Grasp Planning

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CS 6301 Special Topics:
Introduction to Robot Manipulation and Navigation
Fall 2024
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Outline and Learning Goals

Fundamental aspects of modeling a grasp

- Stability analysis

Overview of analytical contact models + Grasp Quality measures

- How to evaluate a grasp?

Learning-based and Data driven methods

- Review of some recent methods for grasp synthesis


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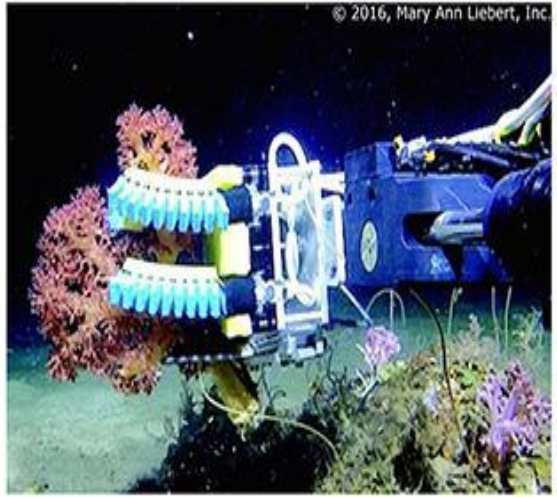
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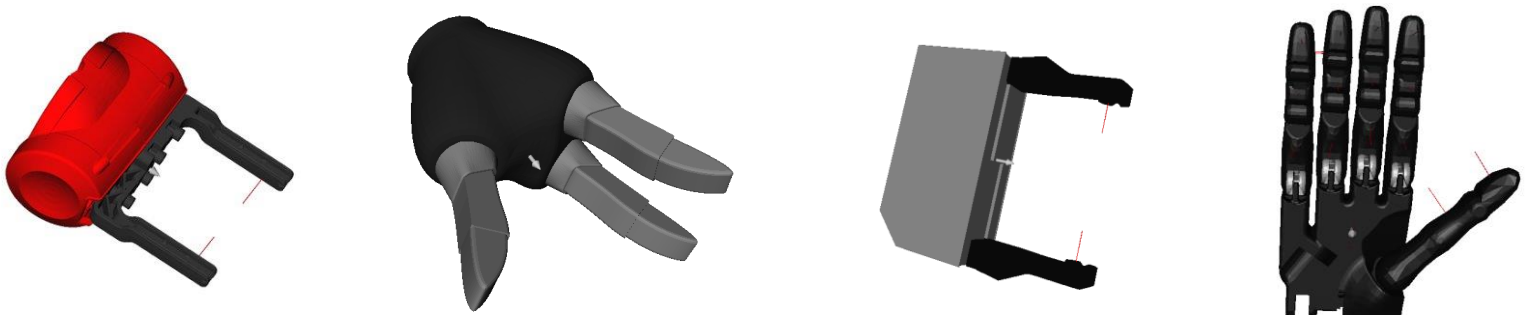
Introduction

Grasping is a part of a broader goal of robot manipulation:

1. Reaching the object: navigation & motion planning
2. Grasping the object:
3. Moving the grasped object: perhaps according some task

Different types of grippers (end effectors) involved: variation along kinematics.



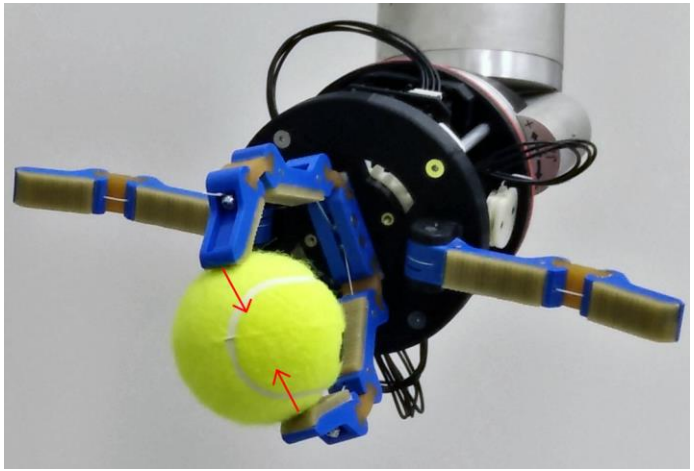
Gripper models loaded in the GraspIt simulator [3]

What does one mean by a Grasp?

- Immobilize the object using the gripper fingers.
- Force/torque applied using the finger to constrain the object's motion

Representation:

- 6D Pose of Gripper Base
- Joint Configuration (e.g. rotation for all finger revolute joints)



Key Questions:

- Where to place the fingers (i.e contact points)
- Is the grasp any good? -- evaluating it.

Challenges

High dimensional problem

- Especially with Multi-fingered grippers
- 6D (Pose) + Joint configuration (2 to N)

Incomplete object observations

Object in a cluttered environment

Feasibility of motion plan

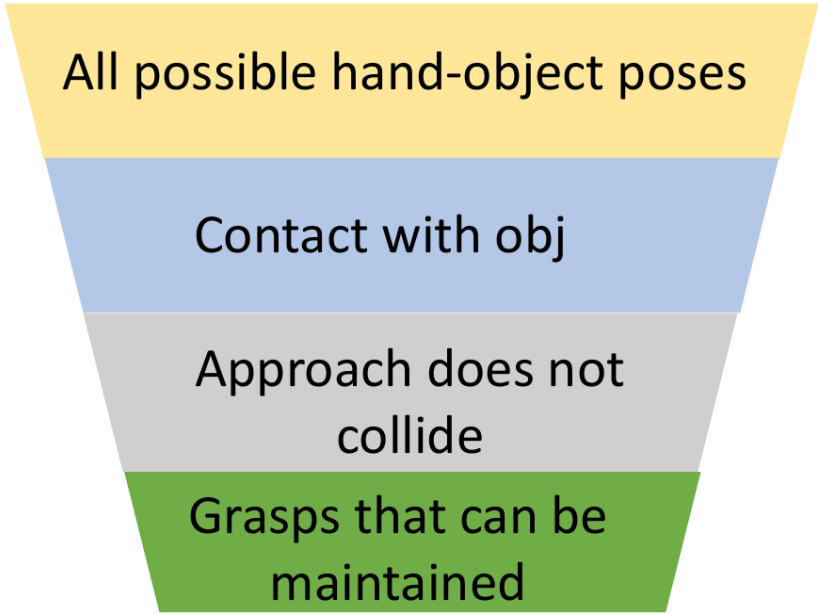
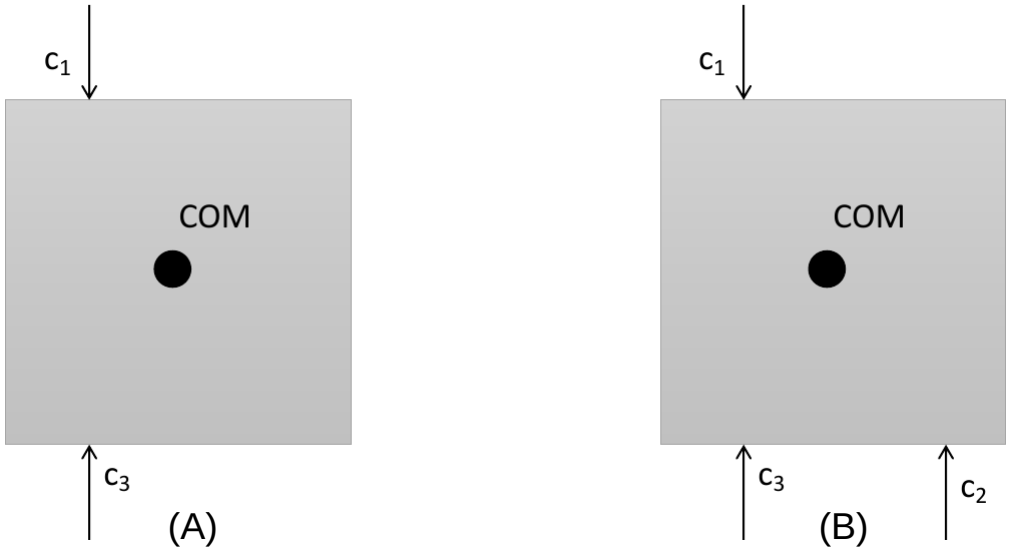


Image Credit: [1]

Grasp Contact Modeling

Goal: restrain object's motion via some force/torque through gripper finger

Simplified example of contacts: Can the object move in case A or B?



Credit: [1]

Grasp Modeling Assumptions

- Rigid Bodies – cannot deform!
- We already know how the grasp looks like:
  - We can apply unlimited force at contact points
  - Contact Type: Point on a Plane
- Presence of friction between object's surface and finger
- Hard-finger contact:
  - Small contact patch (point-based)
  - No moment due to friction, only friction force considered
- Contact points are already known i.e finger locations on object

Start out with modeling a *single* point of contact

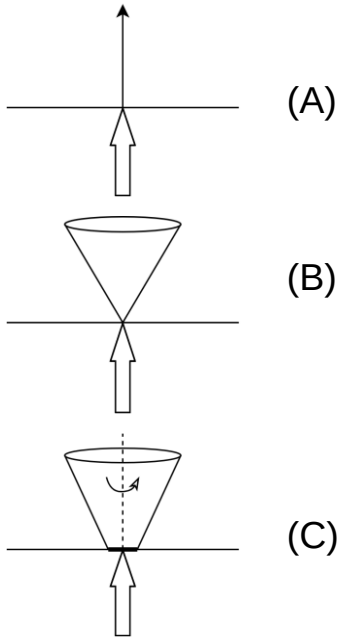
Point Contact Models

Different types of point-plane contact models

A. Frictionless point contact: only normal force

A. Point contact with friction: hard finger

A. Soft-finger: we additionally get a moment due to the friction



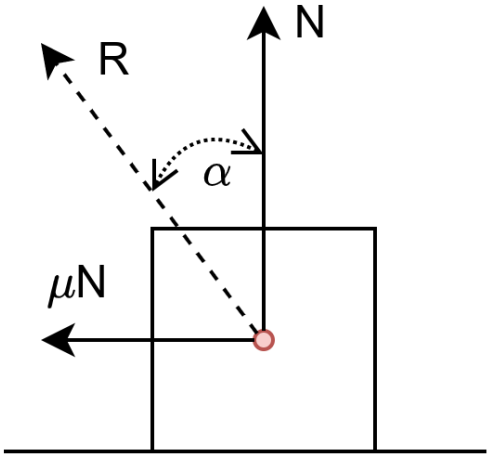
Each model will be encoded into a matrix **G** we will see later

Friction Cone

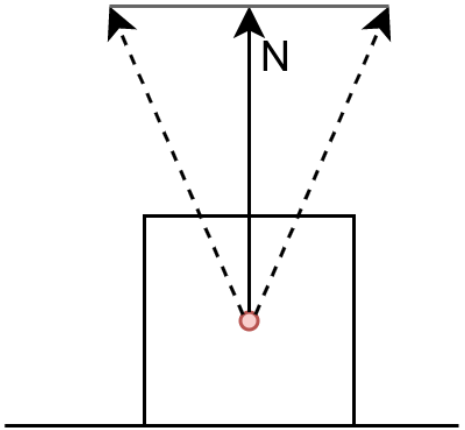
Assume friction on the object's surface with friction coefficient μ

In limiting friction: hence, force from friction Ft <= μ * N

N = Normal force from the surface (shown at COM for convenience)

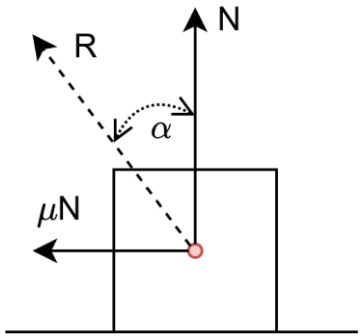


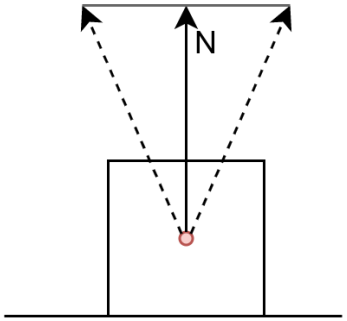
$$\alpha = \tan^{-1}(\mu)$$



Friction Cone

- Due to friction, we not only have normal contact force N, but also some *tangential force*
- Orthogonal to the Normal force vector
- **Alpha**: the maximum angle any resultant force R can make before slipping occurs (**angle of friction**)





The *Cone* is the space of all **valid resultant forces**

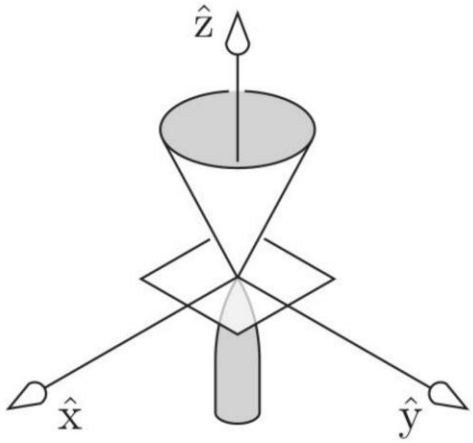
Non-limiting friction => angle will be less than alpha!

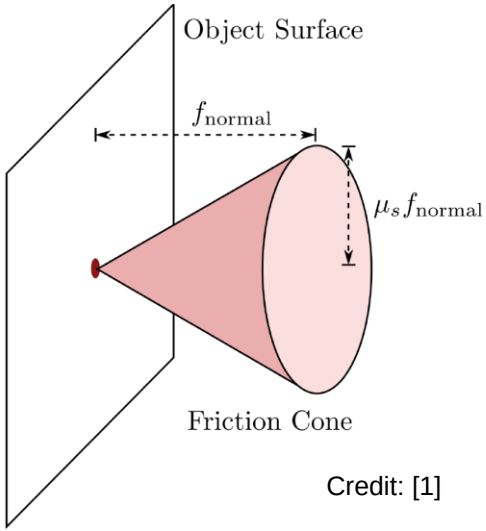
$$\alpha = \tan^{-1}(\mu)$$

Friction Cone in 3D

- Similarly in 3D, we get an actual Cone for the
  - Space of all possible forces from a contact point
- Friction Cone = Set F = { (f_x, f_y, f_z) } satisfying the equation:
  - FC is a **set of vectors! (cone = all valid resultant forces)**
  - **Possibly very large set & hard to enumerate!**

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





Credit: [1]

Approximating the Friction Cone

In practice, we can **approximate the friction cone**

- Use a small set of **m** vectors

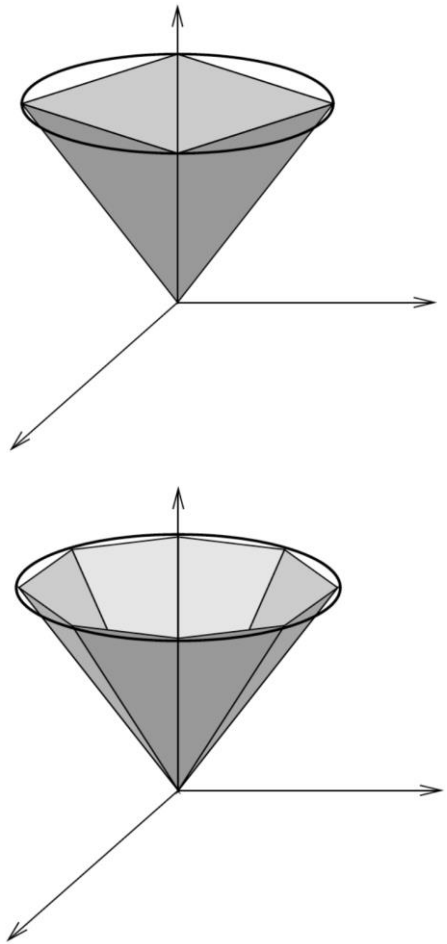
$$f_j \; ; \; j = 1, \ldots, m$$

- Each vector $\mathbf{f_j}$ lies on the cone
- X and Y components ====>
- Assumed that $f_z = 1$ for convenience.

$$f_j^{(x)} = \mu \; \cos(\frac{2\pi j}{m})$$

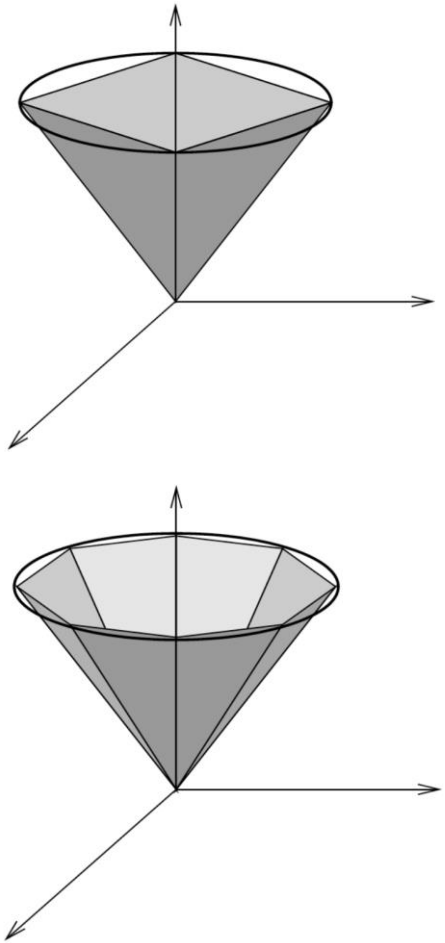
$$f_j^{(y)} = \mu \; \sin(\frac{2\pi j}{m})$$

$$f_j^{(z)} = 1$$



Summary for Friction Cone (FC)

- **Our interest**: modeling forces from contact points
- FC = All possible resultant forces due to friction on the object
- Computing it exactly is not possible ==> So we approximate it using **m** vectors!
  - Break down a force vector into a combination from the m vectors!



Grasp Wrench

- Recall, Wrench = 6D vector for forces + torques acting on a body
- Each contact point applies a wrench on the body
  - For the contact force **f**, there is also a **torque** = **d** X **f** (d = distance to object's center of mass)
  - Note: We analyzed the cone in a *local contact point frame*
- Assume **G** to be a matrix that encodes
  - **Contact model**
  - **Transformation from local contact frame to object centric frame**
- $W_i = G_i * f_i$ (For i-th contact with force f_i)
- Total Wrench = Sum(i=1,..,k) W_i
  - With k contact points

$$w = \sum_{i=1}^{k} G_i f_i$$

Credit: [1]

Grasp Wrench Space (GWS)

Grasp wrench space W: Set of all possible wrenches **w** that can be applied to the object through admissible forces

$$\mathcal{W} := \{\boldsymbol{w} \mid \boldsymbol{w} = \sum_{i=1}^{k} G_i \boldsymbol{f}_i, \quad \boldsymbol{f}_i \in \mathcal{F}_i, \quad i = 1, \ldots, k\}$$

- Note: The space is over all *permissible* force vectors $\mathbf{f_i}$ on each i^{th} contact point
  - i.e. the force vectors f_i lie in the friction cone for that contact point
- Large GWS => Can compensate for bigger set of external forces $\mathcal{F}_i$!
- GWS is 6D for 3D objects and 3D for 2D objects

Credit: [1]

Computing Grasp Wrench Space

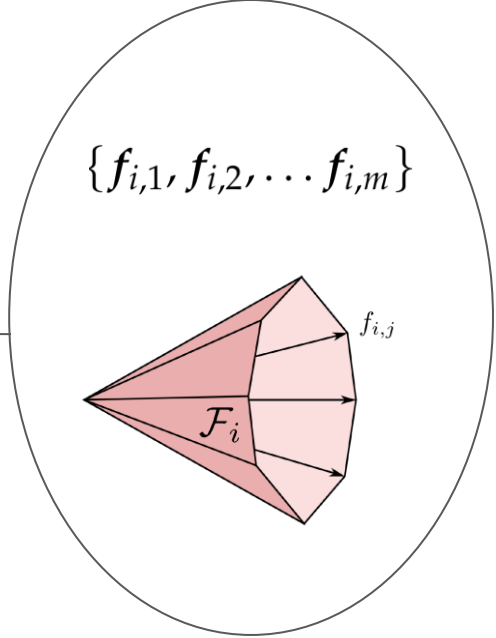
- Computing GWS looks difficult! Many, many combinations!
- Key: Use the *discretized* friction cone
  - Represent **any** force f_i as a **linear, positive combination**

$$\boldsymbol{f}_i = \sum_{j=1}^{m} \alpha_{i,j} \boldsymbol{f}_{i,j}, \quad \alpha_{i,j} \geq 0$$

- Constrain value of each coefficient as we cannot have very large forces in practice!
- If coefs sum bounded by 1 => Cone is approximated by **Convex Hull** of

$$\{\boldsymbol{f}_{i,1}, \boldsymbol{f}_{i,2}, \ldots \boldsymbol{f}_{i,m}\}$$

$$\sum_{j=1}^{m} \alpha_{i,j} \leq 1$$



Credit: [1]

Computing Grasp Wrench Space

Using the approximation to the friction cone, the GWS looks as follows

- K is the number of contact points
- M is the number of forces approximating each friction cone for i^{th} contact

$$\mathcal{W} = \{\boldsymbol{w} \mid \boldsymbol{w} = \sum_{i=1}^{k} \boldsymbol{w}_i, \quad \boldsymbol{w}_i = \sum_{j=1}^{m} \alpha_{i,j} \boldsymbol{w}_{i,j}, \quad \boldsymbol{w}_{i,j} = \begin{bmatrix} \boldsymbol{f}_{i,j} \\ \lambda(\boldsymbol{d}_i \times \boldsymbol{f}_{i,j}) \end{bmatrix}$$

$$\sum_{j=1}^{m} \alpha_{i,j} \leq 1, \quad \alpha_{i,j} \geq 0\}.$$

This is true for **all** i = 1,...,K

Credit: [1]

Recap: Approximations for GWS

K is the number of contact points

M is the number of force approximating each friction cone for i-th contact point

1. Compute the approximate friction cone for *each* contact point
    a. i.e **Convex Hulls for each contact's friction cone**

2. For each i^{th} contact force f_i : break it down using the approximate friction cone vectors: Represent using the coefficients alphas

3. Can use this breakdown in computing GWS – but still difficult to enumerate!
    a. As alpha coefficients have no constraint between them => many many possible combinations!

Credit: [1]

Grasp Wrench Hull (GWH)

Computing the GWS even with the friction cone approximation can be difficult!

Modify the constraint on the coefficients alpha_ij: make it a **convex combination**

Note that sum over the alphas is **now equal to 1** (rather than <= 1)

$$\tilde{\mathcal{W}} = \{\boldsymbol{w} \mid \boldsymbol{w} = \sum_{i=1}^{k}\sum_{j=1}^{m} \alpha_{i,j}\boldsymbol{w}_{i,j}, \quad \boldsymbol{w}_{i,j} = \begin{bmatrix} \boldsymbol{f}_{i,j} \\ \lambda(\boldsymbol{d}_i \times \boldsymbol{f}_{i,j}) \end{bmatrix}, \quad \sum_{i=1}^{k}\sum_{j=1}^{m} \alpha_{i,j} = 1, \quad \alpha_{i,j} \geq 0\}$$

GWH is the Convex Hull of all individual wrenches w_ij (i = contact pt ; j = FC vector at i)

Key point: **GWH is subset of GWS but can be computed!**

Credit: [1]

Grasp Closure: Force & Form

Force Closure Grasp:

- If for any *external* wrench, there exist contact wrenches that can cancel it
- Can resist the external wrench by pushing more firmly.

Form Closure Grasp:

- Object is kinematically constrained and cannot move (even with no application of forces / regardless of surface friction).
- Locked Joint angles for the gripper
- Example: *enveloping an object* -- cannot move in any direction!

Credit: [1]

Force Closure Grasps

To resist any external wrench **w** means cancelling it out via the K contact forces

$$-\boldsymbol{w} = \sum_{i=1}^{k} G_i \boldsymbol{f}_i. \quad \boldsymbol{f}_i \in \mathcal{F}_i, \quad i = 1, \ldots, k$$

Theorem: To resist arbitrary external wrenches, GWS must **contain the origin** in its interior

- Good way to check if a Grasp is in Force Closure or not!
- But need to compute GWS first to check for origin in interior

Credit: [1]

Recap

1. Grasp = K contact points with forces
2. Use *Origin inside interior of GWS* test to check for Force Closure of Grasp
3. GWS is still difficult to compute!
    - But need to compute it to test if origin lies inside or not
4. Compute Grasp Wrench Hull
    - Convex Hull of individual wrenches of friction cone approximating vectors
5. Key point: **GWH is subset of GWS** => Check for presence of origin inside GWH!
6. As GWH <= GWS (subset), If origin inside GWH => origin inside GWS!
    - Note: converse may not be true!

Credit: [1]

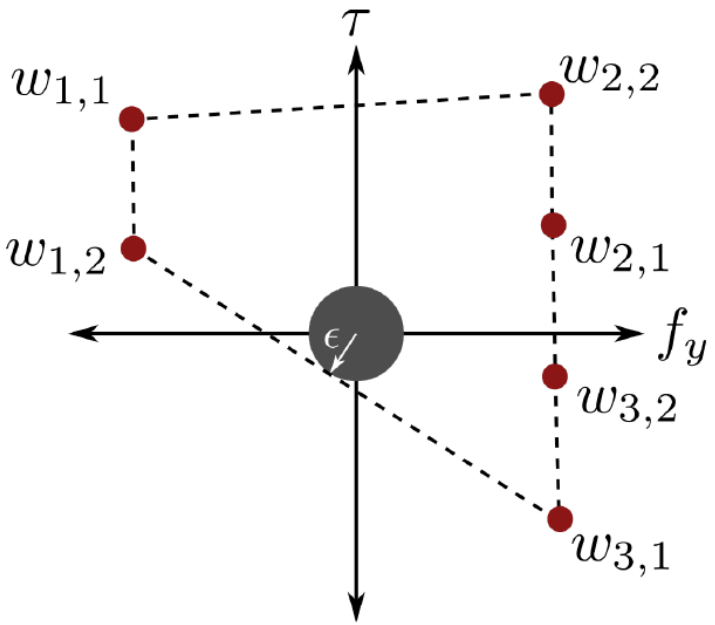
Grasp Quality

Often we may need to go beyond simple force closure. Comparing two force closure grasps → which one is better?

Use metrics based on Grasp Wrench Hull:

(a) **Epsilon**

(b) **Volume**



Credit: [1]

Grasp Quality

Epsilon: Worst Case Metric!

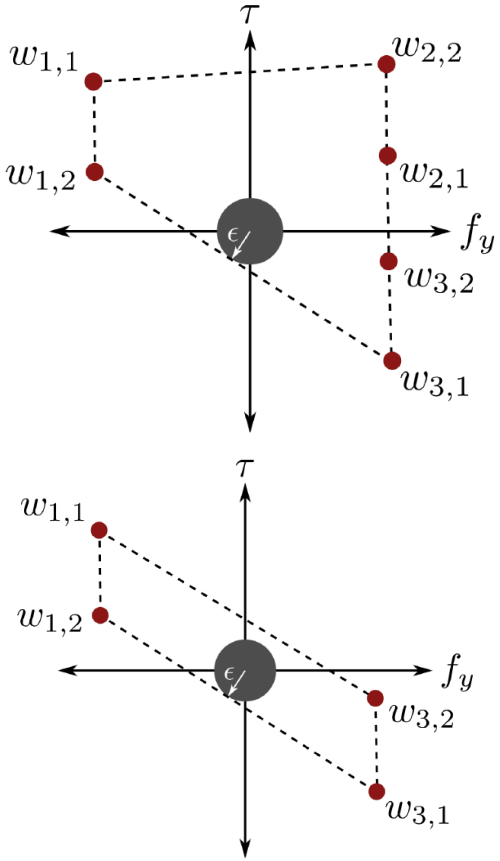
= Radius of largest ball (in 6D) that is centered at origin and contained within the Grasp Wrench Hull

=> Magnitude of *smallest* external wrench that pushes grasp to its limits

Volume: compute the (6D) volume of GWH

=> This quality considers the **average case**!

Can used to select grasps with similar epsilon values i.e **Tie-Breaker**!



Credit: [1]

Graspit: Grasp Planning Workflow

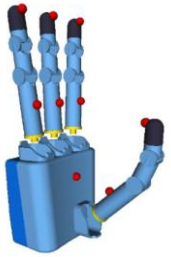
- Graspit uses geometry-based, classical methods to plan grasps
  - Requires 3D model (mesh) for the object!
  - Usually used for *Model-Based Grasp Planning*

- Graspit takes as input a (gripper, object) pair tries to plan grasps as follows
  - Uniformly sample a lot of poses for the gripper around the object as starting config
  - For each start, try to get the gripper and object close to each other by optimizing a “contact energy” function (simulated annealing used for optimization)

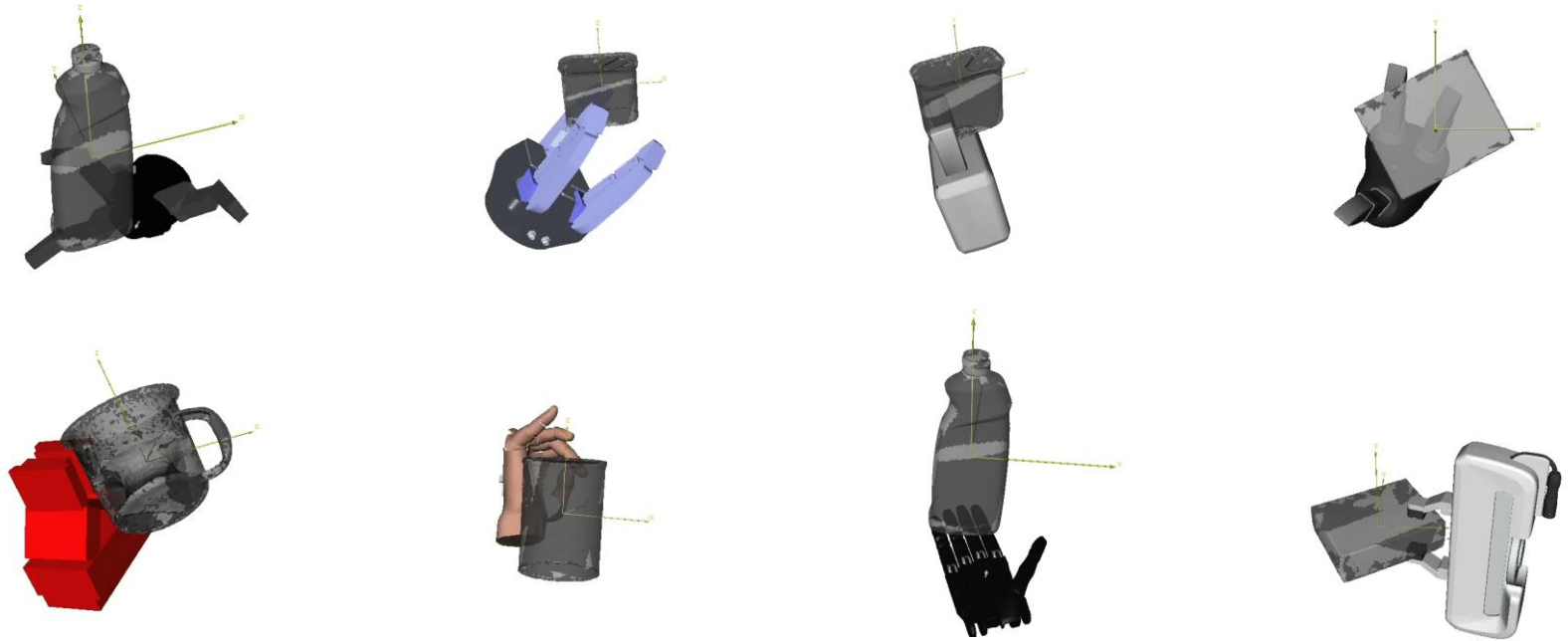
GraspIt Simulator Overview

Graspit: grasp planning = optimization problem on **E**

- **E** is an objective function = F(**p**, **t**)
- **p** is the pose and **t** is the gripper joint configuration.
  - **E** is computed using pre-defined contact points on the gripper. Simulated annealing used to optimize.
  - Sum of distances between gripper contact points and object.
  - Angular differences between the surface normal at contact point and closest object point
- Evaluate intermediate steps using Grasp Quality measures



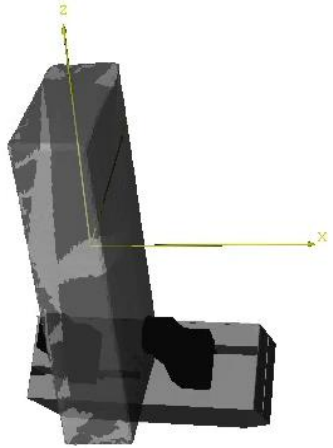
Graspit Grasp Planning: Visualization



Demo of grasp planning in GUI mode

Graspit: Grasp Planning Workflow

- Last optimization iteration:
  - *Close* gripper fingers around object
  - Compute some *analytical quality metrics* for the planned grasps



Problems with such modeling

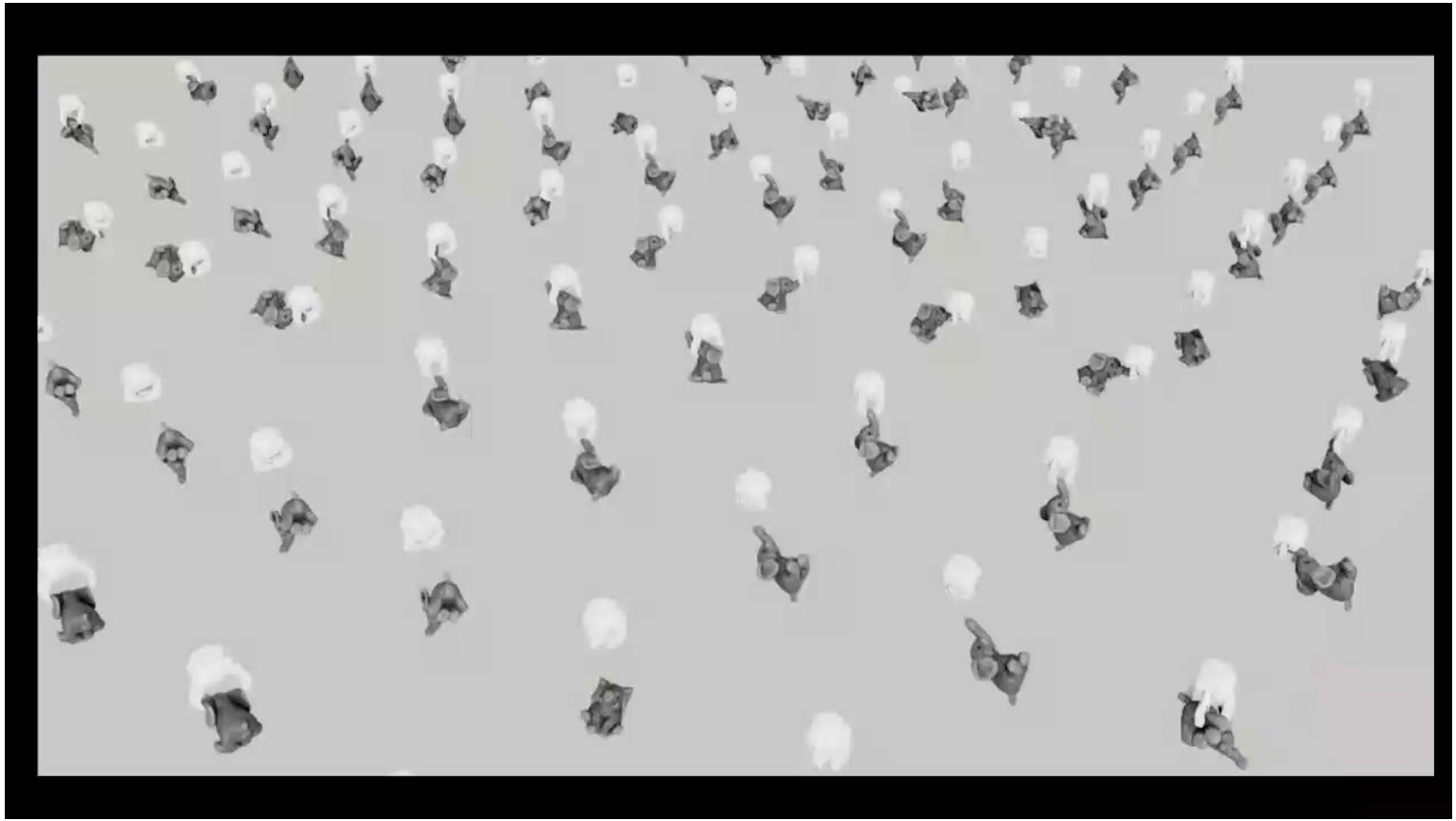
Some assumptions may be invalid in real world grasping!

- Coefficient of friction between gripper finger and object surface = ???
- Complete object model along with its center of mass = ???
- Object Pose may be unknown = ???
- Rigid v/s deformable objects
- Real time computation constraints!
    - Generating on the fly

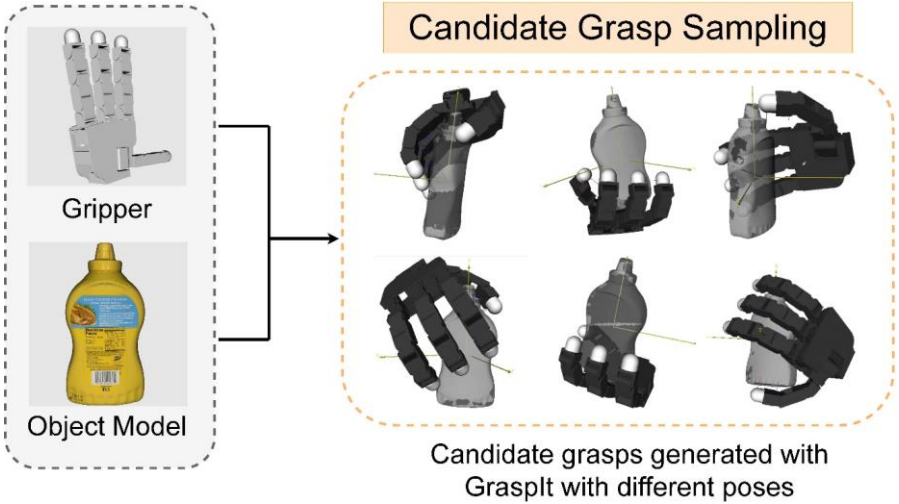
Q: Can we leverage grasping datasets for learning good grasping functions?

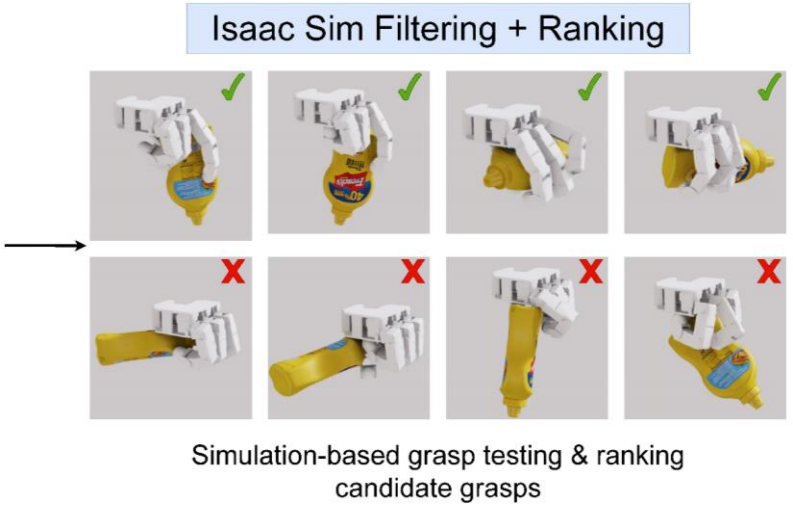
- Step-1: Generate initial grasps using GraspIt!

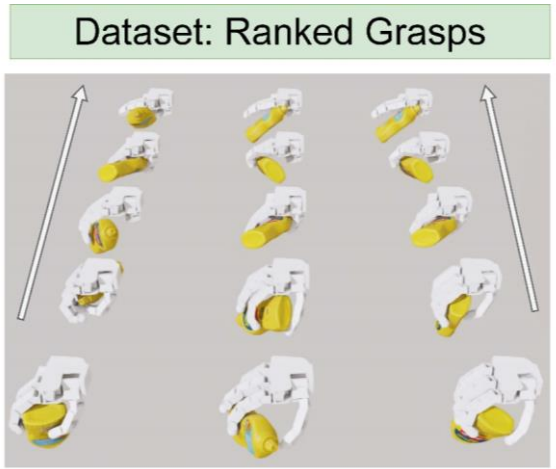
- Step-2: Ranking grasps in Isaac Sim Simulator ==> Good Grasps survive longer!



Creating Grasping Datasets







Learning based methods

Graspit requires access to the object's full 3D model => Infeasible in practice!

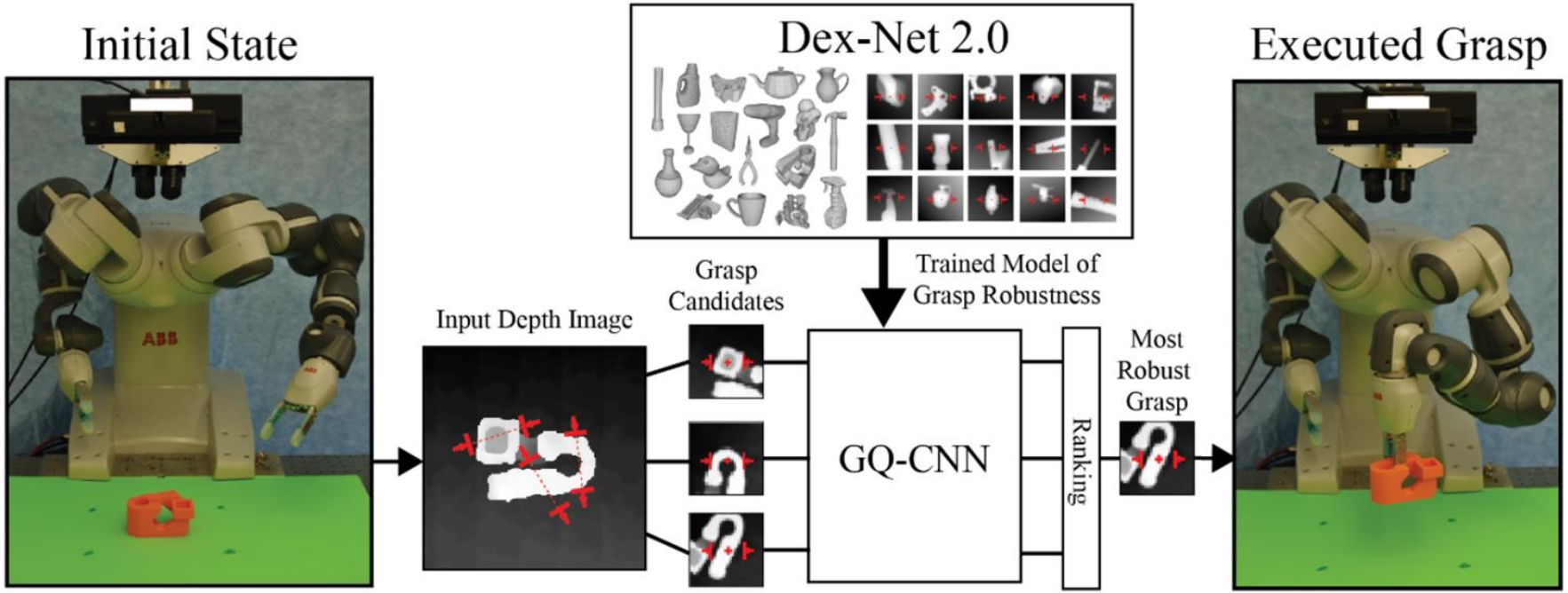
Alternatives:

- Learn mapping from images/point clouds to grasps
- Utilize dataset of synthetic grasps (generated using previous methods)
- Train NNs to evaluate the grasps

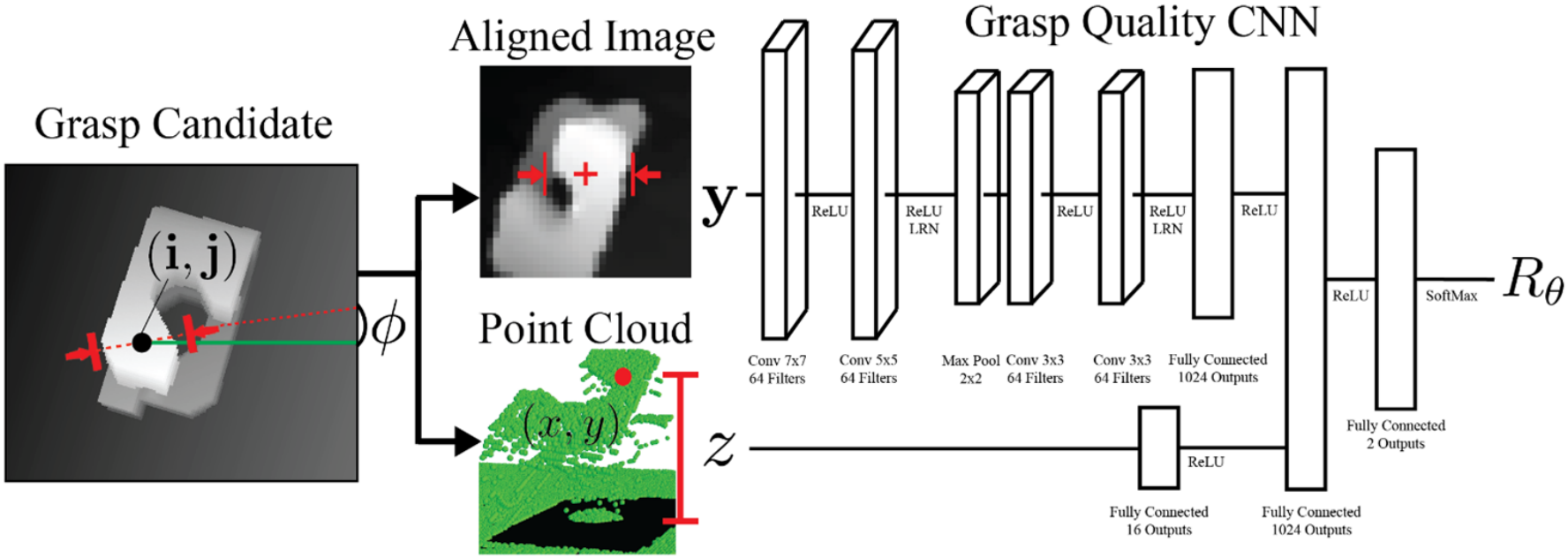
Example: Given a pixel (u,v) on the image, is it a valid grasping point (1) or not (0)

- One Approach: Dex-Net 2.0 [4]

Dex-Net 2.0


Initial State
Dex-Net 2.0
Executed Grasp
Grasp Candidates
Trained Model of Grasp Robustness
Input Depth Image
GQ-CNN
Ranking
Most Robust Grasp

Dex-Net 2.0


Grasp Candidate
(i, j)
ϕ
Aligned Image
y
Point Cloud
(x, y)
z
Grasp Quality CNN
ReLU
ReLU LRN
ReLU
ReLU LRN
ReLU
ReLU
SoftMax
R_θ
Conv 7x7 64 Filters
Conv 5x5 64 Filters
Max Pool 2x2
Conv 3x3 64 Filters
Conv 3x3 64 Filters
Fully Connected 1024 Outputs
Fully Connected 2 Outputs
ReLU
Fully Connected 16 Outputs
Fully Connected 1024 Outputs

Beyond Planar Grasp: 6-DoF Grasping

In DexNet, grasps are represented by oriented rectangles on a 2D image

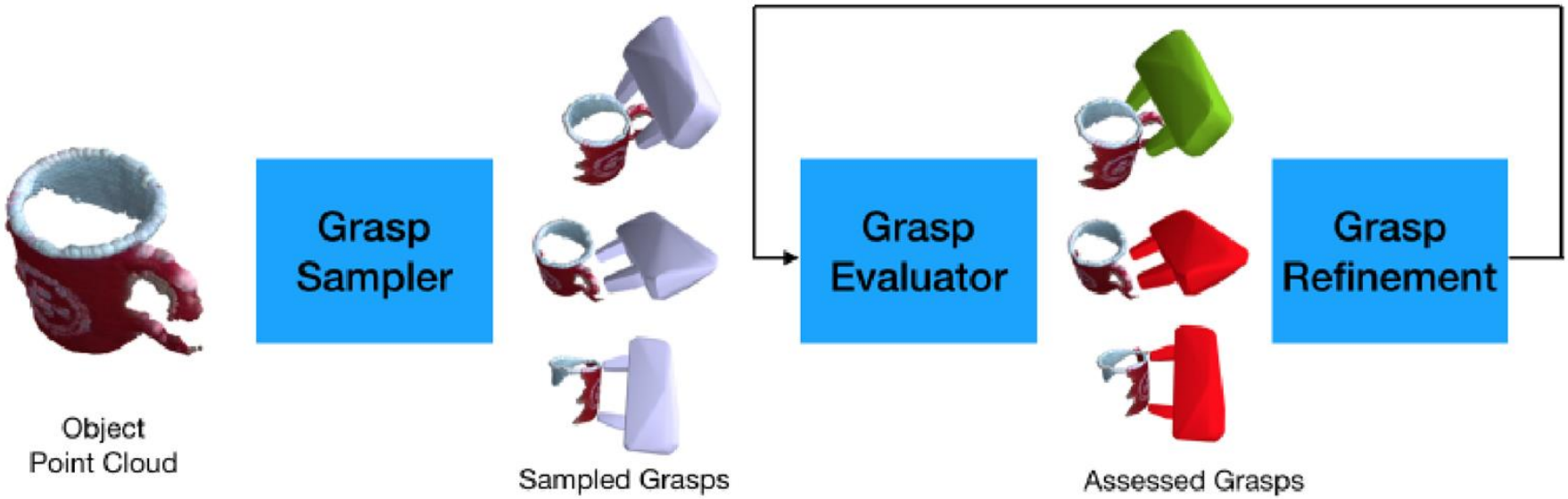
Only anti-podal points considered for grasp candidates

But this does not make full use of robot joints

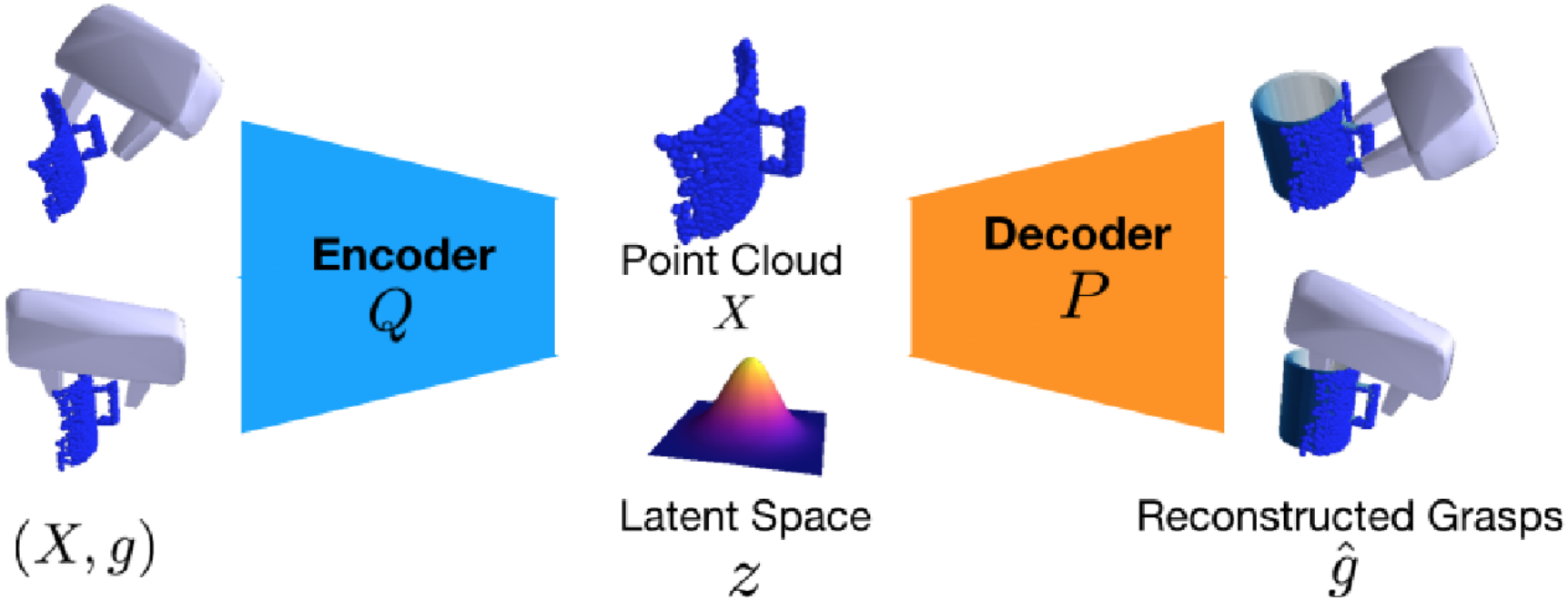
Grasp pose is actually in 6D (3D rotation + translation)

One Approach: 6-DoF GraspNet [5]

6-DoF GraspNet



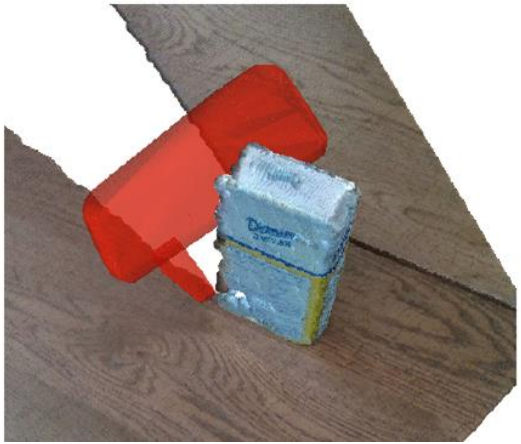
6-DoF GraspNet

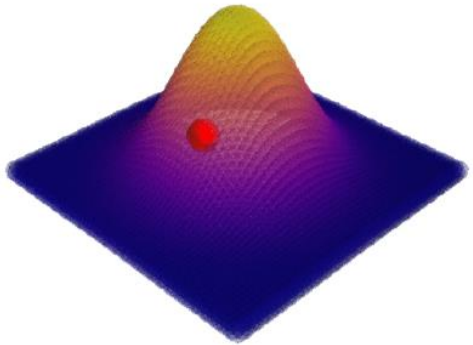


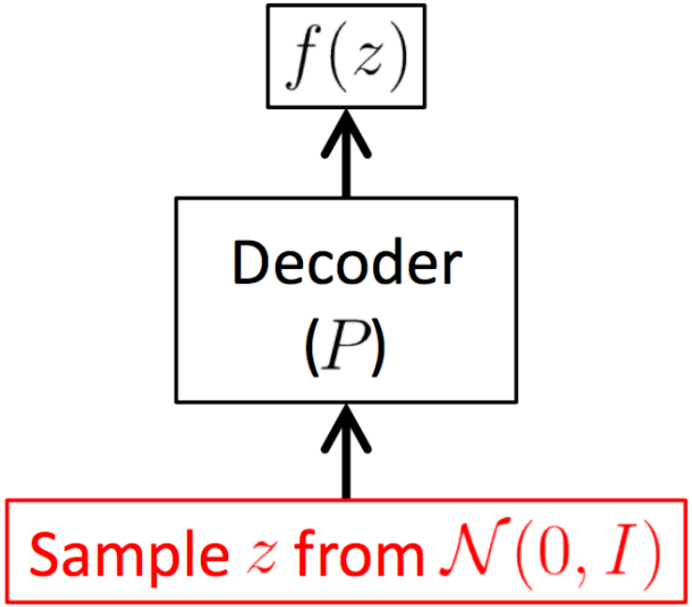
Inference

During inference, decoder Q is discarded and latent zs are sampled from prior distribution of z.

Decoder generates grasps by moving through latent space







Model-based Grasping vs Model-free Grasping

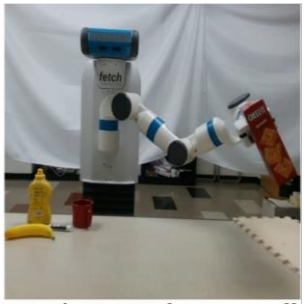
Input real world scene

6D Pose Estimation

Offline Grasp Database

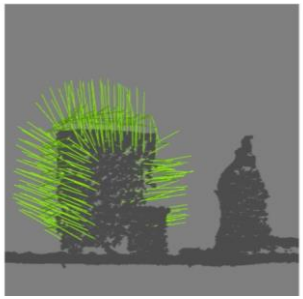
Motion Planning Setup

Grasping & Lifting

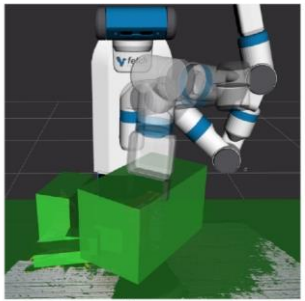


Moving arm for Dropoff

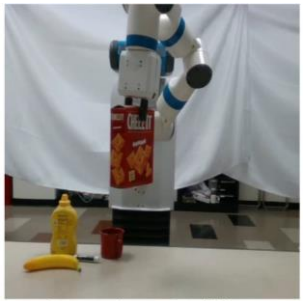
Unseen Object Segmentation



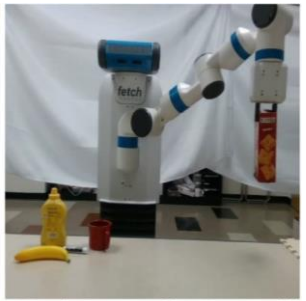
Model-free Grasp Planning



Motion Planning Setup

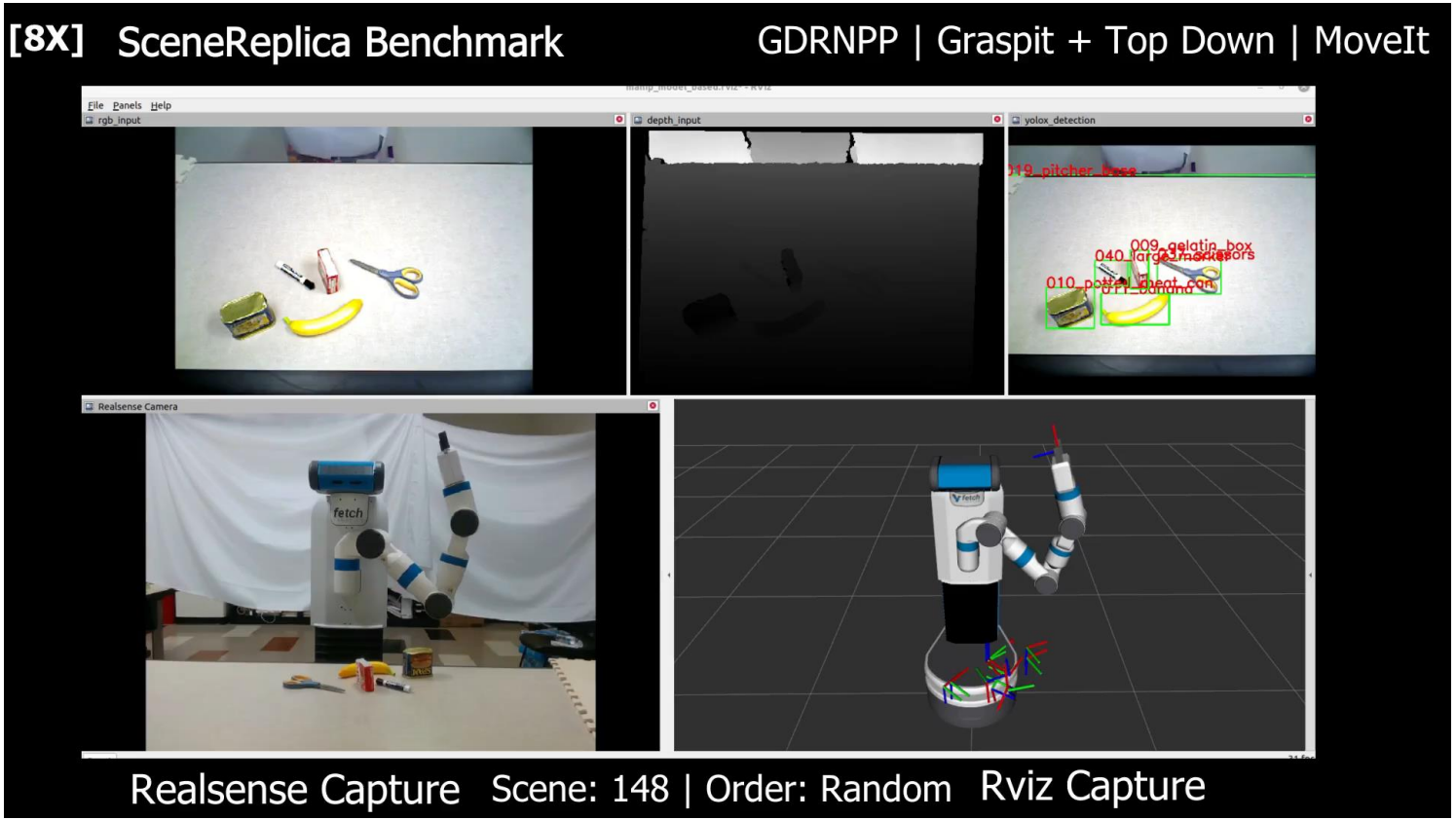


Grasping & Lifting

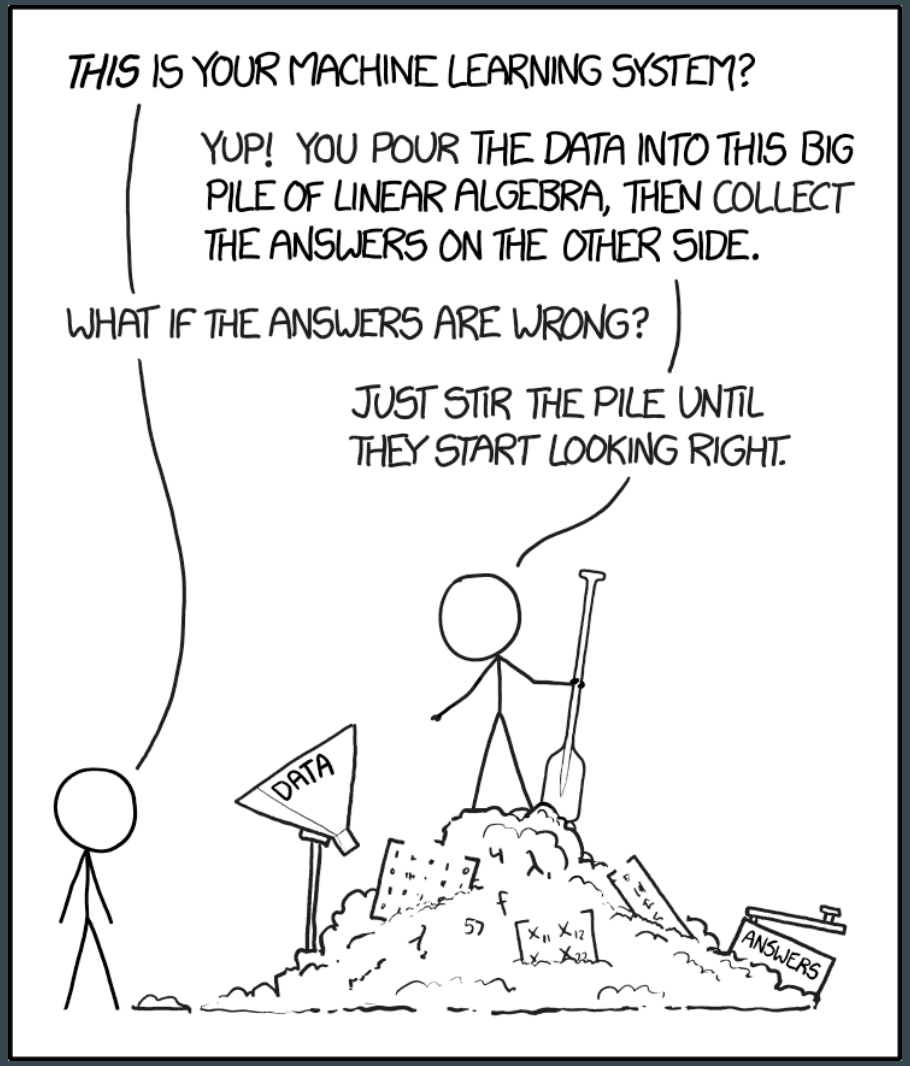


Moving arm for Dropoff

Model-based Grasping Example



Machine Learning???



Credit: xkcd.com

Resources & References

[1] Main reference: Stanford Principles of Robot Autonomy-II: Grasping lectures

[2] Friction Cone

[3] Classical Grasp Planning: GraspIt Simulator

[4] Dex-Net 2.0: Deep Learning to Plan Robust Grasps with Synthetic Point Clouds and Analytic Grasp Metrics

[5] 6-DOF GraspNet: Variational Grasp Generation for Object Manipulation