical Control for Robust In-hand Manipulation

ICRA 2020 Submission
Tingguang Li, Krishnan Srinivasan, Max Q.-H. Meng, Wenzhen Yuan, Jeannette Bohg

Learning Hierarchical Control for Robust In-hand Manipulation. Li et al. ICRA 2020.

Figure adapted from A Grasping Force Optimization Algorithm for Multiarm Robots With Multifingered Hands. Lipiello et al. Transactions on Robotics. 2013

A Data-Efficient Approach to Precise and Controlled Pushing
Hogan et al. CORL 2018.
Case Study – Planar Pushing

Reorient parts
- Mason 1986

Transport large objects
- Meriçli 2015

Push-grasp under clutter
- Dogar 2010

Track object pose
- Koval 2015
Modeling Planar Pushing

**Friction limit surface**: describes friction forces occurring when part slides over support.

When pushed with a wrench within the limit surface: **no motion**.

For **quasi-static pushing**: wrench on the limit surface; object twist normal to limit surface.

Part translates without rotation: friction force magnitude \( \mu mg \)

Relation between wrench cone, limit surface and unit twist sphere. Adopted from Chapter 37, Fig 37.10 in Springer Handbook of Robotics.
Modeling Planar Pushing

\( o \)  position of the object
\( \mathbf{v}_o \)  linear and angular object velocity
\( \mathbf{v}_p \)  linear velocity at the contact point - effective push velocity
\( \mathbf{p} \)  position of the pusher
\( \mathbf{u} \)  linear pusher velocity - action
\( \mathbf{c} \)  contact point (global)
\( \mathbf{c}' \)  contact point relative to \( \mathbf{o} \)
\( \mathbf{n} \)  surface normal at \( \mathbf{c} \)
\( l \)  ratio between maximal torsional and linear friction force
\( \mu \)  friction coefficient pusher-object

\( f_b \)  left or right boundary force of the friction cone
\( m_b \)  torques corresponding to the boundary forces
\( \mathbf{v}_{o,b} \)  object velocities resulting from boundary forces
\( \mathbf{v}_{p,b} \)  effective push velocities corresponding to the boundary forces
\( b = l, r \)  placeholder for left or right boundary
\( s \)  contact indicator, \( s \in [0,1] \)
\( k \)  rotation axis

Fig. 1: Overview and illustration of the terminology for pushing.

Validating Models for Planar Pushing

IROS 2016, "More than a Million Ways to Be Pushed: A High-Fidelity Experimental Dataset of Planar Pushing" by Peter Yu and Maria Bauza.
Validating Models for Planar Pushing

IROS 2016, "More than a Million Ways to Be Pushed: A High-Fidelity Experimental Dataset of Planar Pushing" by Peter Yu and Maria Bauza.
Validating Models for Planar Pushing

More than a Million Ways to Be Pushed.
A High-Fidelity Experimental Dataset of Planar Pushing

Kuan-Ting Yu, Maria Bauza, Nima Fazeli, and Alberto Rodriguez
Computer Science and Artificial Intelligence Lab & Mechanical Engineering Department, MIT

IROS 2016, "More than a Million Ways to Be Pushed: A High-Fidelity Experimental Dataset of Planar Pushing" by Peter Yu and Maria Bauza.
Validating Models for Planar Pushing

IROS 2016, "More than a Million Ways to Be Pushed: A High-Fidelity Experimental Dataset of Planar Pushing" by Peter Yu and Maria Bauza.
Next time

- Learning-based Approaches to
  - Grasping
  - Manipulation