Finding Two Soft-Finger Contacts in 3D point clouds
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• Summary
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
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
Types of contact

• Point contact with friction

• Friction cone
  • a cone centered about the surface normal
  • $\alpha$ is the static coefficient of friction

• Forces must lie in friction cone

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

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

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

- Transform the forces to the object frame
  - The force exerted by a contact with respect to the object frame
    \[ \vec{F}_o = \begin{bmatrix} R_{oci} & 0 \\ p_{oci} R_{oci} & R_{oci} \end{bmatrix} B_{ci} f_c \]  
    \( f_c \in FC_{ci} \)
  - \((p_{oci}, R_{oci})\): the configuration of the ith contact frame relative to the object frame
  - \(B_{ci}\): wrench basis

- The contact map is defined as
  \[ G_i = \begin{bmatrix} R_{oci} & 0 \\ p_{oci} R_{oci} & R_{oci} \end{bmatrix} B_{ci} \]

- 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
The grasp map

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

\[
G_i = \begin{bmatrix} R_{c_i} & 0 \\ \hat{p}_{c_i} R_{c_i} & R_{c_i} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ -r & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & +r & 0 & 0 & 0 \\ -r & 0 & 0 & 0 & -1 \end{bmatrix}
\]
Force-closure grasps

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

• Force-closure grasp
  • any external wrench $F_e \in R^p$ applied to the object
  • exist contact forces $f_c \in FC$ such that $Gf_e = -F_e$
  • 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
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
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
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
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
Estimating Object Surface Curvature

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

\[ \min_c \sum_{i=1}^{n} f(c, x^i)^2 = c^T M c \]
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 \(i^{th}\) point
  • \(\lambda_i = (x^i)^2 + (y^i)^2, I_i = (-x^i, -y^i, 1)^T\)
  • \(W = -\left(\sum_{i=1}^{n} I_i I_i^T\right)^{-1} \sum_{i=1}^{n} \lambda_i I_i\)
  • \((h_x = -0.5a, h_y = -0.5b, r = \pm \sqrt{h_x^2 + h_y^2 - c})\)
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
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
Algorithm outline

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

- hand, $h \in \mathcal{H}$, 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
- $\theta_d$: the distance between the fingers
- $R(h)$: closing region
- $r(h)$: points in closing region
- the closing plane
  $$C(h) = \{ p \in R(h) \mid (p - r(h))^T \hat{a}(h) = 0 \}$$
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 \( p \)
Sampling Hands

• Define a lower-dimensional sample space
  • constrained by the geometry of the point cloud \( C \)
  • 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:
    \( B(h) \cap C = \emptyset \)
  • 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 \( p: \)
    \( \hat{\alpha}(p) = \hat{\alpha}(h) \)

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

[3]
Hand Sampling Process

Algorithm 2 Sample_Hands

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

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

Grasping in Dense Clutter

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

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


Reference
