Finding Two Soft-Finger Contacts in 3D point clouds

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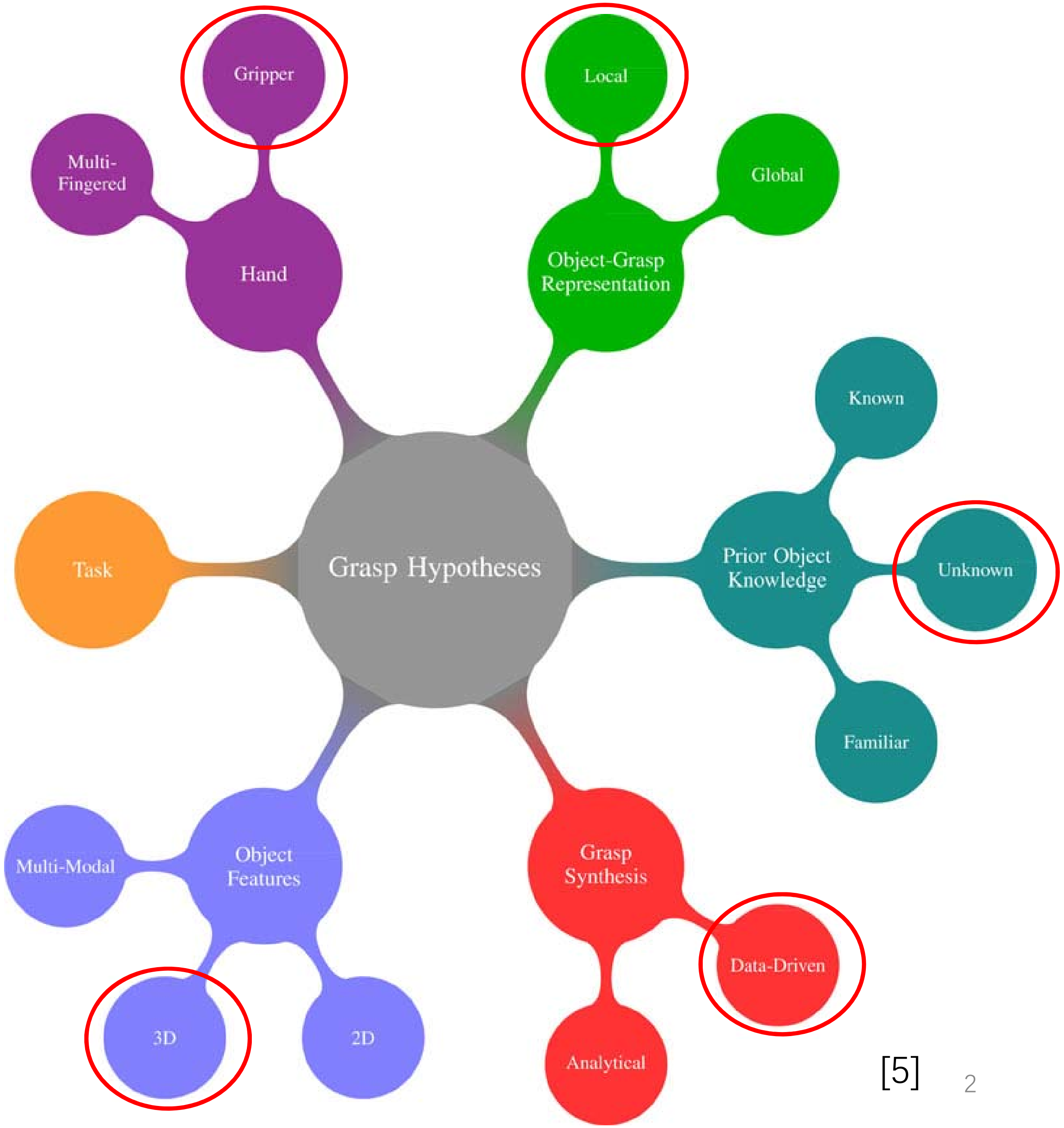
Introduction

- 3-D data
  - 3-D point cloud
- Data-Driven
  - learn how to grasp by experience that is gathered during grasp execution
- Unknown
  - not assume to have access to object models
- local object attributes
  - e.g., curvature, contact area around a candidate grasp



[5]

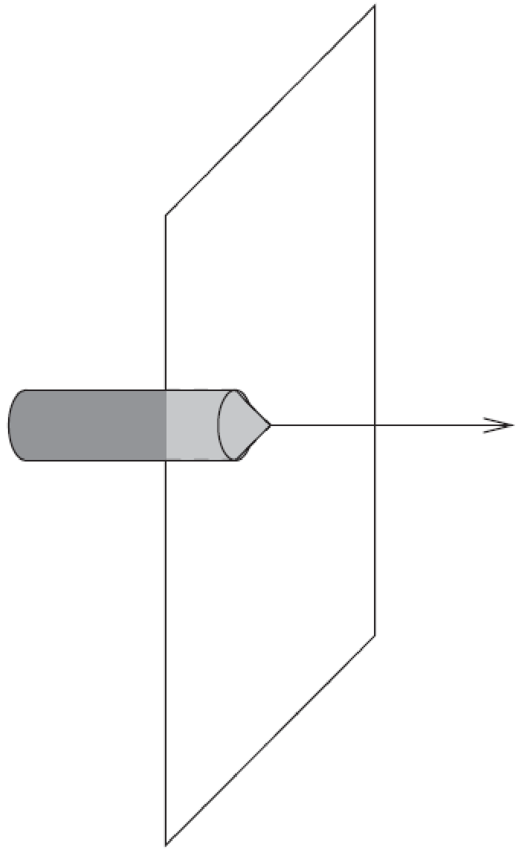
Contract Model

- Three types of contact:
  - 1. frictionless point contact
  - 2. Point contact with friction
  - 3. Soft-finger contact
- The grasp map
- Force-closure grasps and Form-closure grasps
- Examples of Force-closure grasps
  - Two Opposing Fingers
  - 3D Grasps with two Soft-Finger Contacts

Types of contact

- Frictionless point contact

- A model for contacts in which the friction between the finger and the object is low or unknown



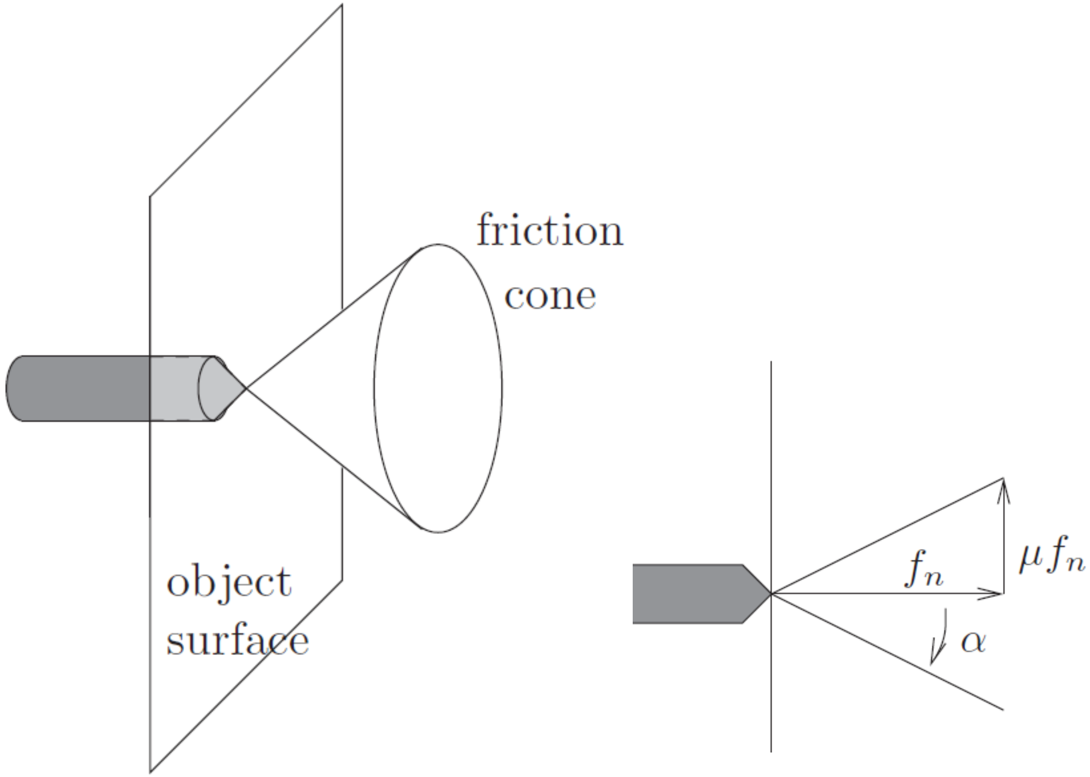
[6]

Types of contact

- Point contact with friction

- Friction cone
  - a cone centered about the surface normal
  - α is the static coefficient of friction

- Forces must lie in friction cone

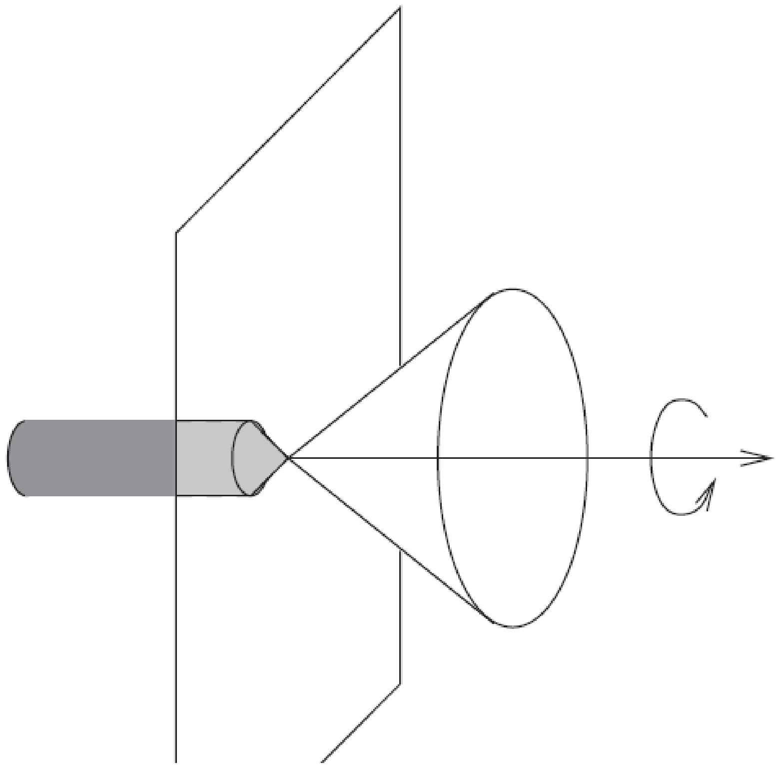


$$FC_{c_i} = \{f \in \mathbb{R}^3 : \sqrt{f_1^2 + f_2^2} \leq \mu f_3,\ f_3 \geq 0\}$$

[6]

Types of contact

- A more realistic contact model
- Torques about that normal
  - γ is the coefficient of torsional friction



$$FC_{c_i} = \{f \in \mathbb{R}^4 : \sqrt{f_1^2 + f_2^2} \leq \mu f_3,\ f_3 \geq 0,\ |f_4| \leq \gamma f_3\}$$

[6]

The grasp map

$$\widehat{a} = (a)^\wedge = \begin{bmatrix} 0 & -a_3 & a_2 \\ a_3 & 0 & -a_1 \\ -a_2 & a_1 & 0 \end{bmatrix}$$

$$a \times b = (a)^\wedge b$$

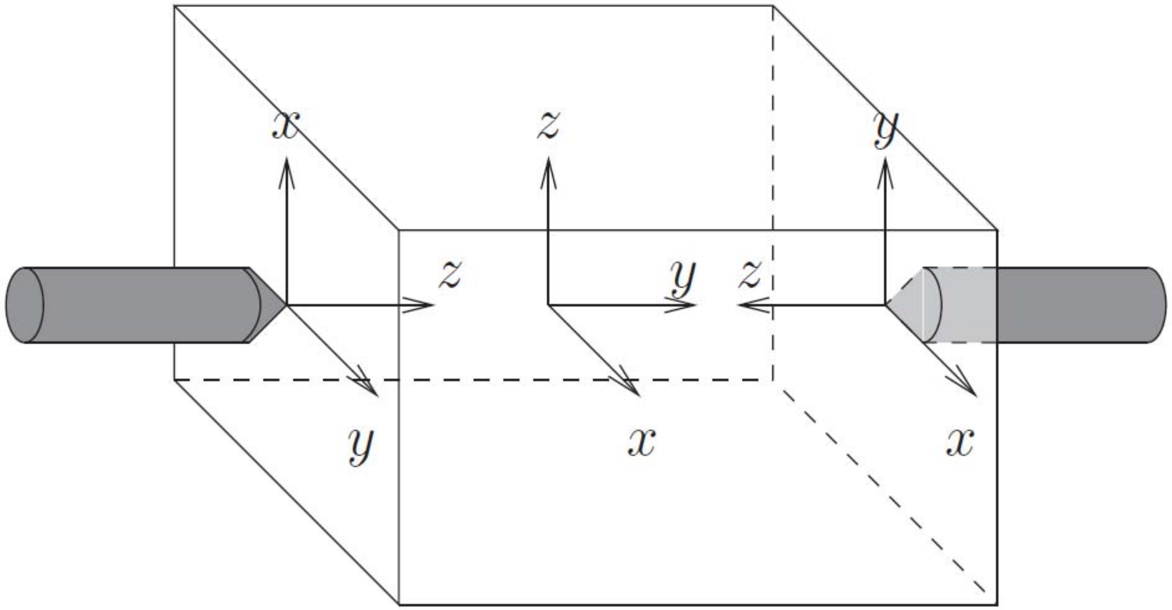
- Transform the forces to the object frame
    - The force exerted by a contact with respect to the object frame

$$\vec{F}_o = \begin{bmatrix} R_{oc_i} & 0 \\ \widehat{\vec{p}_{oc_i}} R_{oc_i} & R_{oc_i} \end{bmatrix} B_{c_i} f_{c_i} \qquad f_{c_i} \in FC_{c_i}$$

    - $(\vec{p}_{oc_i}, R_{oc_i})$: the configuration of the ith contact frame relative to the object frame
    - B_{c_i}: wrench basis
    - The contact map is defined as $G_i = \begin{bmatrix} R_{oc_i} & 0 \\ \widehat{\vec{p}_{oc_i}} R_{oc_i} & R_{oc_i} \end{bmatrix} B_{c_i}$
- The grasp map G: is the map between the contact forces and the total object force. For k fingers contacting, $G = [G_1 \ \ldots \ G_k]$. [6]

The grasp map

- Example: Soft-finger grasp of a box



[6]

The grasp map

$$R_{c_1} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix} \quad p_{c_1} = \begin{bmatrix} 0 \\ -r \\ 0 \end{bmatrix} \quad R_{c_2} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{bmatrix} \quad p_{c_2} = \begin{bmatrix} 0 \\ r \\ 0 \end{bmatrix}$$

$$G_i = \begin{bmatrix} R_{c_i} & 0 \\ \widehat{p}_{c_i} R_{c_i} & R_{c_i} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} G = \left[\begin{array}{cccc|cccc} 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & -1 & 0 \\ 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ \hline -r & 0 & 0 & 0 & 0 & +r & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 \\ 0 & +r & 0 & 0 & -r & 0 & 0 & 0 \end{array} \right]$$

[6]

Force-closure grasps

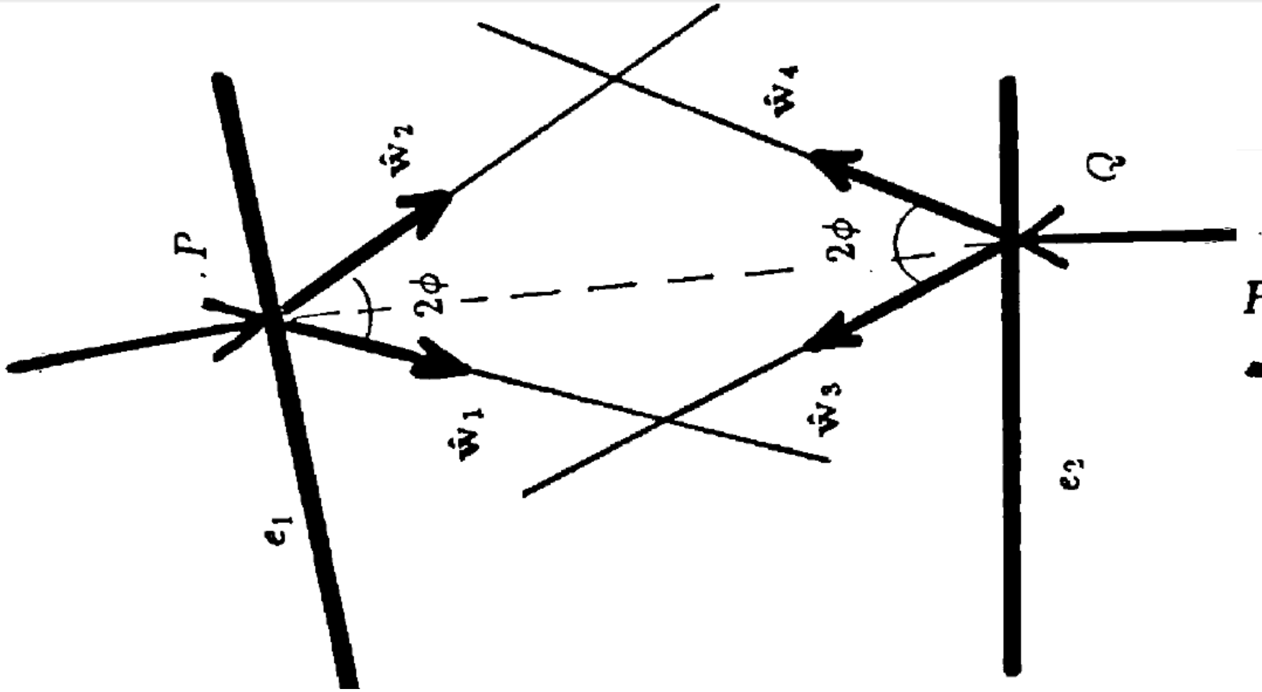
- Representation of a grasp consists of
  - a matrix $\mathrm{G} = R_{p*m}$ for grasp map
  - a set $\mathrm{FC} = R^m$

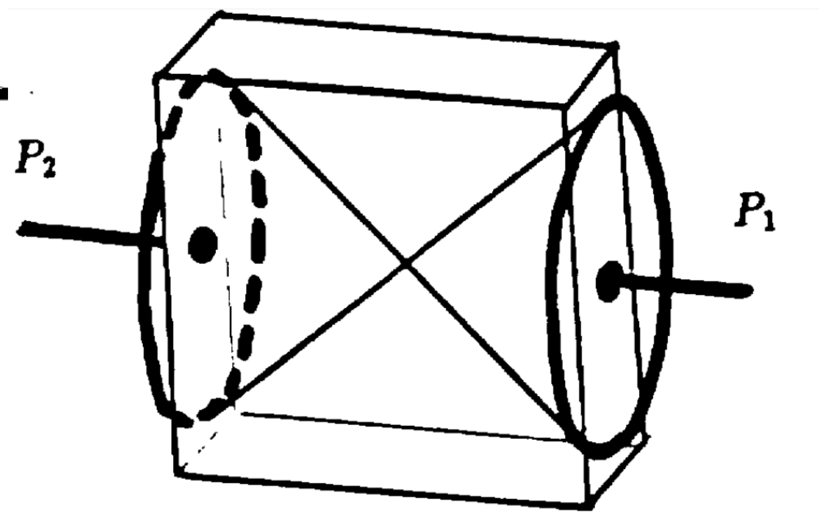
- Force-closure grasp
  - any external wrench $F_e \in R^p$ applied to the object
  - exist contact forces $f_c \in \mathrm{FC}$ such that $G f_e = -F_e$
  - Literally, it can resist any applied wrench

- Form-closure grasps
  - the grasped object is totally constrained by the set of contacts, irrespective of the magnitude of the contact forces
  - force-closure with frictionless contacts only

[1]

Examples of Force-closure grasps



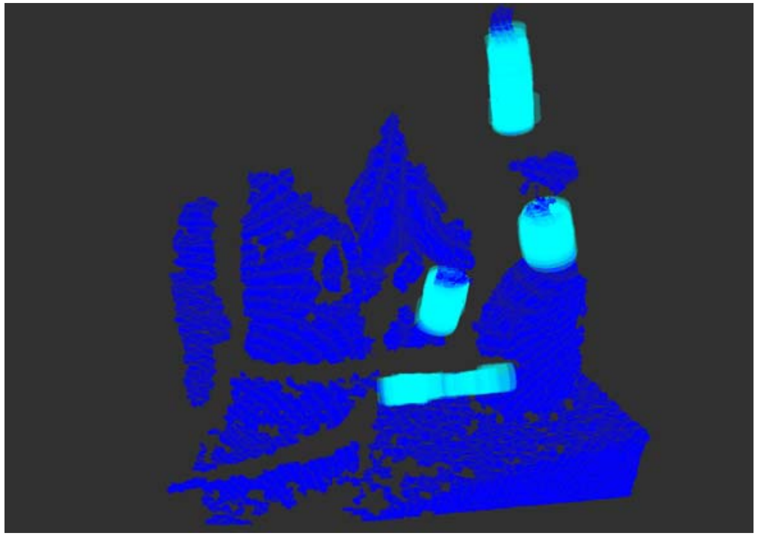


3D Grasps with Two Soft-Finger Contacts
Coupling opposite contact forces

[1]

Localizing Handle-Like Grasp Affordances in 3D Point Clouds

- Localizing handle-like grasp affordances



- Identify a set of sufficient geometric conditions

http://wiki.ros.org/handle_detector [4]

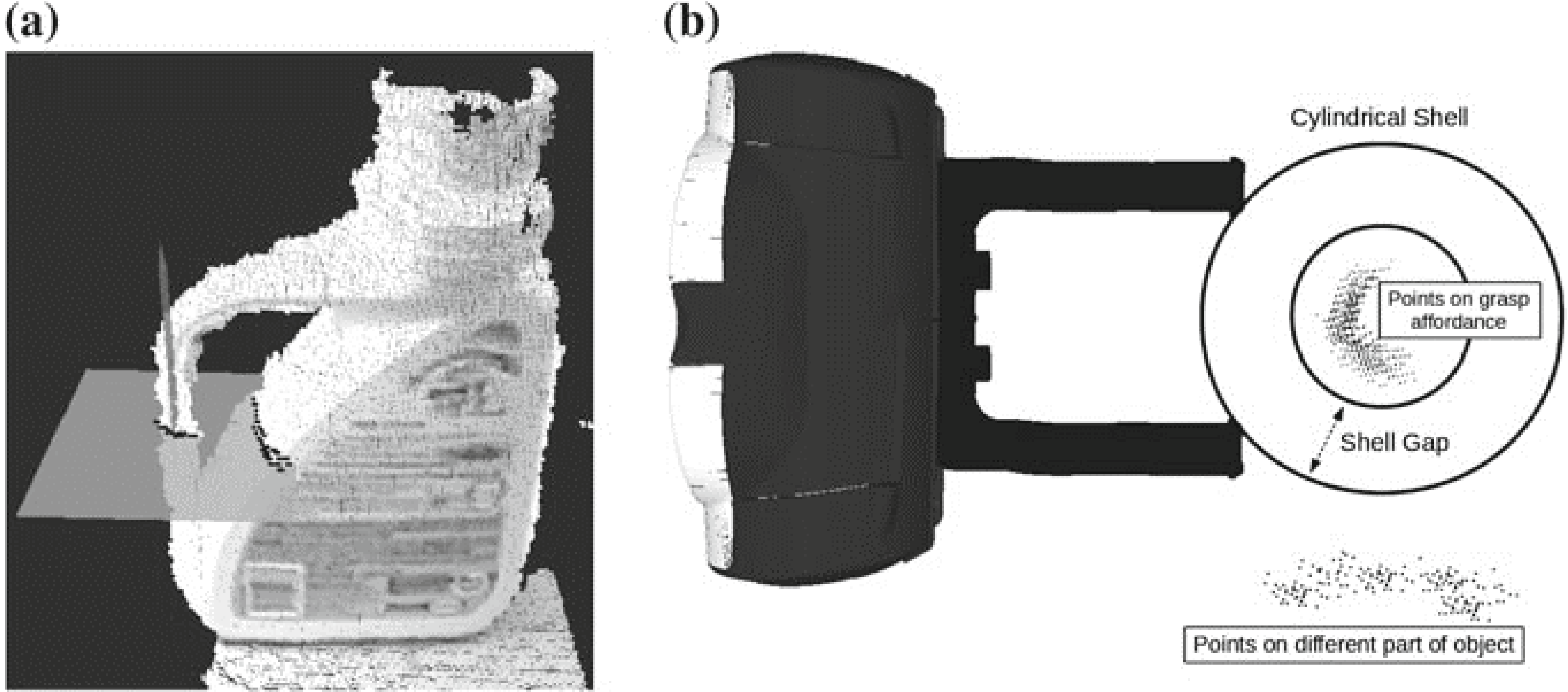
An enveloping grasp affordance

- A handle-like object geometry that can be grasped by encircling it with the thumb and fingers of the robot hand

- Geometry criteria with respect to local neighborhoods of the point cloud
  - Points near the center of the neighborhood must lie on a curved object surface
  - The axis of the cylindrical shell must be parallel to the secondary axis of curvature of the local object surface
  - The gap between the inner and outer cylinders must contain zero points and be wide enough to contain the robot fingers
  - The radius of the innermost cylinder must be no larger than the maximum hand aperture

[4]

Example of an enveloping grasp affordance



[4]

Algorithm outline

- 1. Randomly sample spherical point neighborhoods approximately 2 or 3cm in radius
- 2. Fit an implicit quadratic function (in three variables) to each of these point neighborhoods
- 3. calculate the magnitudes and axes of principal surface curvature in the point neighborhood
- 4. eliminate neighborhoods with an surface curvature below some parametrized threshold
- 5. project the point neighborhood onto the plane orthogonal to the axis of minor principal curvature

[4]

Algorithm outline

- 6. fit a circle to the projected points
- 7. perform a 1-D search for cylindrical shells satisfying the enveloping grasp affordance conditions
- 8. search for sets of affordances that are roughly aligned and that exceed a minimum length

[4]

Estimating Object Surface Curvature

$$f(\mathbf{c}, \mathbf{x}) = c_1 x_1^2 + c_2 x_2^2 + c_3 x_3^2 + c_4 x_1 x_2 + c_5 x_2 x_3 + c_6 x_1 x_3 + c_7 x_1 + c_8 x_2 + c_9 x_3 + c_{10},$$

$$\min_c \sum_{i=1}^{n} f(\mathbf{c}, \mathbf{x}^i)^2 = \mathbf{c}^T M \mathbf{c}$$

[4]

Cylindrical Shell Search

- Project the points in the local neighborhood onto the plane orthogonal to the minor principal curvature axis

- Fitting a circle to the points near the center of the neighborhood
  - (h_x, h_y, r): the circle model, (x^i, y^i): coordinates of the ith point
  - $\lambda_i = (x^i)^2 + (y^i)^2$, $I_i = (-x^i, -y^i, 1)^T$
  - $W = -\left(\sum_{i=1}^{n} I_i {I_i}^T\right)^{-1} \sum_{i=1}^{n} \lambda_i I_i$
  - $(h_x = -0.5a, h_y = -0.5b, r = \pm\sqrt{h_x^2 + h_y^2 - c})$

[4]

Handle Search

- Handle: sets of affordances that are roughly aligned and that cover some minimum length.

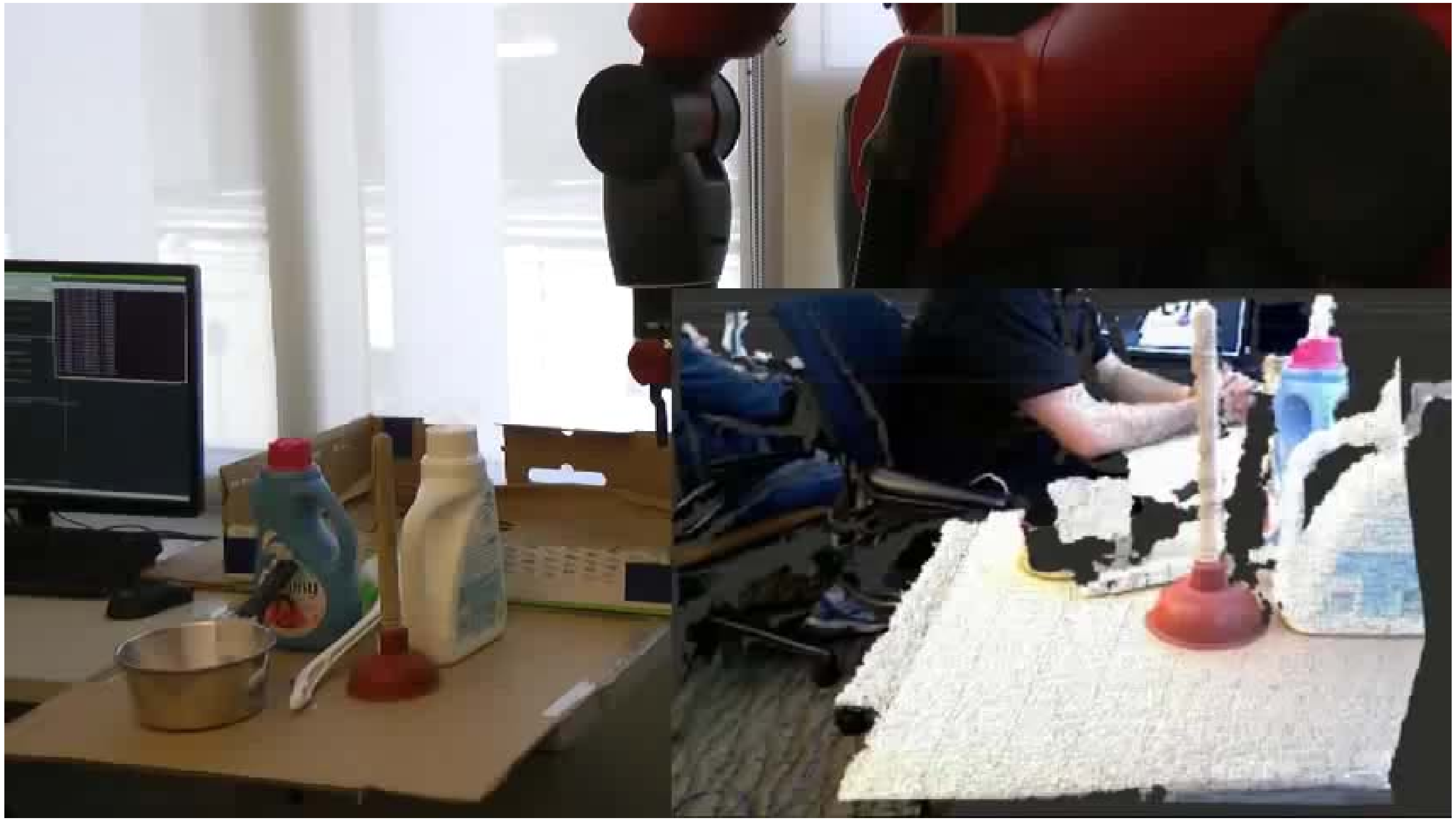
- brute-force search over all pairs of enveloping grasp affordances

- For enveloping grasp affordances i, j with centroids h_i, h_j, major principal axes v_i, v_j, and radii r_i, r_j. compute the following three distances:
  - $d_o = \|(I - v_i {v_i}^T)v_j\|, d_c = \|(I - v_i {v_i}^T)(h_i - h_j)\|, d_r = |r_i - r_j|$

- If d_o, d_c and d_r are below parametrized thresholds and an enveloping grasp affordance i is aligned with at least a minimum number of other grasp affordances, then it is considered to be a handle affordance

[4]

Example



https://www.youtube.com/watch?v=qjE5X7pTjKE&feature=youtu.be

Using Geometry to Detect Grasp Poses in 3D Point Clouds

- Novel objects presented in clutter

- Input:
  - 3-D point cloud
  - geometric parameters of the robot hand

- Output:
  - a set of hand poses
  - Antipodal hands

[3]

Algorithm outline

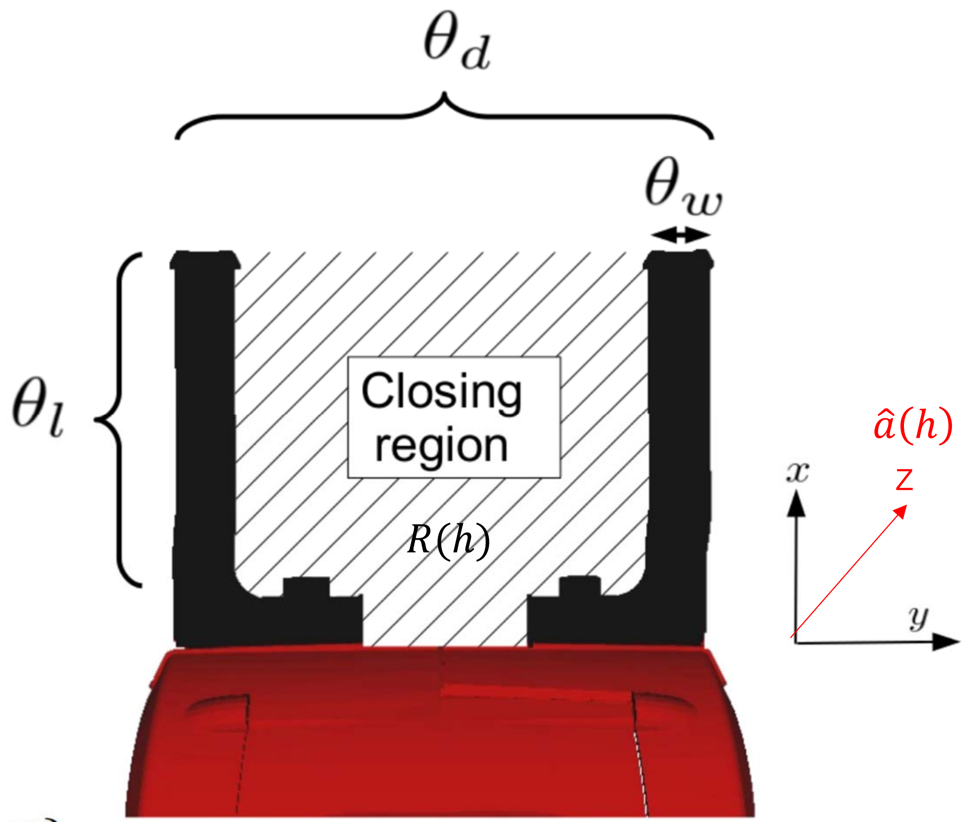
- Input: a point cloud: $\mathcal{C}$, and hand parameters: θ
- Output: antipodal hands: $\mathcal{H}$
  - Step 1: $\mathcal{H}_{hyp} = Sample\ Hands(\mathcal{C})$
  - Step 2: :$\mathcal{H} = Classify\ Hands(\mathcal{H}_{hyp})$

[3]

The Hand model

- hand, $\mathbf{h} \in \mathcal{H}$, is a parallel jaw gripper comprised of two parallel fingers each modeled as a rectangular prism that moves parallel to a common plane.
- $\hat{a}(h)$: a unit vector orthogonal to the common plane
- $\theta_l, \theta_w, \theta_t$: the length, width, and thickness of the fingers
- θ_d:the distance between the fingers
- $R(h)$: closing region
- r(h): points in closing region
- the closing plane

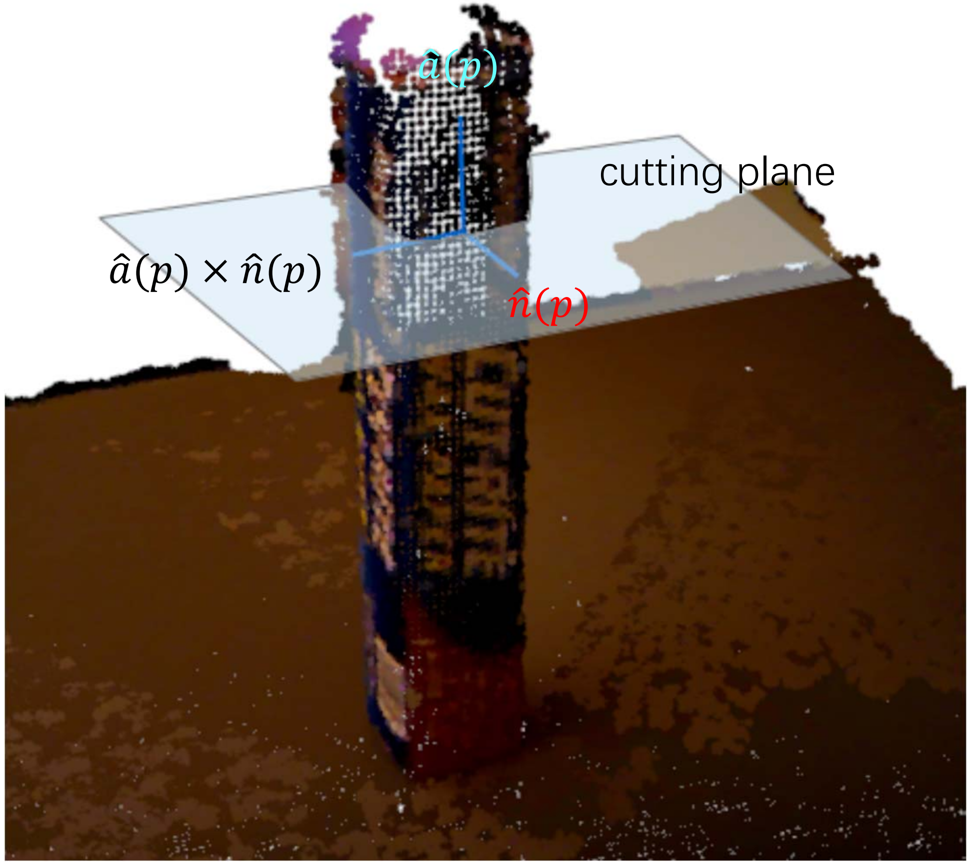
$$C(h) = \{p \in R(h) | (p - r(h))^T \hat{a}(h) = 0\}$$



[3]

The Model of Object Surface

- A differentiable surface
- the Darboux frame at point p
  - a surface normal: $\hat{n}(p)$
  - two principal curvatures
    - the direction of minimum principal curvature: $\hat{a}(p)$
  - $(\hat{n}(p), \hat{a}(p) \times \hat{n}(p), \hat{a}(p))$
- the cutting plane
  - plane orthogonal to $\hat{a}(p)$ that passes through p



[3]

Sampling Hands

- Define a lower-dimensional sample space
  - constrained by the geometry of the point cloud $\mathcal{C}$
  - focus detection on likely candidates

- Hand Sample Set $\mathcal{H}$
  - Constraint 1: The body of the hand is not in collision with the point cloud: $B(h) \cap \mathcal{C} = \emptyset$
  - Constraint 2: The hand closing plane contains p: $p \in C(h)$
  - Constraint 3: The closing plane of the hand is parallel to the cutting plane at p: $\hat{a}(p) = \hat{a}(h)$

- $\mathcal{H}(p)$ is three-DOF: 2 DOF of orientation and one DOF of position

[3]

Hand Sampling Process

Algorithm 2 Sample_Hands

Input: point cloud, $\mathcal{C}$, hand parameters, θ
Output: grasp hypotheses, $\mathcal{H}$

$\mathcal{H} = \emptyset$
Preprocess $\mathcal{C}$ (voxelize; workspace limits; *etc.*)
for i = 1 to n **do**
    Sample $p \in \mathcal{C}$ uniformly randomly
    Calculate θ_d-ball about p: $N(p) = \{q \in \mathcal{C} : \|p - q\| \leq \theta_d\}$
    Estimate local Darboux frame at p: $F(p) = Estimate\_Darboux(N(p))$
    $H = Grid\_Search(F(p), N(p))$
    $\mathcal{H} = \mathcal{H} \cup H$
end for

[3]

Classifying Hand Hypotheses

- Goal: classify each hypothesis $\mathcal{H}(p)$ as antipodal or not.

- Ideal method:
  - Infer object surface geometry from the point cloud
  - Check against the definition of antipodal hand

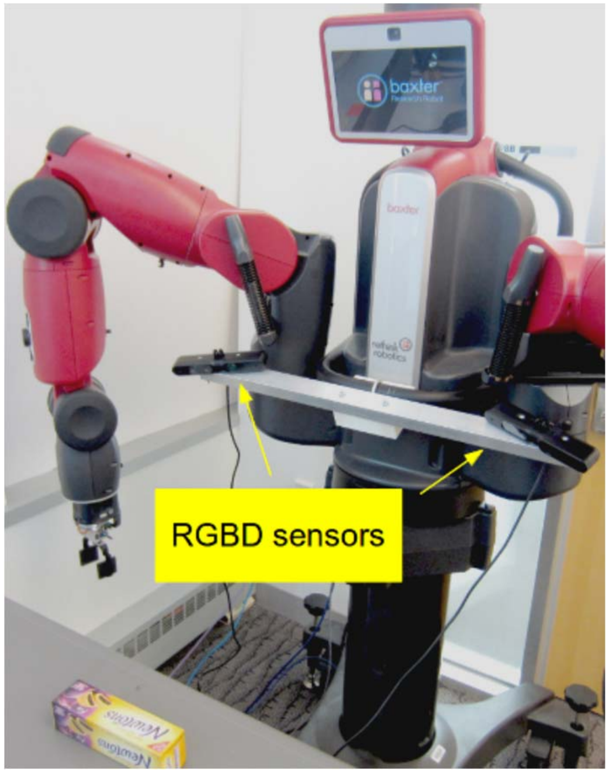
- Problem
  - point clouds are partial
  - Information is not sufficient

[3]

Classifying Hand Hypotheses

- Solution
  - Infer which hypotheses are likely to be antipodal using machine learning

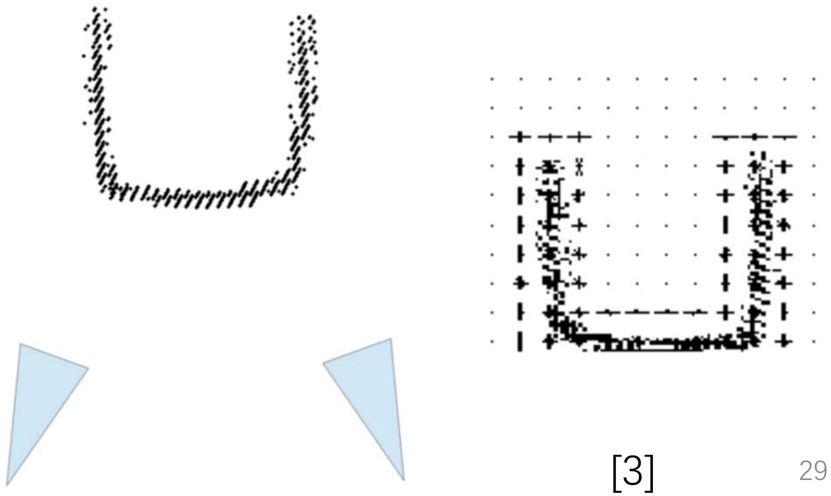
- Labeling Grasp Hypotheses
  - Automatically labels a set of training images
  - Checking a relaxed version of the conditions of antipodal hand definition
    - points that have a surface normal parallel to the direction of closing
    - at least k points are found with an appropriate surface normal
  - Least two point clouds observed the scene from different perspectives



[3]

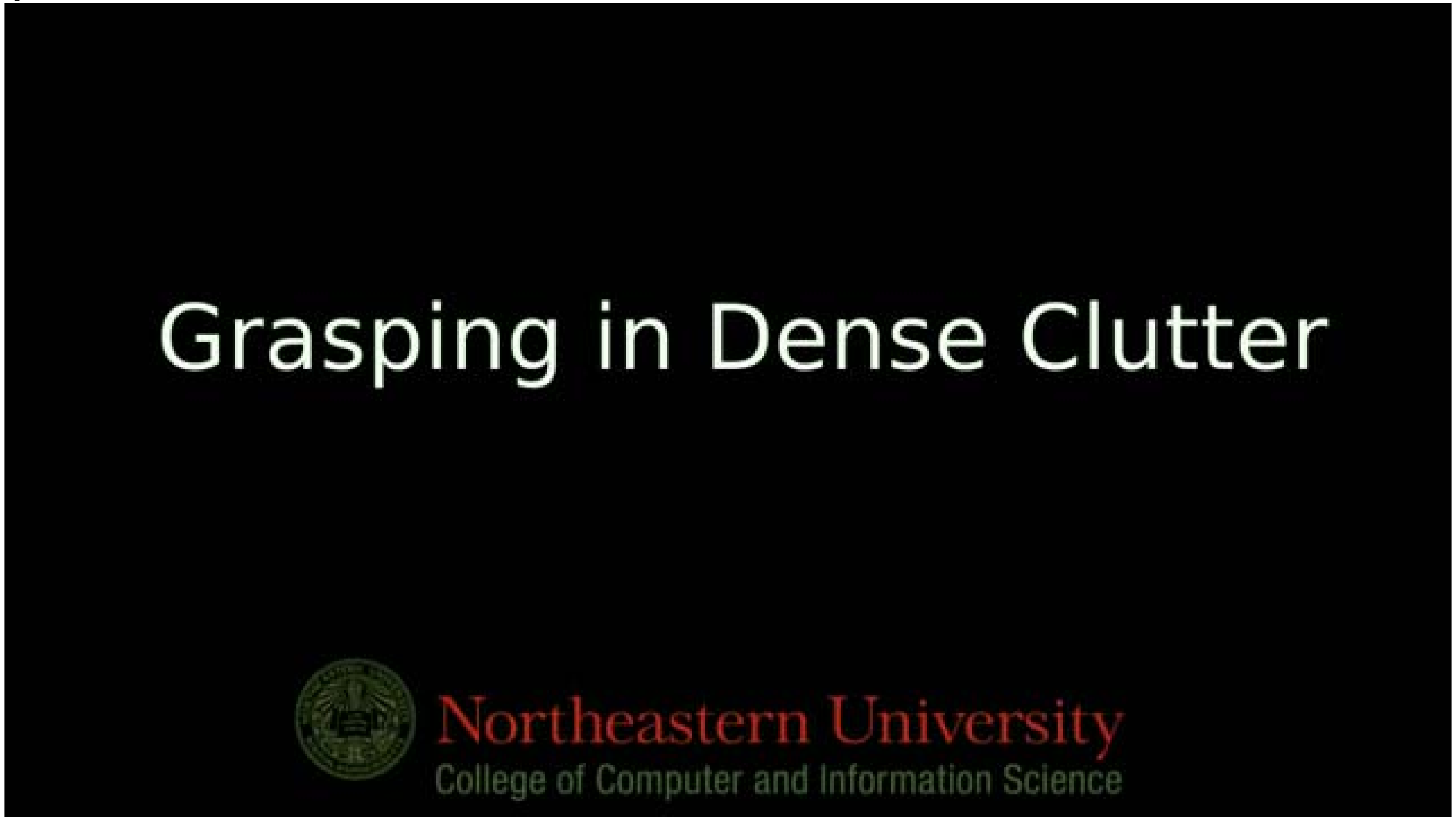
Classifying Hand Hypotheses

- Feature Representation
  - based on HOG features
- Creating the Training Set
  - 18 objects
  - two configurations for each object
  - Checking the conditions of each $\mathcal{H}(p)$ with respect to the relaxed version of the conditions of antipodal hand definition
- Classifier: SVM



[3]

Example



https://www.youtube.com/watch?v=Dm64UC3uGVY&feature=youtu.be

Summary

- Two Soft-Finger Contacts
- Contact model
- Handle-Like Grasp
- Antipodal hands

Reference

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