Aalto University
School of Electrical Engineering

ELEC-E8126: Robotic Manipulation
Friction and grasping

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Learning goals

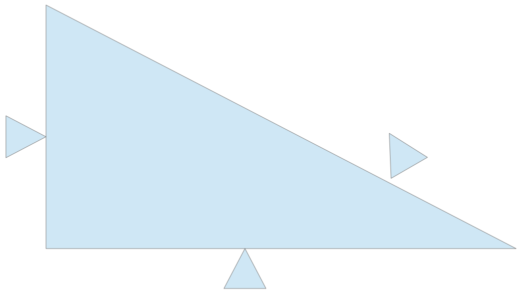
- Understand analytical models of contact with friction.
- Use those to define quality measures for grasps.

Recap: Grasp planning

- Where an object needs to be grasped in order to perform a particular task?
  - Where to place contacts on the object to immobilize it?
  - Or where to place the hand?

Several contacts in plane

- Can the object move? Around which point?
- What about if there's friction?



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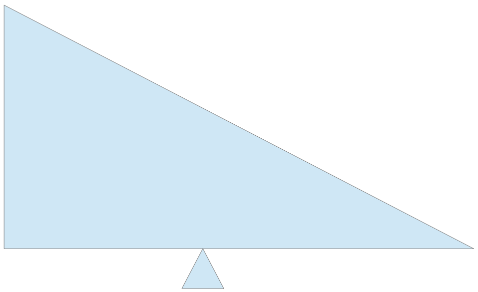
Contact with friction

- What's the range of possible forces caused by the contact?



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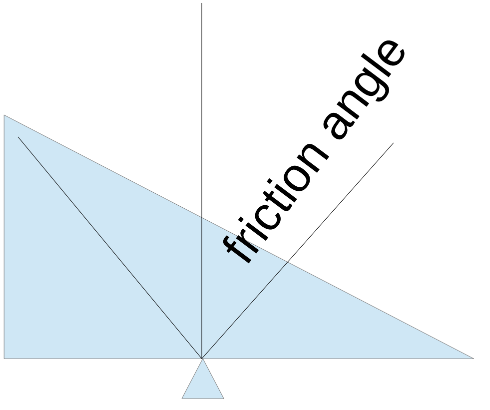
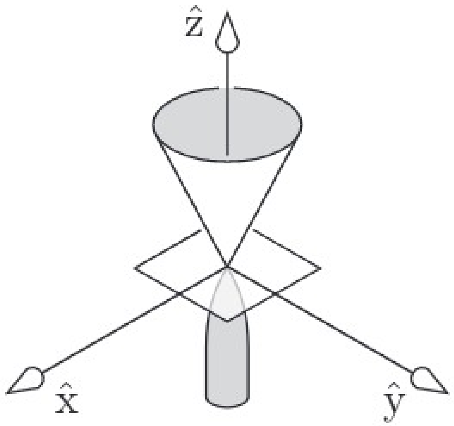
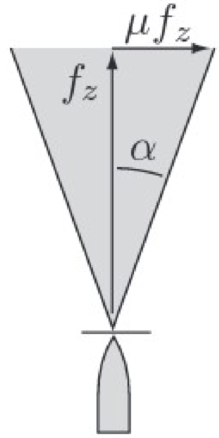


$$\sqrt{f_x^2 + f_y^2} \leq \mu f_z, f_z \geq 0$$

Friction cones





$$\sqrt{f_x^2+f_y^2} \le \mu f_z, f_z \ge 0$$

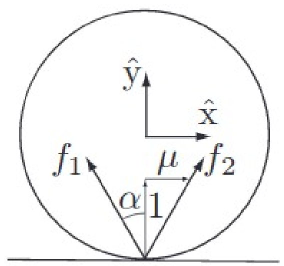
- In 2-D: positive span of edges

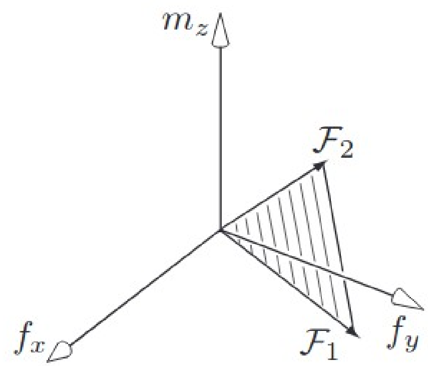
$$FC = \left\{ k_1 \begin{pmatrix} \mu \\ 1 \end{pmatrix} + k_2 \begin{pmatrix} \mu \\ 1 \end{pmatrix} \middle| k_1, k_2 \ge 0 \right\}$$

Wrench cone

contact point　　contact normal

- Remember wrench for single contact $\boldsymbol{F} = (\boldsymbol{p} \times \boldsymbol{n}, \boldsymbol{n})$



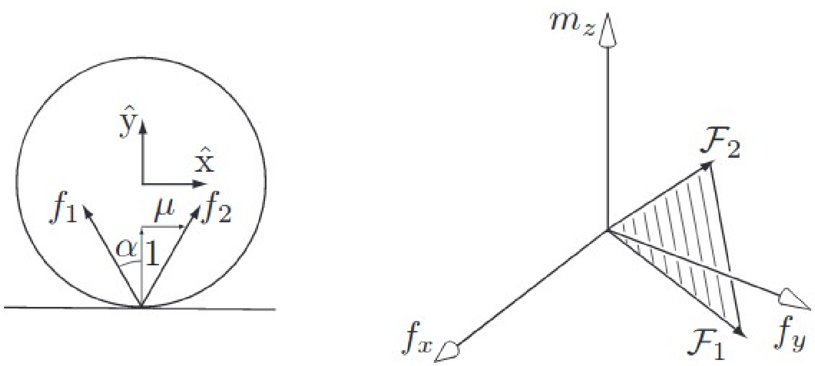


- What's now the wrench cone corresponding to the friction cone $FC = \left\{ k_1 \begin{pmatrix} \mu \\ 1 \end{pmatrix} + k_2 \begin{pmatrix} \mu \\ 1 \end{pmatrix} \middle| k_1, k_2 \geq 0 \right\}$

Wrench cone

contact point → $\boldsymbol{p}$; contact normal → $\boldsymbol{n}$, $\boldsymbol{n}$

- Remember wrench for single contact $\boldsymbol{F} = (\boldsymbol{p} \times \boldsymbol{n}, \boldsymbol{n})$

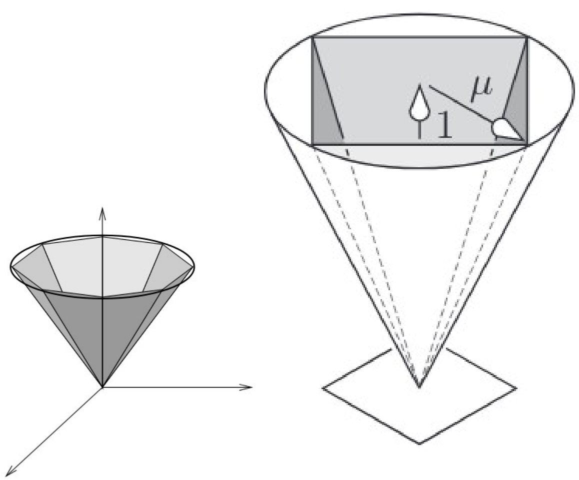


- What's now the wrench cone corresponding to the friction cone $FC = \left\{ k_1 \begin{pmatrix} \mu \\ 1 \end{pmatrix} + k_2 \begin{pmatrix} \mu \\ 1 \end{pmatrix} \middle| k_1, k_2 \geq 0 \right\}$

- Wrench cone $WC = \left\{ k_1 \boldsymbol{F_1} + k_2 \boldsymbol{F_2} \middle| k_1, k_2 \geq 0 \right\}$

3-D: Friction cone approximation

- In 3-D, friction cone is usually approximated, because analytical solution is difficult.
- Conservative polyhedral approximation (different number of basis forces can be used)



$$FC = \left\{ \sum_i k_i \boldsymbol{n}_i \middle| k_i \geq 0 \right\}$$

Example: With 4 basis forces,

$$\boldsymbol{n}_1 = \begin{pmatrix} \mu \\ 0 \\ 1 \end{pmatrix} \quad \boldsymbol{n}_2 = \begin{pmatrix} -\mu \\ 0 \\ 1 \end{pmatrix} \quad \boldsymbol{n}_3 = \begin{pmatrix} 0 \\ \mu \\ 1 \end{pmatrix} \quad \boldsymbol{n}_4 = \begin{pmatrix} 0 \\ -\mu \\ 1 \end{pmatrix}$$

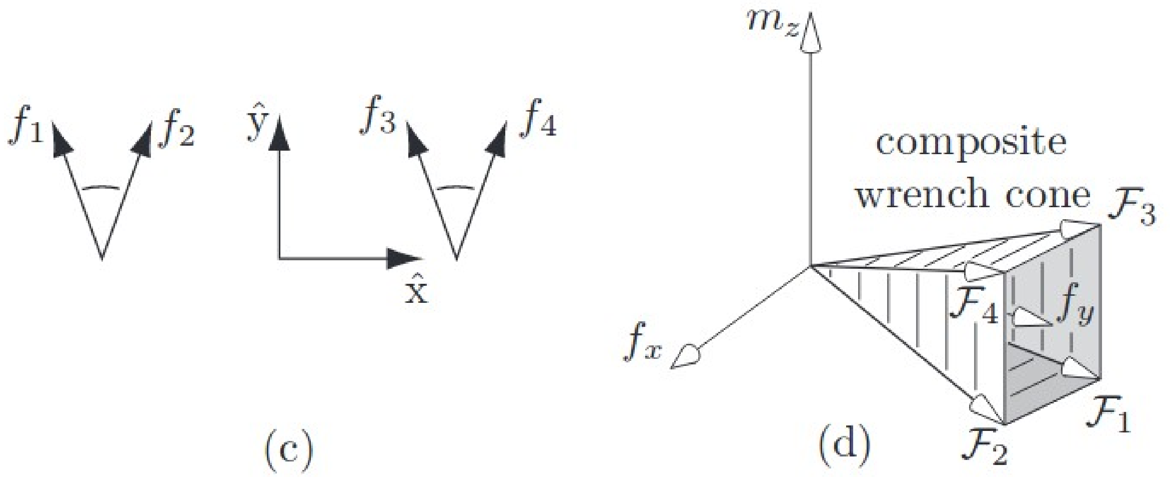
Wrench cone

$$\boldsymbol{F} = (\boldsymbol{p} \times \boldsymbol{n}, \boldsymbol{n})$$

- WC again positive span of individual wrenches

$$WC = \left\{ \sum_i k_i \boldsymbol{F}_{\boldsymbol{i}} \middle| k_i \geq 0 \right\}$$

- Same also across multiple contacts.



Why is F_1 different from F_3 even if f_1 and f_3 seem to be the same?

Force closure

- A grasp is *force closure* if for any external wrench there exist contact wrenches that cancel it.
- In other words, if we apply sufficient force at each contact, any external wrench can be compensated for.

  e.g. gravity, contact with environment

- This is equivalent to first-order form closure.
  - Contact wrenches span positively entire space

$$\left\{ \sum_i k_i \boldsymbol{F}_i \middle| k_i \geq 0 \right\} = R^6$$

- Is there a force closure grasp for any object?

Existence of force closure grasps

- Theorem: For any bounded shape that is not a surface of revolution, a force closure grasp exists (Mishra et al., 1987).

- Any non-exceptional surface requires at least p+1 contacts without friction (wrench space dimension p)
- Any non-exceptional surface can be grasped by choosing at most 2p contacts without friction.

$$p = 3 \text{ (planar)} \implies 4 \le k \le 6$$
$$p = 6 \text{ (spatial)} \implies 7 \le k \le 12.$$

With friction, 3 contacts may be sufficient in 3D.

Determining force closure

- Force-closure is equivalent to
  - Contact wrenches positively span $\mathbb{R}^p$
  - Convex hull of contact wrenches contains a neighborhood of the origin

Consider this without friction:
What are the wrenches?

How about with friction?
Draw to illustrate.

How could you check the convex hull condition?
What are the boundaries of the convex hull?

Grasp quality metrics

Without friction

- Reminder: Contact forces $CF = \left\{ \sum_i k_i \boldsymbol{F}_i \middle| 0 \le k_i \le f_{max} \right\}$

- Approach:
  - Since contact forces at each point not known, normalize wrench basis vectors ***F*** to unit length.
    - First scale moments (torques) by characteristic length of object.
    - Origin at object CoM.
  - Construct convex hull and its supporting hyperplanes.
  - Find shortest distance from origin to any of the hyperplanes.
    - Assumes sum of forces is bounded.

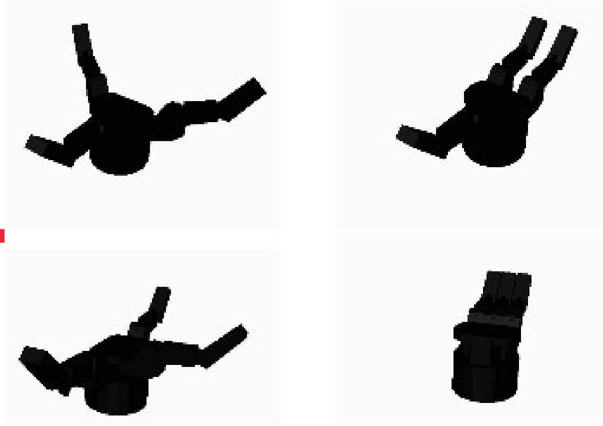
$$CF = \left\{ \sum_i k_i \boldsymbol{F}_i \middle| k_i \ge 0, \sum_i k_1 \le 1 \right\}$$

Ferrari & Canny, 1992

Sampling based grasp planning revisited

- Sampling approach
  - Choose candidate contacts.
  - Evaluate resulting grasp.

- Instead of choosing contact locations, sample location to place *preshaped* hand, and simulate where contacts happen after closing fingers.
  - Preshapes for prototypical grasps, e.g. pinch grasp, power grasp, cylindrical grasp.
  - Miller et al. 2003.



Caveats

- Quality measures are based on assumptions that are not necessarily entirely true.
- Many quality measures (with different assumptions) have been proposed.
  - Address different issues such as minimizing finger forces, contact placement accuracy, hand configuration (manipulability, joint limits), task compatibility.
  - Recent review: Roa & Suarez, "Grasp quality measures: review and performance", 2015.

Summary

- Force closure means that a grasp is able to cancel any external wrench if contact forces are sufficiently high.

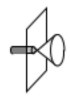
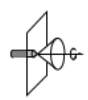
- Grasps can be planned by maximizing grasp quality metrics.

Extra topics

- Soft contacts
- Complex hands
  - Posture subspaces
- Data-driven grasping
  - Grasp databases
  - Grasping as learning problem

Modeling friction of soft fingertips

- Soft fingertips can be modeled with friction “cones” that include torsional friction.

Point contact with friction		$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$	$\sqrt{f_1^2 + f_2^2} \leq \mu f_3$ $f_3 \geq 0$
Soft-finger		$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$	$\sqrt{f_1^2 + f_2^2} \leq \mu f_3$ $f_3 \geq 0$ $\lvert f_4 \rvert \leq \gamma f_3$

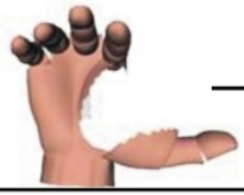
Torsional friction

Ciocarlie & Allen 2009

Grasping and complex hands

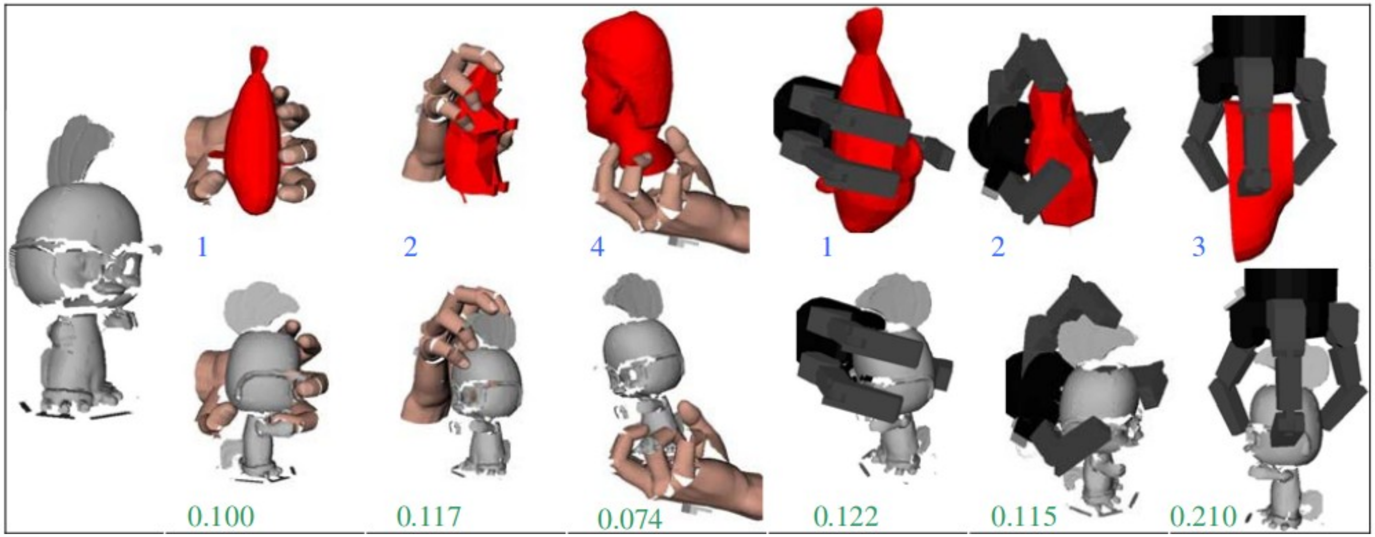
- How to plan with complex hands beyond preshapes?
- Idea: Use low-dimensional posture space.

Correlated joints

Model	DOFs	Eigengrasp 1			Eigengrasp 2		
		Description	min	max	Description	min	max
Barrett	4	Spread angle opening	 →		Finger flexion	 →	
DLR	12	Prox. joints flexion Finger abduction Thumb flexion	 →		Dist. joints flexion Prox. joints extension Thumb flexion	 →	
Robonaut	14	Thumb flexion MCP flexion Index abduction	 →		Thumb flexion MCP extension PIP flexion	 →	
Human	20	Thumb rotation Thumb flexion MCP flexion Index abduction	 →		Thumb flexion MCP extension PIP flexion	 →	

Data-driven grasping for unknown objects

- Idea: Database-driven grasping
  - Pre-compute (as above) grasps for many objects of different sizes and shapes, store in a database.
  - Measure shape of object.
  - Find closest corresponding object (or its part) in database and use its grasps.

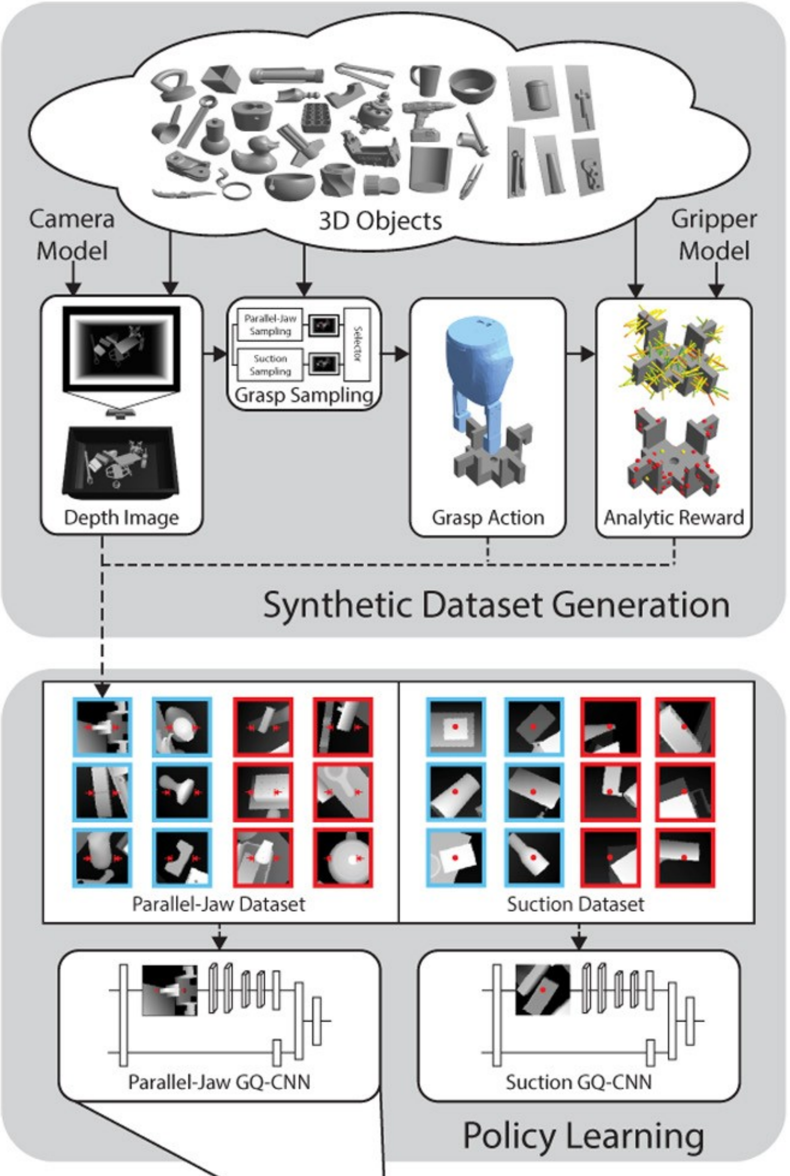


Goldfeder et al. 2009

Grasping as a learning problem

Training from physical trials an option but expensive!

- Optimization of metrics slow and difficult from visual information.
- Idea: Learn mapping from images to grasps.
  - Generate synthetic "good" grasps using existing approaches.
  - Train a neural network to predict grasp success.
- Training data metrics may still limit.



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berkeleyautomation.github.io/dex-net/

Next time: Closed kinematic chains

- Readings:
  - Lynch & Park, Chapter 7-7.1.3