Grasping

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Recap

- We've talked about how to move robots so they don't collide
- But how do we get robots to move objects in the world?
  - ***Grasping*** studies how to stably make contact with objects and move them

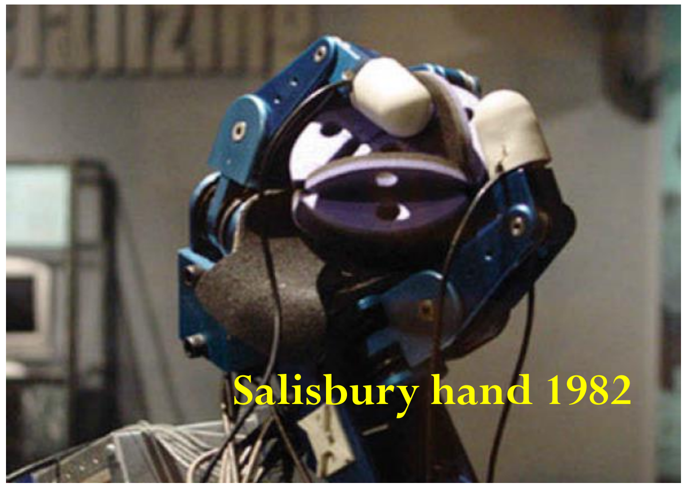
- Now we want to collide! (i.e. make contact with objects)
  - But how do we know if a given grasp is ***stable*** or not?

Outline

- Model & Definitions
- Form Closure
- Force Closure
- Current methods for grasp planning

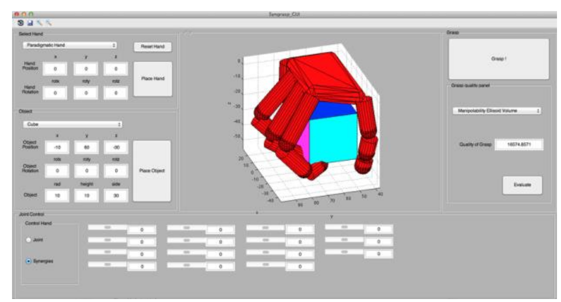
Towards Dexterous Manipulation

- First robotic hand for dexterous manipulation



- Software for grasp modeling & analysis

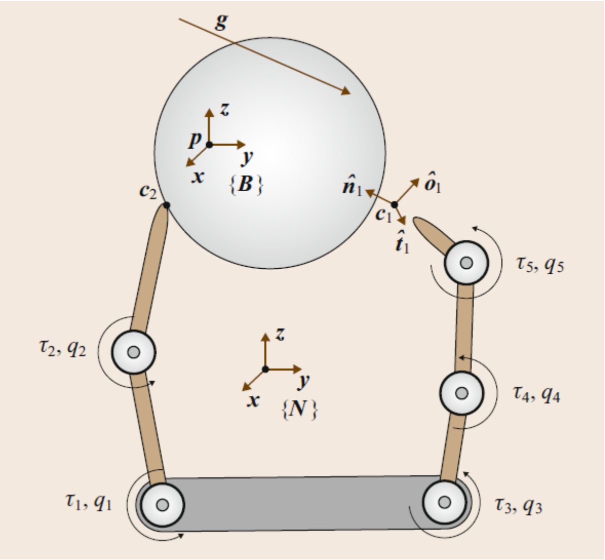
- Models for several robot hands
- Tools for grasp selection



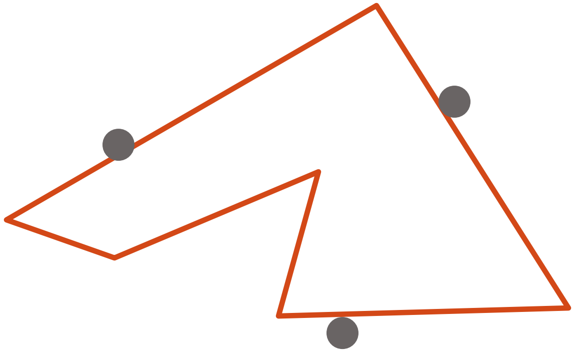
- Matlab toolbox
- Grasp analysis with fully/under-actuated hands

Mathematical Model

- Model
  - Predict the behavior of the hand and object under various loading conditions that may arise during grasping
  - Disturbance
    - Inertia force – e.g. fast motion
    - Applied force – e.g. Gravity
  - Grasp maintenance
    - No contact separation
    - No unwanted contact sliding
  - Closure grasp
    - The special class of grasps that can be maintained for every possible disturbing load



Model Simplification



Real World

- Complex mechanism
- Soft contacts
- Soft objects
- Bounded force
- Object is free-floating

Simplified Problem

- Ignore hand mechanism
- Assume n point contacts
- Assume rigid object
- Assume unlimited force
- Assume object is fixed

Definition

- Finger – A point contact
- Twist
  - A combination of translational and rotational velocity of the object

$$\boldsymbol{\nu} = [\boldsymbol{v}^{\mathrm{T}}\ \boldsymbol{\omega}^{\mathrm{T}}]^{\mathrm{T}}$$

- Wrench
  - A combination of the force and torque applied to the object (at object origin)

$$\boldsymbol{g} = [\boldsymbol{f}^{\top}\boldsymbol{m}^{\top}]^{\top}$$

- Wrench space
  - Space of wrenches applied to the object
    - 3D: 6 dimensional wrench space (3 force, 3 torque)
    - 2D: 3 dimensional wrench space (2 force, 1 torque)

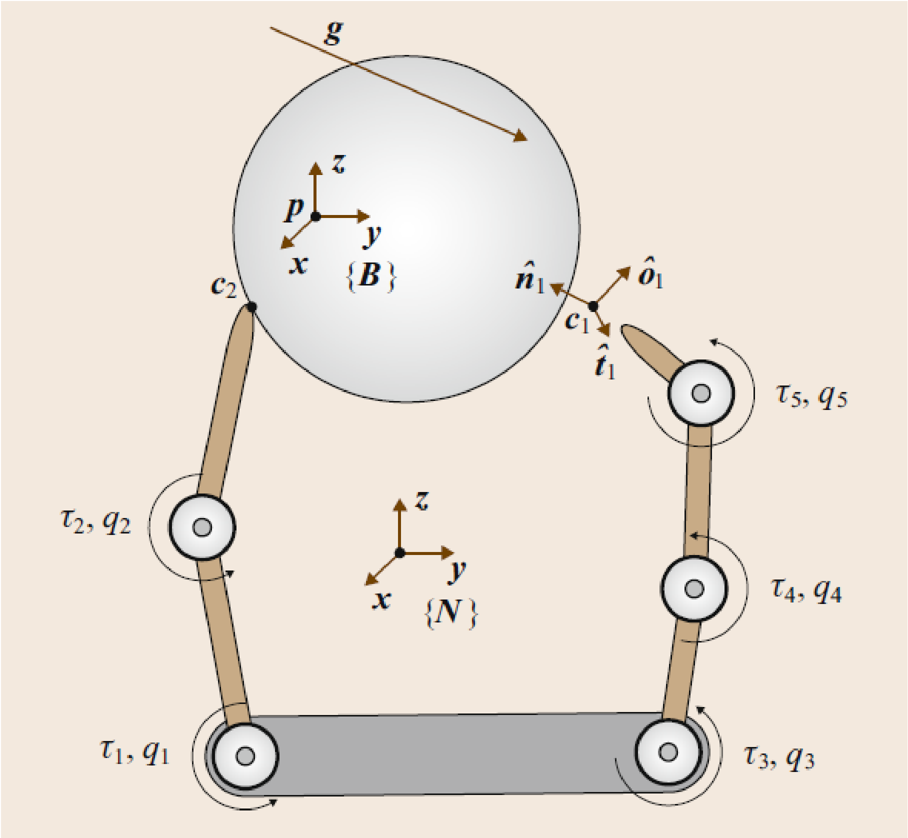
Grasp Kinematics

- Partial Grasp Matrix
  - Object twist in world frame {N} → Object twist in the contact frame {C}

$$\nu_{i,\text{obj}} = \tilde{\mathbf{G}}_i^{\mathrm{T}} \nu$$

where

$$\tilde{\mathbf{G}}_i^{\mathrm{T}} = \overline{\mathbf{R}}_i^{\mathrm{T}} \mathbf{P}_i^{\mathrm{T}}$$



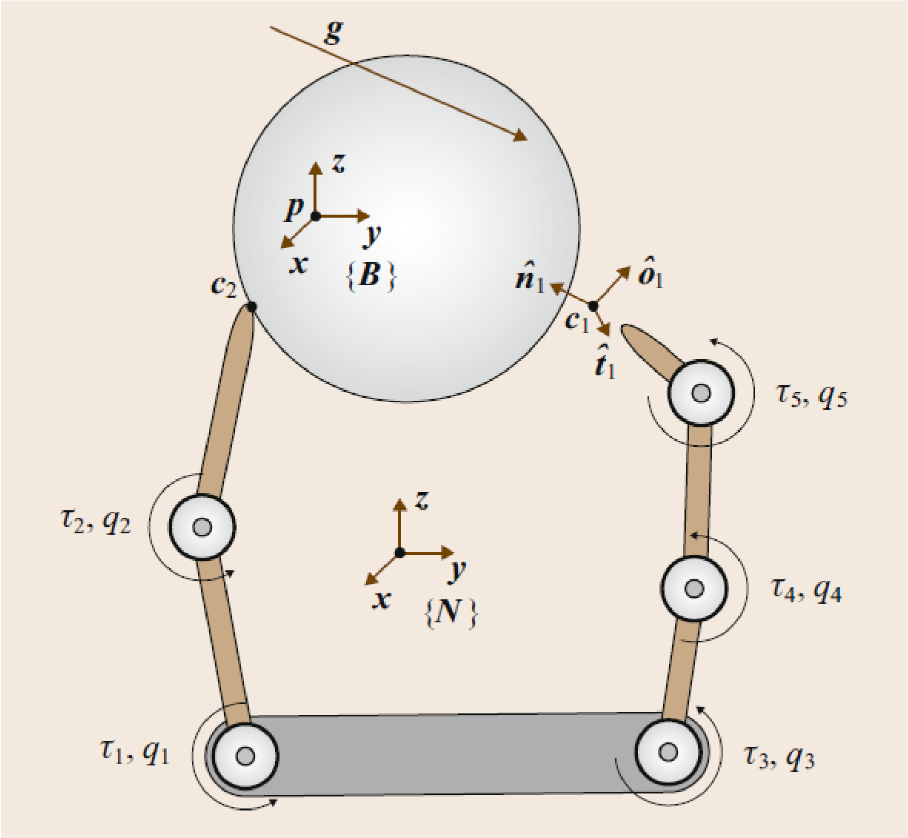
Grasp Kinematics

- Partial Hand Jacobian
  - Map joint velocities of hand → twist of the hand in {**N**} → twist of hand in {**C**}

$$\nu_{i,\text{hnd}} = \tilde{\mathbf{J}}_i \dot{q}$$

where

$$\tilde{\mathbf{J}}_i = \overline{\mathbf{R}}_i^{\mathrm{T}} \mathbf{Z}_i$$



Definition

- Kinematics

$$\boldsymbol{\nu}_{c,\text{obj}} = \tilde{\mathbf{G}}^{\mathrm{T}} \boldsymbol{\nu}\,, \qquad \boldsymbol{\nu}_{c,\text{hnd}} = \tilde{\mathbf{J}} \dot{q}\,,$$

where

$$\tilde{\mathbf{G}}^{\mathrm{T}} = \begin{pmatrix} \tilde{\mathbf{G}}_1^{\mathrm{T}} \\ \vdots \\ \tilde{\mathbf{G}}_{n_c}^{\mathrm{T}} \end{pmatrix}, \quad \tilde{\mathbf{J}} = \begin{pmatrix} \tilde{\mathbf{J}}_1 \\ \vdots \\ \tilde{\mathbf{J}}_{n_c} \end{pmatrix}$$

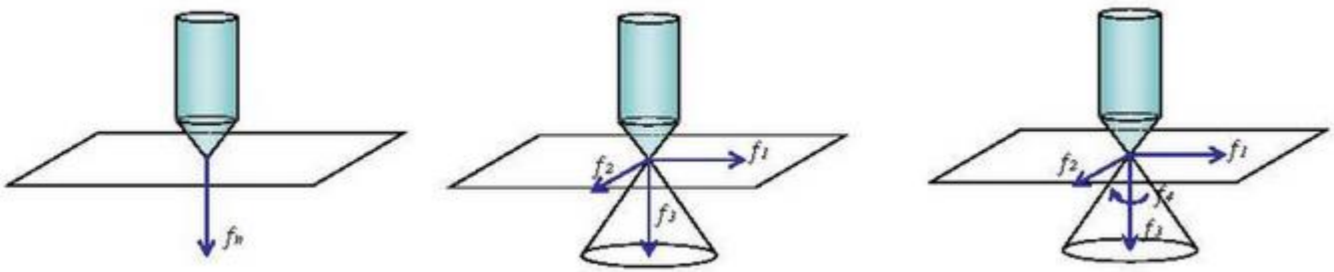
- Contact
  - Two coincident points – one on the hand, one on the object

$$\mathbf{H}_i(\boldsymbol{\nu}_{i,\text{hnd}} - \boldsymbol{\nu}_{i,\text{obj}}) = \mathbf{0}\,. \qquad \mathbf{H}_i = \left[\begin{array}{c|c} \mathbf{H}_{iF} & \mathbf{0} \\ \hline \mathbf{0} & \mathbf{H}_{iM} \end{array}\right]$$

- Immobilization
  - A grasp can counter any wrench applied to the object
  - Guarantees the stability of the grasp

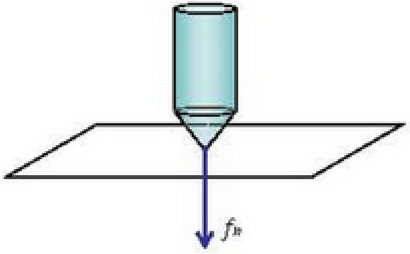
Contact Modeling

- Point contact without friction
- Hard-finger
- Soft-finger



Contact Modeling

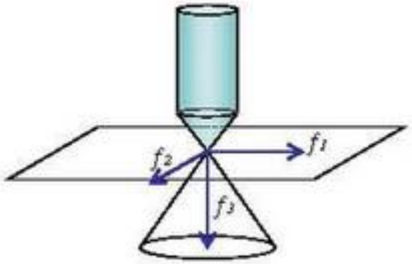
- Point contact without friction (PwoF)
  - Contact properties
    - Contact patch is small
    - Contact surface is slippery → no surface friction
  - Transmitted to the object
    - Normal component of the translational velocity
    - Normal component of the contact force



Contact Modeling

- Hard Finger (HF)
  - Contact properties
    - Small contact patch
    - Large enough surface friction

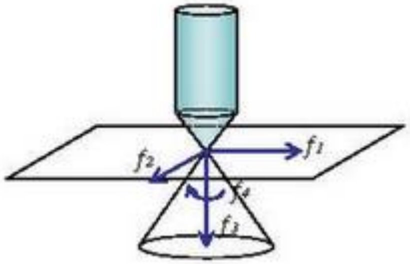
    } friction force, but no appreciable friction moment
  - Transmitted to the object
    - All three components of the translational velocity
    - All three components of the contact force
    - No angular velocity or moment



Contact Modeling

- Soft Finger (SF)
  - Contact properties
    - Large enough contact patch
    - Large enough surface friction

    } appreciable friction moment
  - Transmitted to the object
    - All three components of the translational velocity
    - All three components of the contact force
    - Normal component of contact moment



Contact Modeling

- Relative twist at each contact point

$$\begin{pmatrix}\tilde{\mathbf{J}}_i & -\tilde{\mathbf{G}}_i^{\mathrm{T}}\end{pmatrix}\begin{pmatrix}\dot{q}\\ \nu\end{pmatrix} = \nu_{i,\mathrm{hnd}} - \nu_{i,\mathrm{obj}}$$

- When object is stably grasped
  - $\mathbf{H}_i(\nu_{i,\mathrm{hnd}} - \nu_{i,\mathrm{obj}}) = \mathbf{0}$, where $\mathbf{H}_i = \left[\begin{array}{c|c}\mathbf{H}_{i\mathrm{F}} & \mathbf{0}\\ \hline \mathbf{0} & \mathbf{H}_{i\mathrm{M}}\end{array}\right]$
- Kinematic contact constraint equation

$$\mathbf{H}(\nu_{c,\mathrm{hnd}} - \nu_{c,\mathrm{obj}}) = \mathbf{0}$$

which is

$$\begin{pmatrix}\mathbf{J} & -\mathbf{G}^{\mathrm{T}}\end{pmatrix}\begin{pmatrix}\dot{q}\\ \nu\end{pmatrix} = \mathbf{0}$$

where

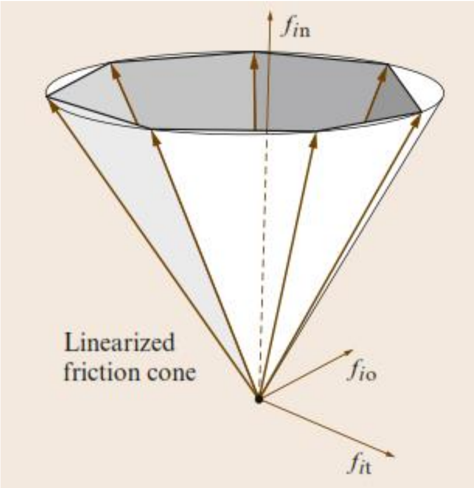
$$\mathbf{G}^{\mathrm{T}} = \mathbf{H}\tilde{\mathbf{G}}^{\mathrm{T}} \in \mathbb{R}^{n_\lambda \times 6}$$
$$\mathbf{J} = \mathbf{H}\tilde{\mathbf{J}} \in \mathbb{R}^{n_\lambda \times n_q}.$$

Contact Modeling

- Friction cone
  - The set of forces that can be applied at a contact point without sliding on the object
  - Friction cone for ith contact point is the set

$$\mathcal{F}_i = \left\{ (f_{in}, f_{it}, f_{io}) \mid \sqrt{f_{it}^2 + f_{io}^2} \leq \mu_i f_{in} \right\}$$

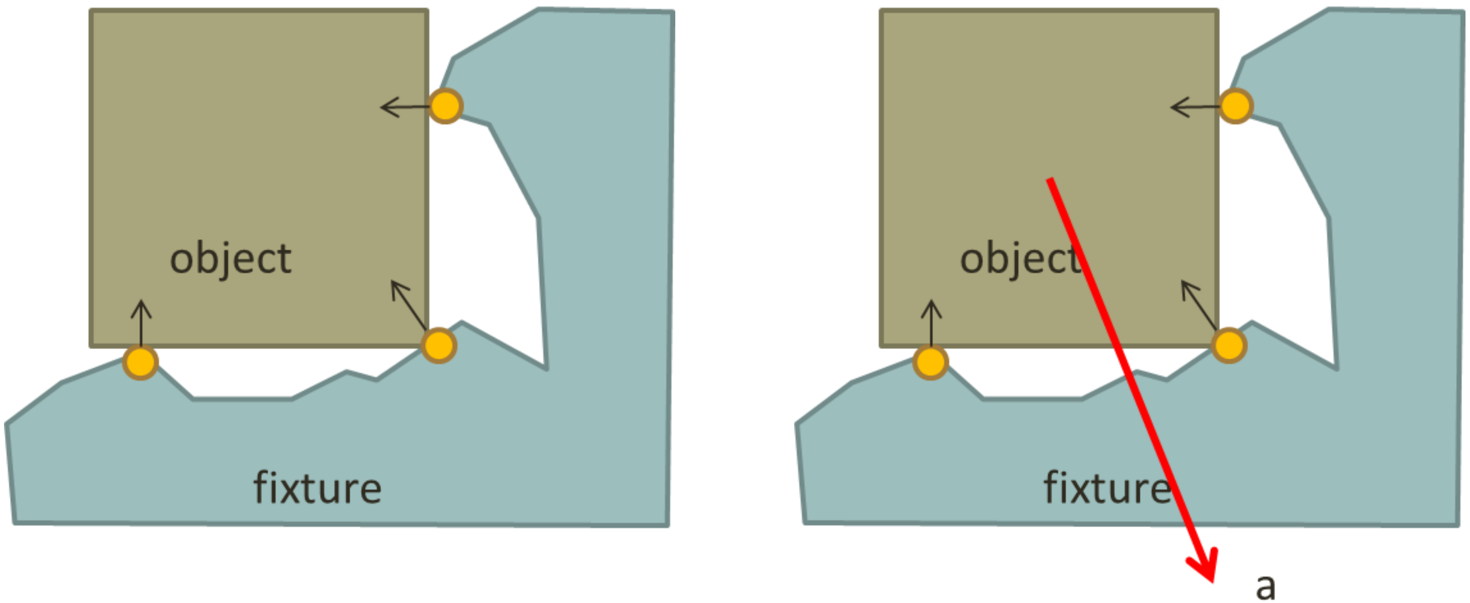
    - f_{in} is the force applied normal to the surface
    - f_{io} and f_{it} are the forces applied along the surface



- Notes
  - Coulomb friction
  - Depends on coefficient of friction between hand and object (μ)
  - Bigger μ implies wider friction cone

Grasp Restraint

- Form closure
- Force closure



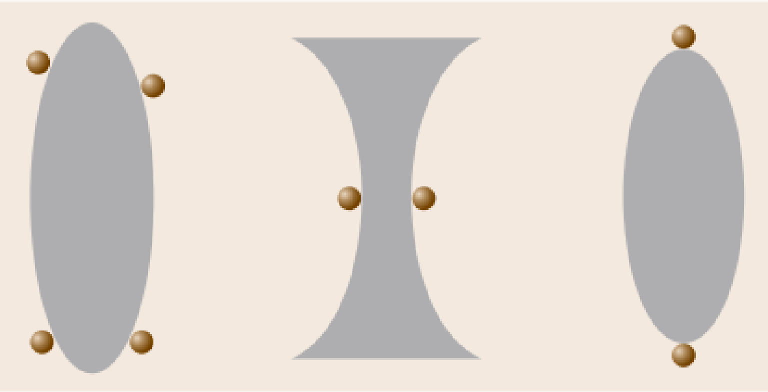
Form Closure

- Form closure grasp
  - The object cannot move **regardless of surface friction**

- What does this imply?
  - If the grasping hand has its joints locked, it is impossible to move the object, even infinitesimally

Form closure

- Which of these is in form closure?



- Example – power (enveloping) grasp
  - Palm and finger wrap around the object

Form Closure

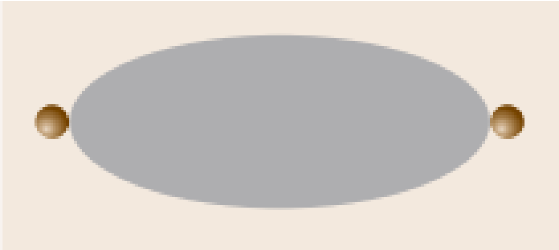
- You need ***at least*** N+1 contacts to achieve first-order form closure, where N is the number of DOF of the object

Dimension of Object	Minimum Number of Contacts for First-Order Form Closure
2D (3 DOF)	4
3D (6 DOF)	7

[K. Lakshminarayana: Mechanics of form closure, Amer. Soc. Mech. Eng. Tech. Rep. **78-DET-32** (1978)]

Force Closure

- Definition
  - **Frictional properties** of the object can be used to immobilize the object

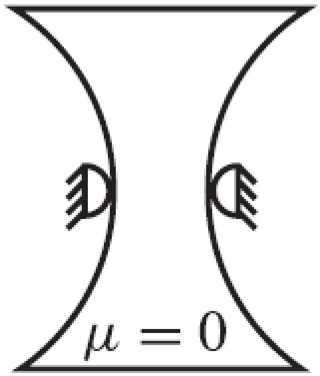


- What does it imply?
  - If the grasping hand has its joints locked, stability of this grasp depends on friction between contacts and object (μ)

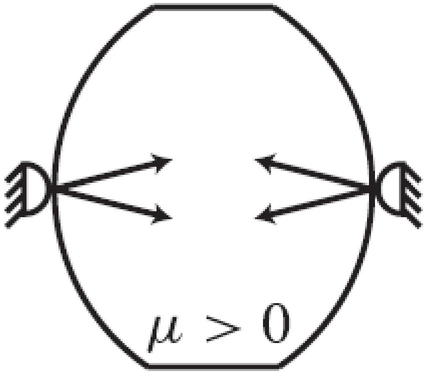
Form closure VS Force closure

- If a grasp achieves form closure, does it also achieve force closure?
  - First order form closure → form closure
  - Frictionless force closure → force closure
  - First order form closure = Frictionless force closure
- All first-order form closure grasps are also force closure
  - How about second-order form closure?

Force Closure



Form closure $\not\longrightarrow$ force closure.



Force closure $\not\longrightarrow$ form closure.

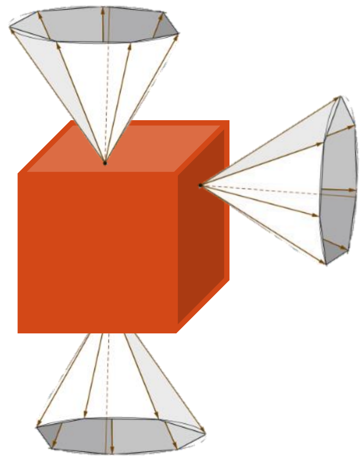
Testing of Force Closure

- Many algorithms exist to test for force closure, here is one:

Input: Contact locations

Output: Is the grasp in Force-Closure? (Yes or No)

1. Approximate the friction cone at each contact with a set of wrenches
2. Combine wrenches from all cones into a set of points *S* in wrench space
3. Compute the *convex hull* of *S*
4. If the origin is inside the convex hull, return YES. If not, return NO.



Friction cones at contacts

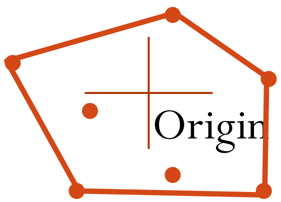
Wrench space
(6 dimensional)

Testing for Force Closure

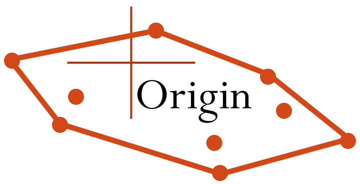
- Why does this algorithm work?
  - Hint: the convex hull represents the positive linear combination of all the wrenches

Force Closure

- Which grasp do you think is more sensitive to error in contact position?



Wrench space



Wrench space

Note: wrench space is 6-dimensional, these are only cartoons

- Yes or no answer isn't enough to choose between grasps

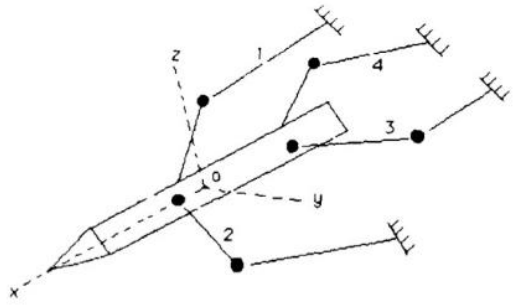
Force Closure Metrics

- A popular metric
  - Radius of largest hyper-sphere you can fit in convex hull (centered at origin)

Wrench space

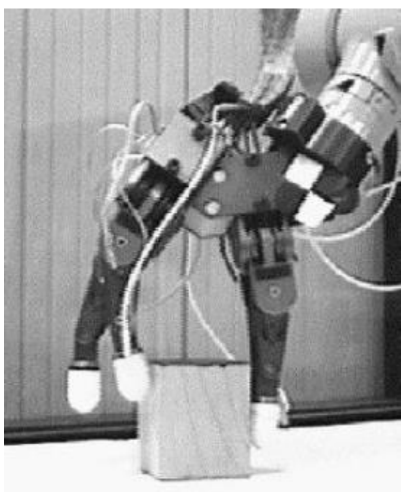
Wrench space

- Task-specific metric of Li and Sastry
  - Use **task-specific ellipsoid** instead of hyper-sphere



Force Closure

- For a 3D object
  - Minimum number of contacts to achieve force closure is 3 (compare to 7 for form closure)
  - Not surprisingly, 3-finger grippers are very popular



Stanford/JPL Hand

Barrett Hand

Robotiq Hand

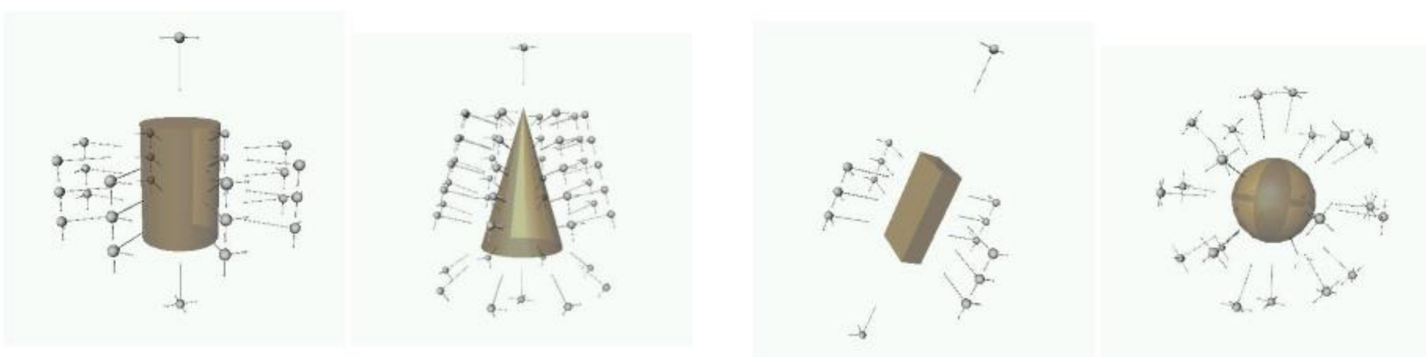
Schunk SDH Hand

Searching for Force Closure Grasps

- In the 90s
  - Search for a **set of *n* point contacts** on **the surface of an object**, where *n* is the number of fingers of your hand
- Search is in 2*n* dimensional space (since surface of object is 2-dimensional)
- Disadvantage
  - Ignores hand kinematics → probability that these contacts are reachable while obeying hand kinematics is low
  - Search space scales poorly with number of fingers

Searching for Force Closure Grasps

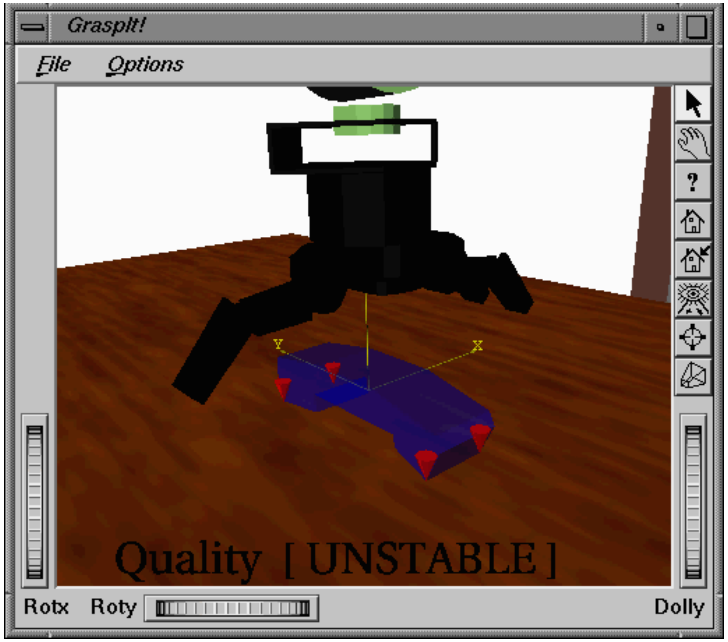
- In the 2000s (Peter Allen et al.):
  - Sample pose of hand relative to object with fingers in a pre-shape
  - Approach object until contact and close the fingers
  - Get contact points between fingers and object
  - Test these contact points for force closure
- Advantages
  - **Search space** is only 6-dimensional (pose of hand) + set of pre-shapes
  - Search can be arranged so hand always approaches parallel to surface of object



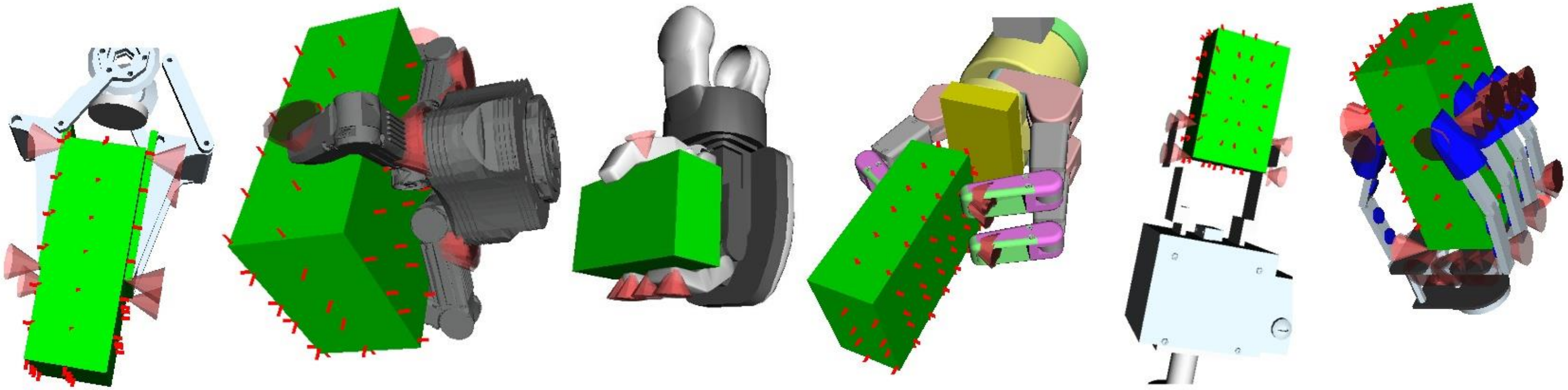
Pre-computing Grasp Sets

- Searching for grasps is slow!
  - Especially with dynamics

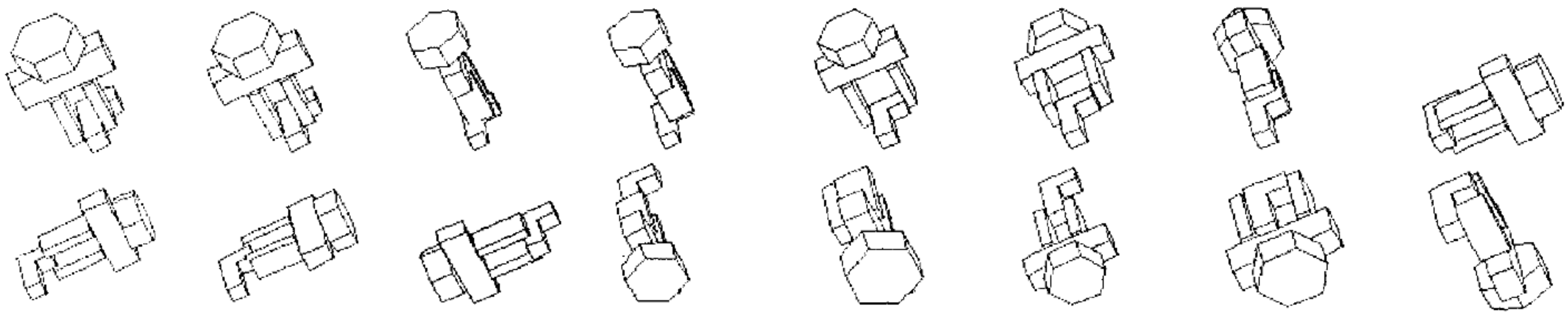
    (i.e. if you don't assume object is fixed)



- But, we can **pre-compute** a set of stable grasps for a given object



Pre-computing grasp sets is not new!



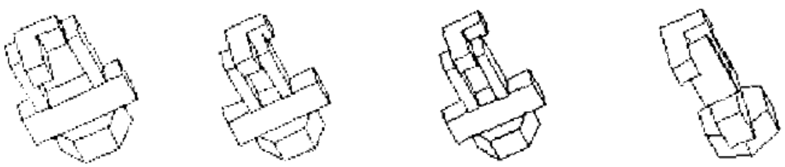


Figure 6. The different groups of approach directions and grasp classes for a particular orientation of an L-shaped object, heuristically ranked by desirability.

5.1 Choosing a grasp

Before attempting a detailed plan of the grasp, Handey examines different classes of candidate grasps and evaluates their feasibility both at the pickup point and the putdown point. A grasp class is characterized by a choice of object surfaces. Within a

[Handey: A robot system that recognizes, plans, and manipulates, Lozano-Perez, T., Jones, J., Mazer, E.. O'Donnell, P., Grimson, W., Tournassoud, P., Lanusse, A., ICRA 1987]

Columbia Grasp Database

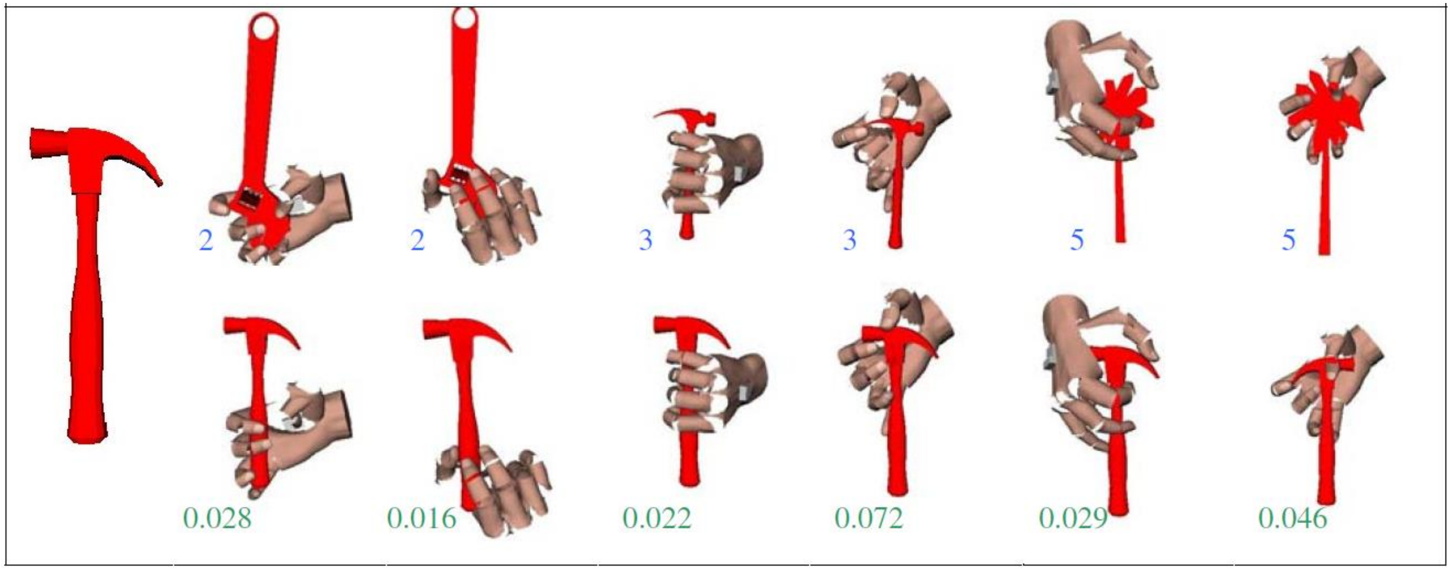
- http://grasping.cs.columbia.edu/
- Reuse the 3D models from the Princeton Shape Benchmark (PSB)
  - Well known academic dataset of 1,814 models
  - All models resized to "graspable" sizes
  - PSB models were not originally selected with an eye towards robotic grasping
    - Some of the models are not obvious choices for grasping experiments.
- Provide grasps at 4 scales
  - …because grasping is scale dependent
  - .75, 1.0, 1.25 and 1.5 times the size of each model
  - 7,256 3D models in all

*Shilane *et al.*, SMI 2004

The Columbia Grasp Database. Goldfeder, Ciocarlie, Dang, and Allen, ICRA 2009

Columbia Grasp Database

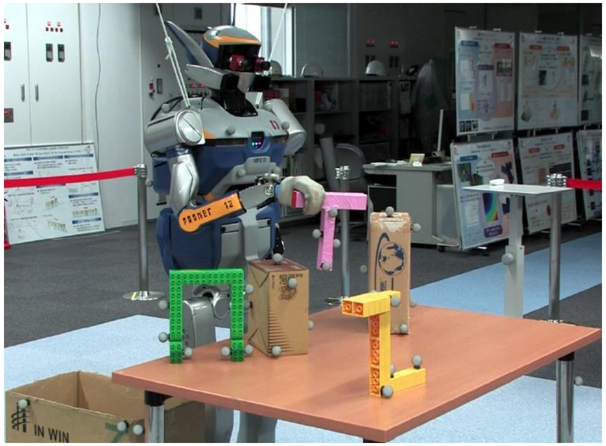
- How to compute a grasp given the database?
  - Shape matching, collocating and grasp computing



- Performance
  - 20 seconds, from shape matching to final output

Integrating Grasping and Manipulation Planning

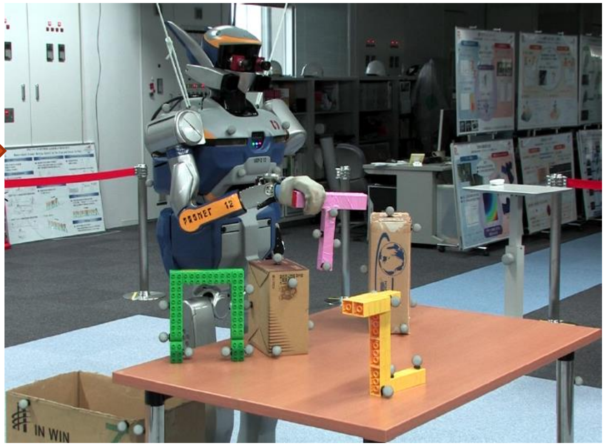
- So far …
  - We only test for collision with obstacles online (ignore them when computing grasp set)
  - We wanted to integrate grasp planning with motion planning (consider obstacles and reachability, too)



[Berenson, D., Diankov, R., Nishiwaki, K., Kagami, S., & Kuffner, J. (2007). Grasp Planning in Complex Scenes. *IEEE-RAS International Conference on Humanoid Robots (Humanoids07)*]

Integrating Grasping and Manipulation Planning

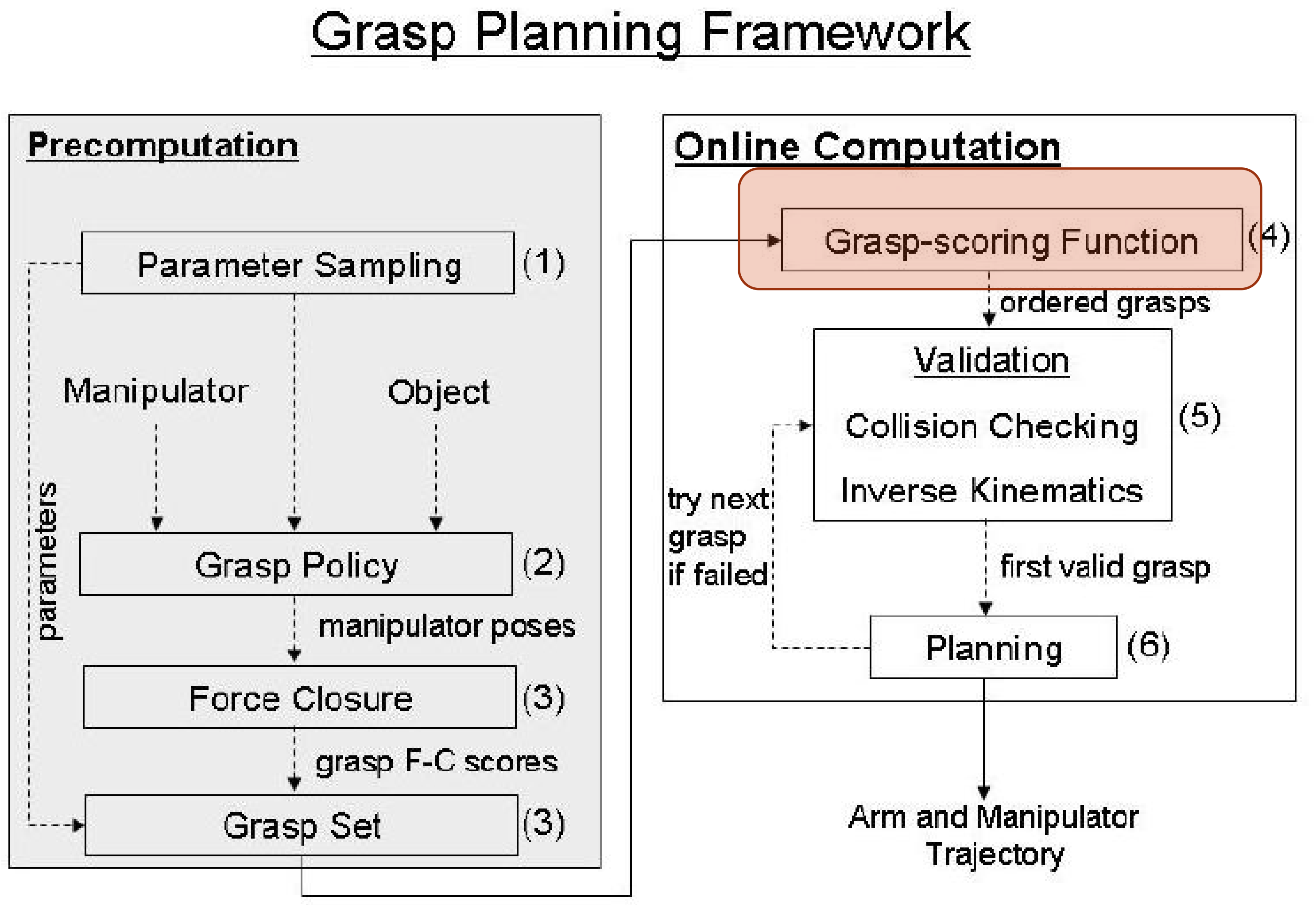
Find a Valid grasp in a cluttered environment



- Grasping + Manipulation planning
  - Valid grasp – Grasp quality metric
  - Local information – object, robot kinematics, etc.
- Approach
  1. Pre-compute grasp set offline, get force-closure score
  2. Online, compute 2 scores for each grasp
     - Environment Clearance Score
     - Reachability Score

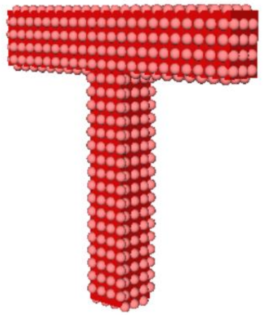
[Berenson, D., Diankov, R., Nishiwaki, K., Kagami, S., & Kuffner, J. (2007). Grasp Planning in Complex Scenes. *IEEE-RAS International Conference on Humanoid Robots (Humanoids07)*]

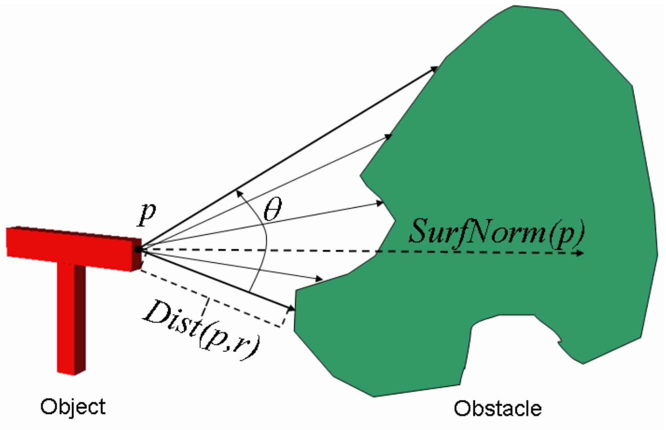
Integrating Grasping and Manipulation Planning

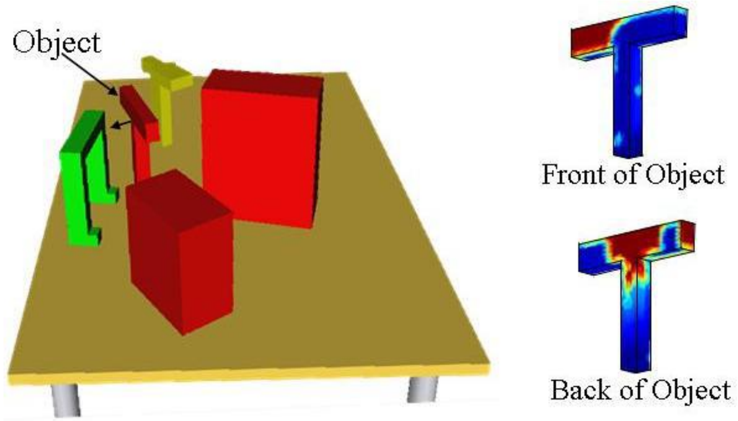


Computing Environment Clearance Score

- Compute **clearance** from points on object to nearest obstacle

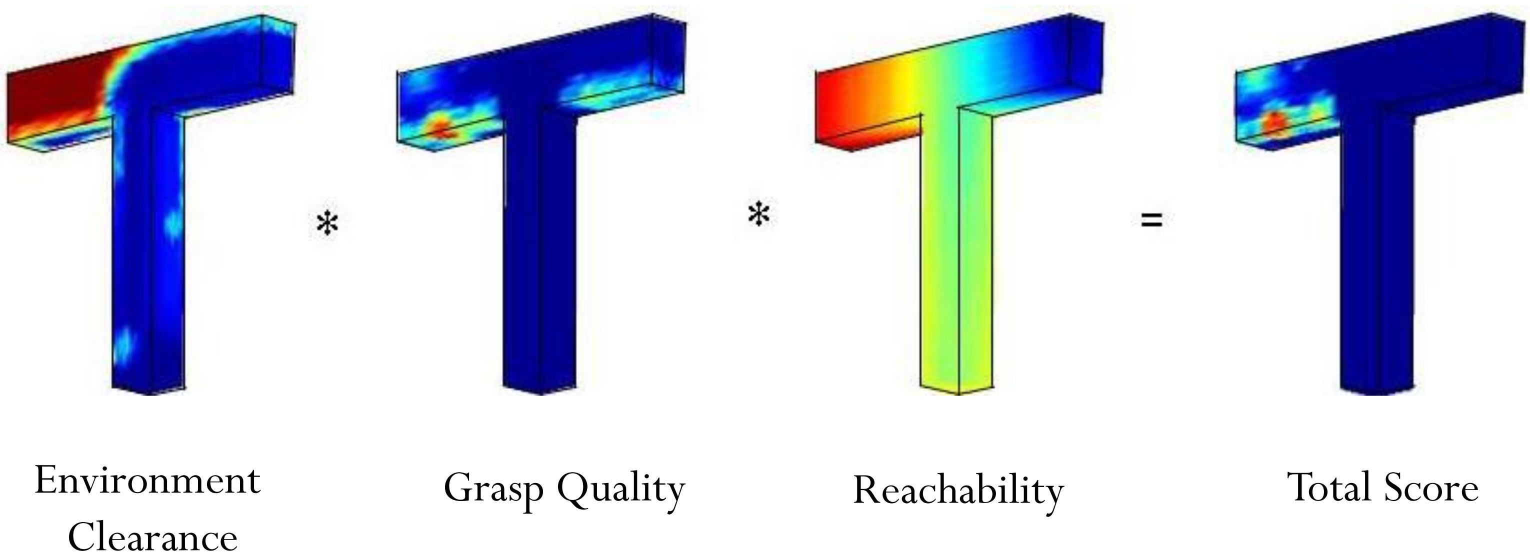






Integrating Grasping and Manipulation Planning

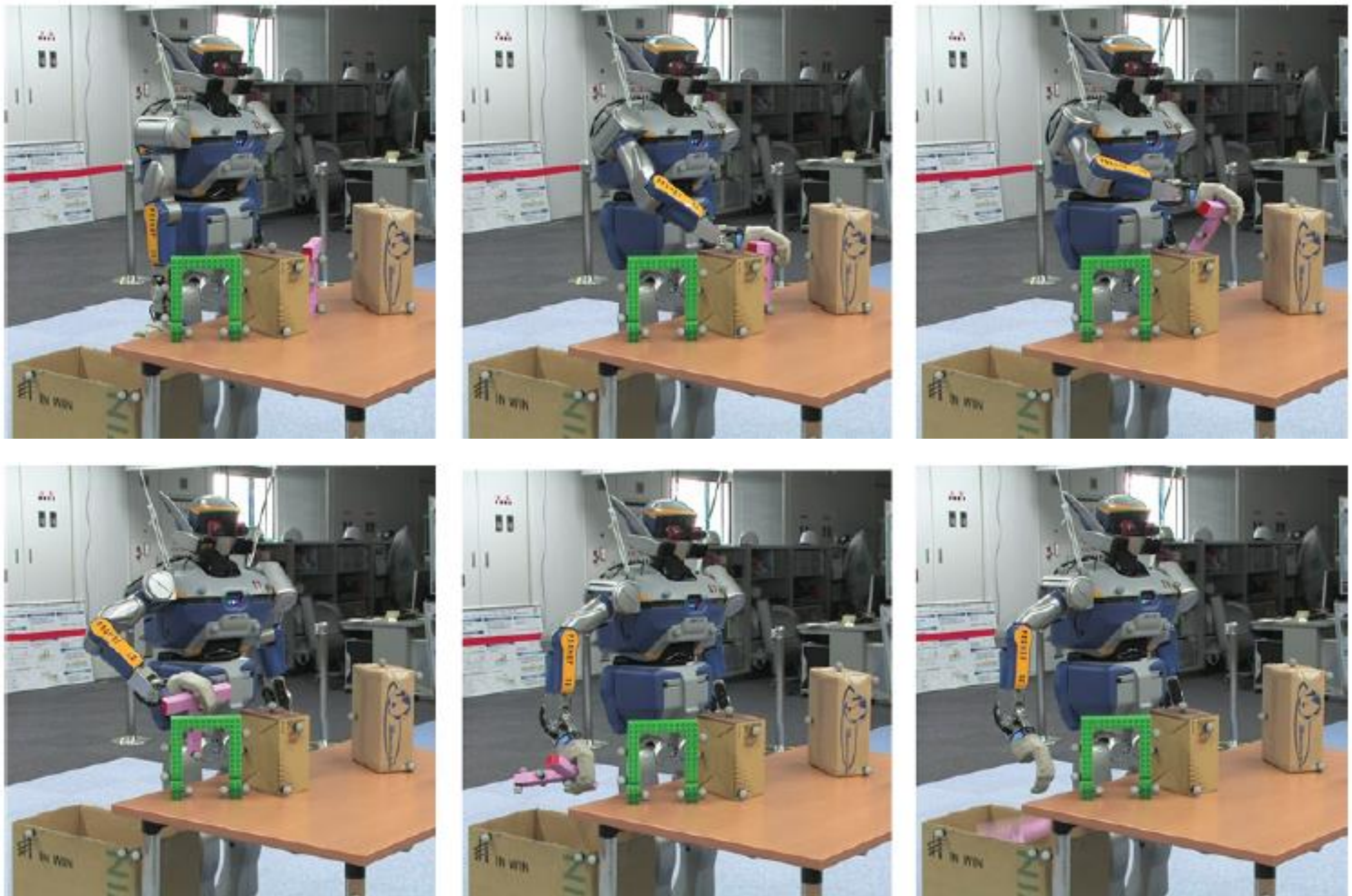
- Combine scores to create grasp ranking



- Test grasps in order of ranking
  - We showed this is much faster than testing in random order

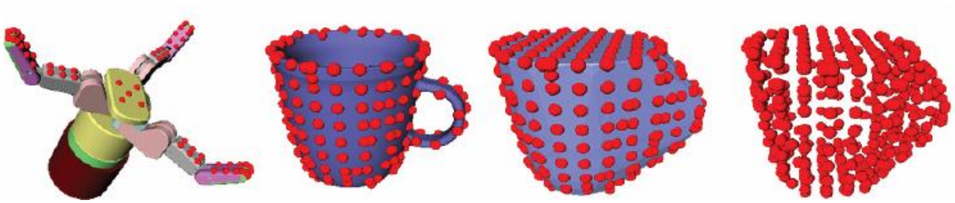
[Berenson, D., Diankov, R., Nishiwaki, K., Kagami, S., & Kuffner, J. (2007). Grasp Planning in Complex Scenes. *IEEE-RAS International Conference on Humanoid Robots (Humanoids07)*]

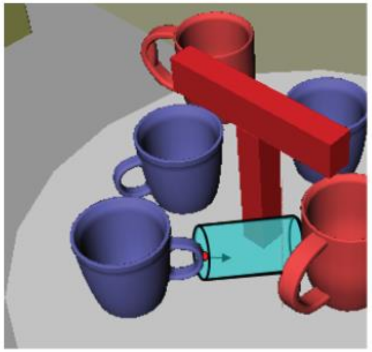
Integrating Grasping and Manipulation Planning

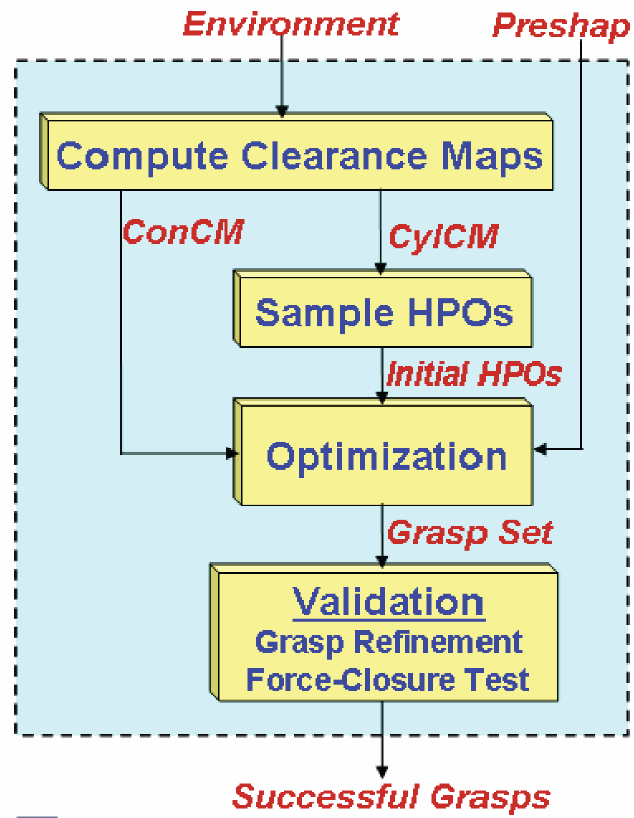


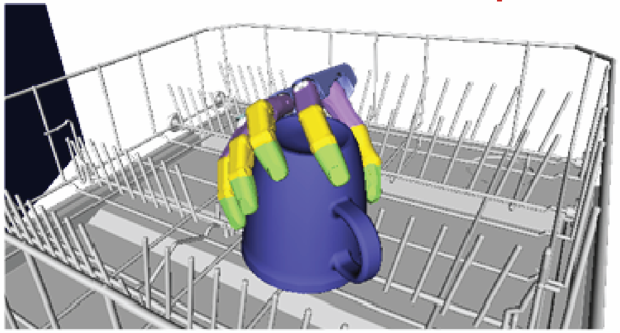
Grasp Planning in Complex Scenes

- Motivation
  - Integration of grasp and manipulation planning is still limited to a fixed set of grasps
  - Next, we tried searching for grasps **online** using similar scoring









Grasp Planning in Complex Scenes

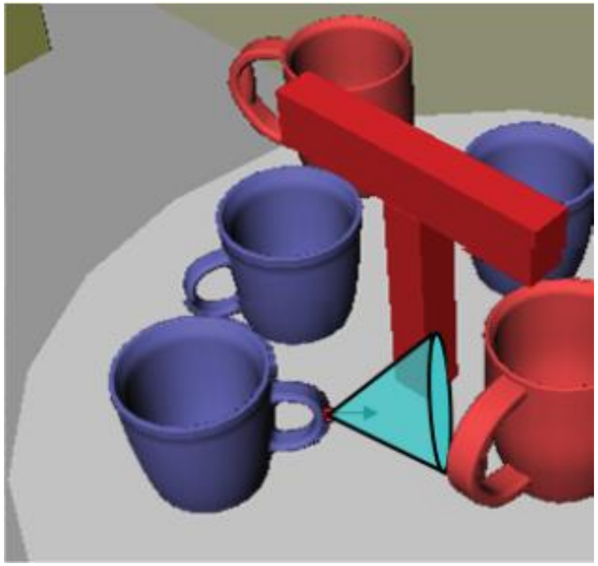
- Cost function for optimization

$$C(\mathrm{HPO}, O, E) = \frac{F(\mathrm{HPO}, O) + \zeta S(\mathrm{HPO}, O)}{X(\mathrm{HPO}, E)}$$

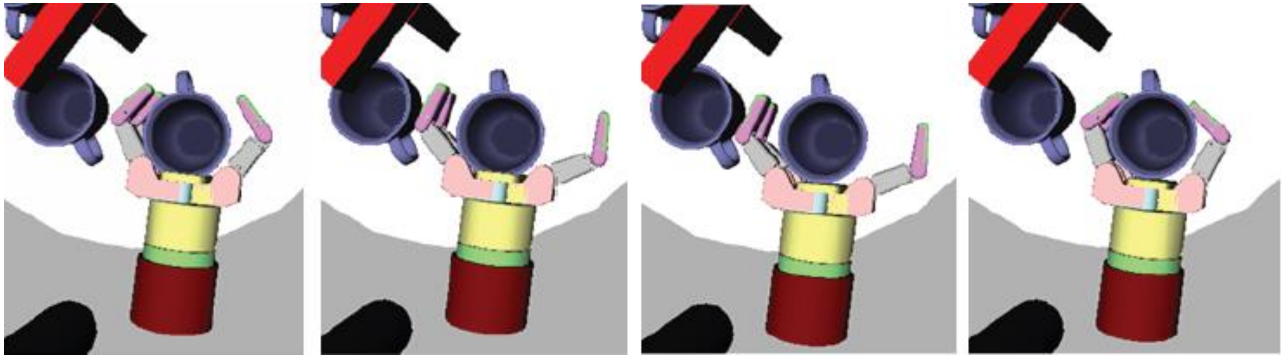
  - Approximate Collision – F(HPO,O)
    - Whether the fixed part of the hand will be in collision
  - Fit Cost – S(HPO,O)
    - The error of the fit between the preshape and the object at this HPO
  - Contact Safety Cost – X(HPO, E)
    - The likelihood of the fingers being able to reach the desired contact points without collision – **how**?

Grasp Planning in Complex Scenes

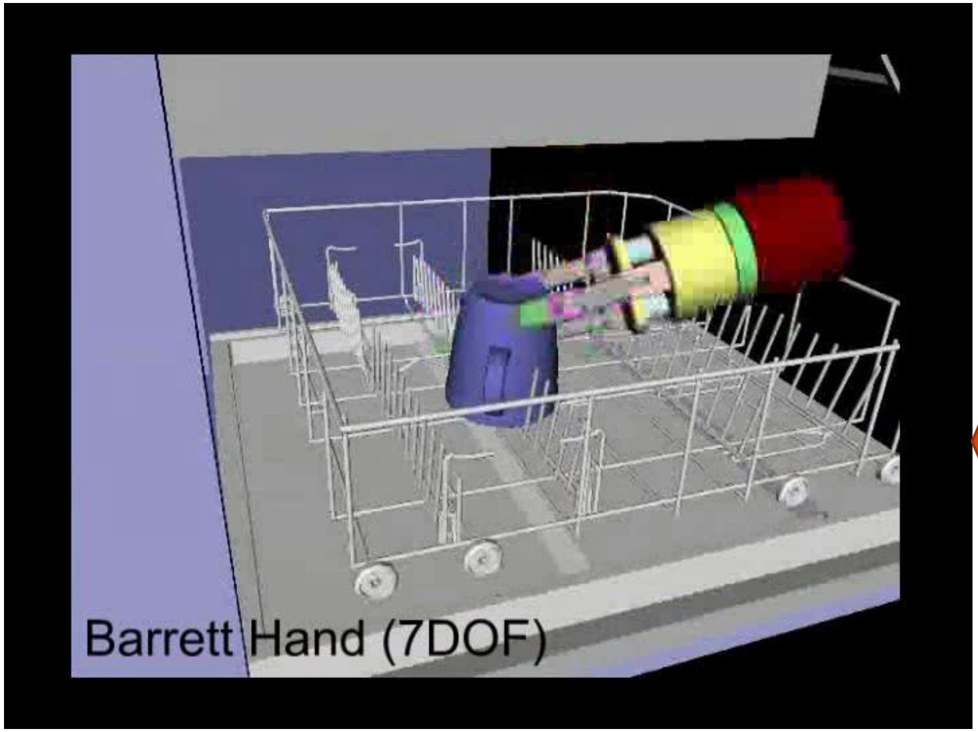
- Conical Clearance Map (ConCM)
  - To evaluate the cost of contacting the object



Grasp Planning in Complex Scenes



Grasp refinement to avoid interpentration of the palm



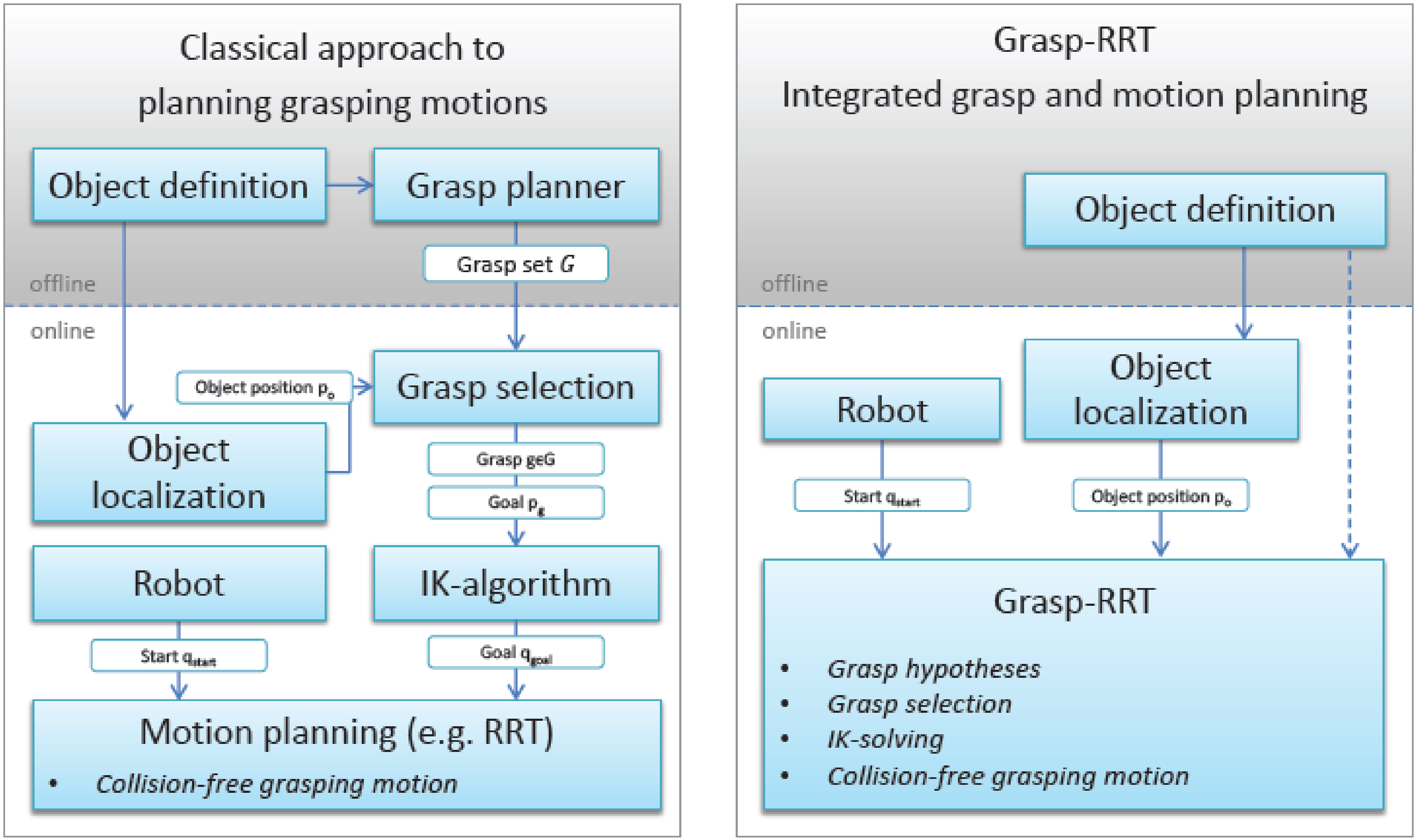
[Grasp Synthesis in Cluttered Environments for Dexterous Hands. Berenson and Srinivasa, Humanoids 2008]

Grasp–RRT planner

- Motivation
  - What if the object model is incomplete and/or inaccurate?
    - The pre-computed grasps may not fit well
  - No pre-calculated grasping data → pure online search

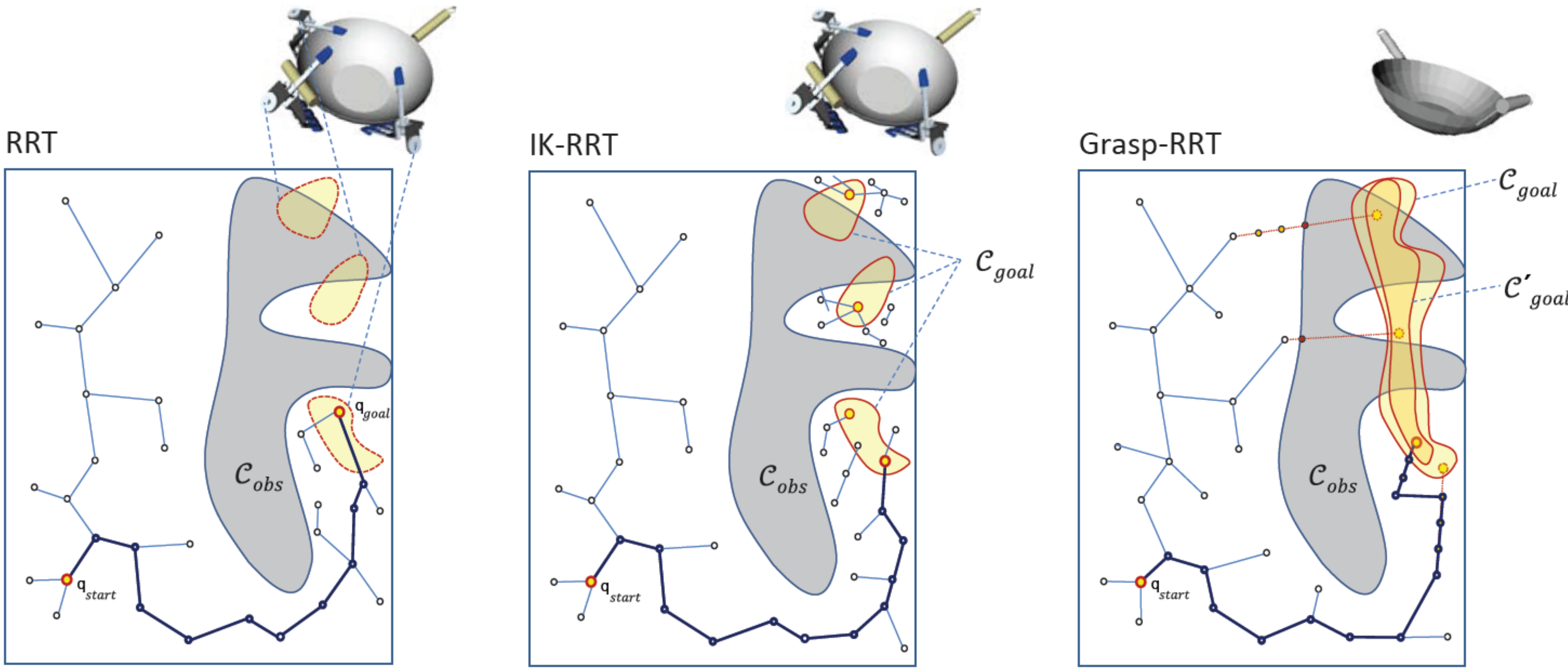
- Grasp–RRT planner
  - Build a feasible grasp +
  - Solving IK +
  - Search a collision-free trajectory to the grasping pose

Comparison


Classical approach to planning grasping motions
Object definition
Grasp planner
Grasp set G
offline
online
Object position p_o
Grasp selection
Object localization
Grasp $g \in G$
Goal p_g
Robot
IK-algorithm
Start q_{start}
Goal q_{goal}
Motion planning (e.g. RRT)
• *Collision-free grasping motion*
Grasp-RRT
Integrated grasp and motion planning
Object definition
offline
online
Robot
Object localization
Start q_{start}
Object position p_o
Grasp-RRT
• *Grasp hypotheses*
• *Grasp selection*
• *IK-solving*
• *Collision-free grasping motion*

Grasp–RRT planner

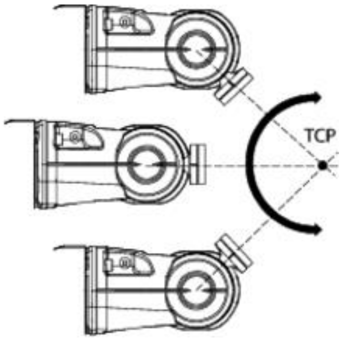
- Grasp-RRT

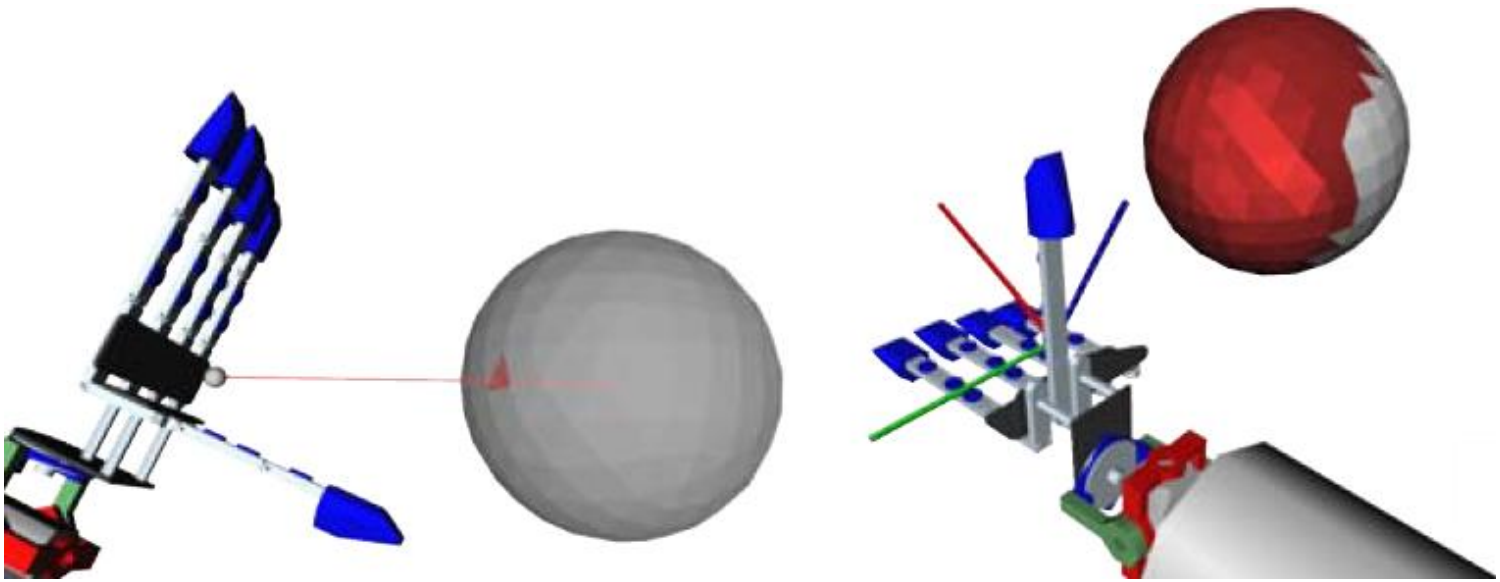


Vahrenkamp N, Asfour T, Dillmann R. Simultaneous grasp and motion planning: Humanoid robot ARMAR-III. IEEE Robotics & Automation Magazine. 2012 Jun;19(2):43-57.

Grasp–RRT planner

- Determine the approach direction
  - Approach sphere
  - Sampling distribution





Grasp–RRT planner

- Based on the approach direction
  - Compute a virtual target pose
  - Resolve IK and move towards the target pose as far as possible
  - Validate the grasping pose
    - Closing the fingers, determining the contacts and performing grasp wrench space analysis

Grasp–RRT planner

- Compute a target pose