Grasp Planning

CS 6341 Robotics

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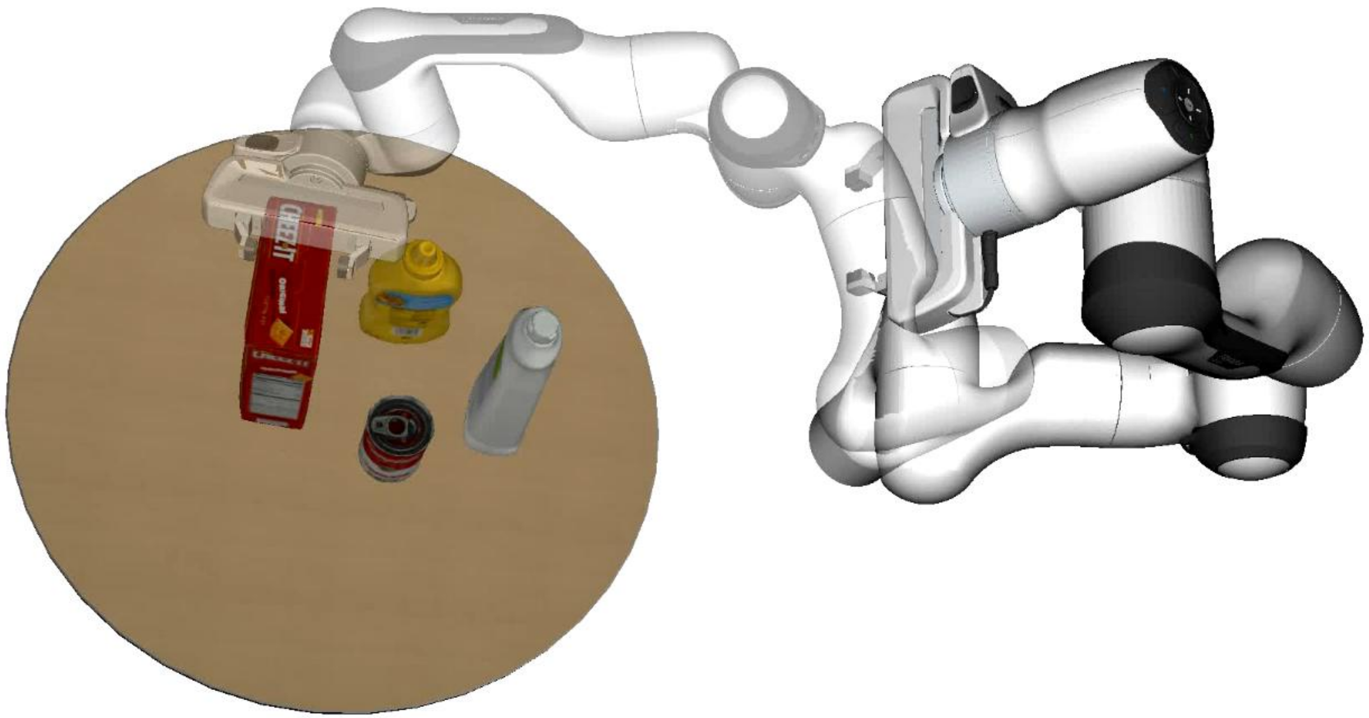
Introduction

GraspIt! https://graspit-simulator.github.io/

Andrew Miller and Peter K. Allen. "Graspit!: A Versatile Simulator for Robotic Grasping". IEEE Robotics and Automation Magazine, V. 11, No.4, Dec. 2004, pp. 110-122.

Grasps are used as the goals for motion planning

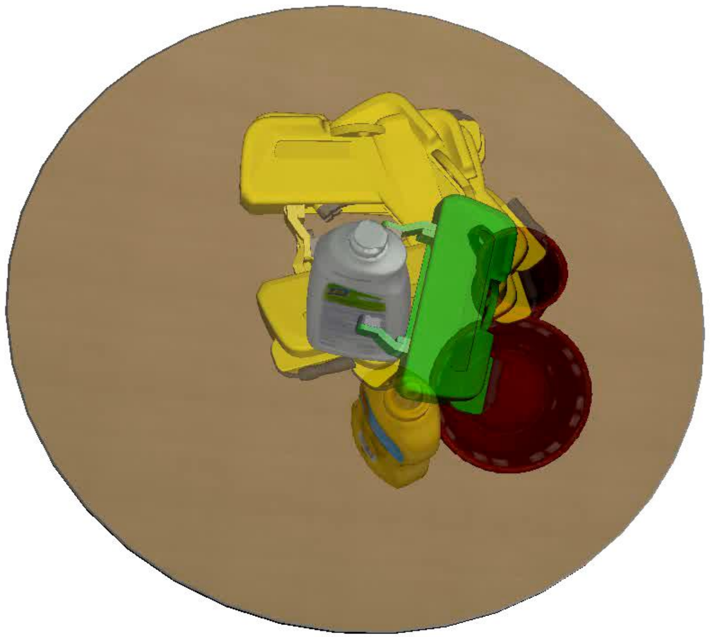


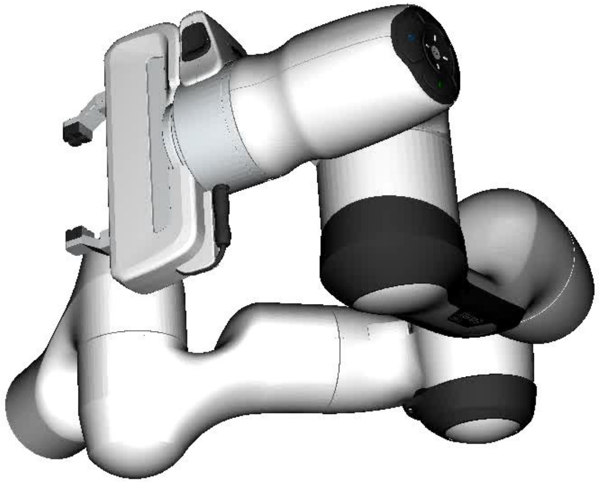
Covariant Hamiltonian Optimization for Motion Planning (CHOMP): Ratliff-Zucker-Bagnell-Srinivasa, ICRA'09

Grasps are used as the goals for motion planning

OMG Iter: 50

100 grasps





Modeling the goal set distribution

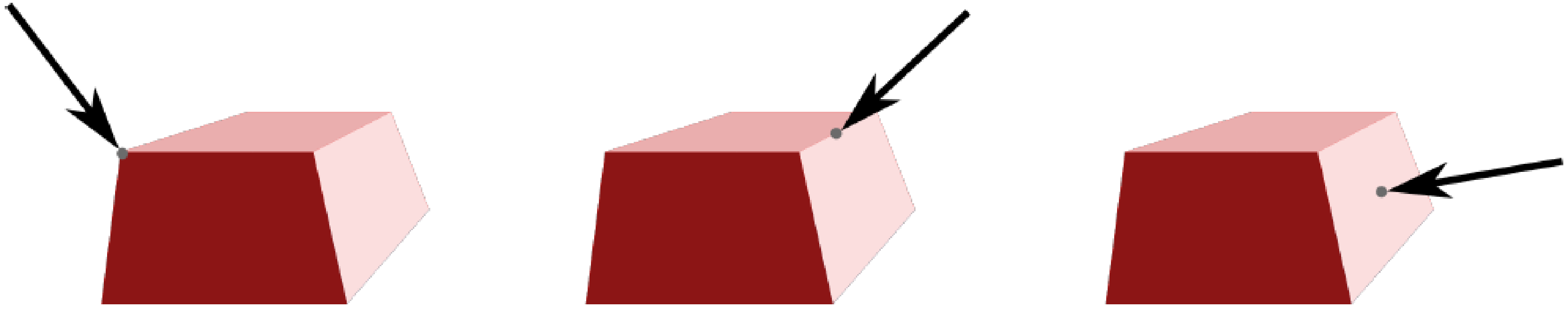
Wang-Xiang-Fox, Manipulation Trajectory Optimization with Online Grasp Synthesis and Selection RSS'20

Grasp Planning

- Model-based methods
  - Force closure analysis
  - Physics simulation

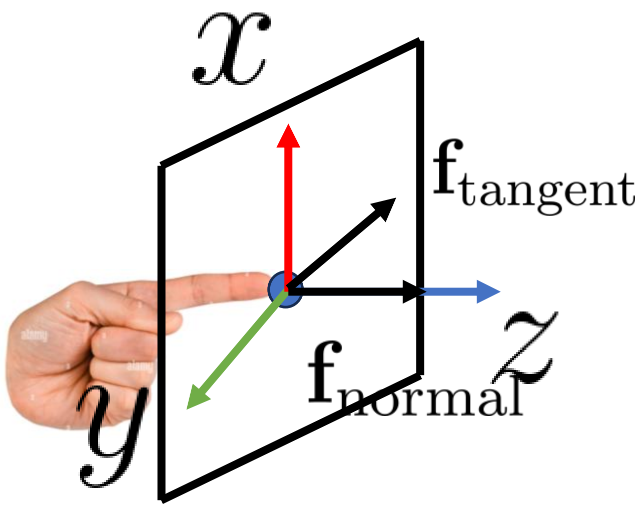
- Learning-based methods
  - Learning generative models with grasping datasets
  - Predicting contact maps, keypoints on object surfaces
  - Predicting hand configurations

Contact Modeling



Point-on-point Point-on-line Point-on-plane

Point-on-Plane Contact Models

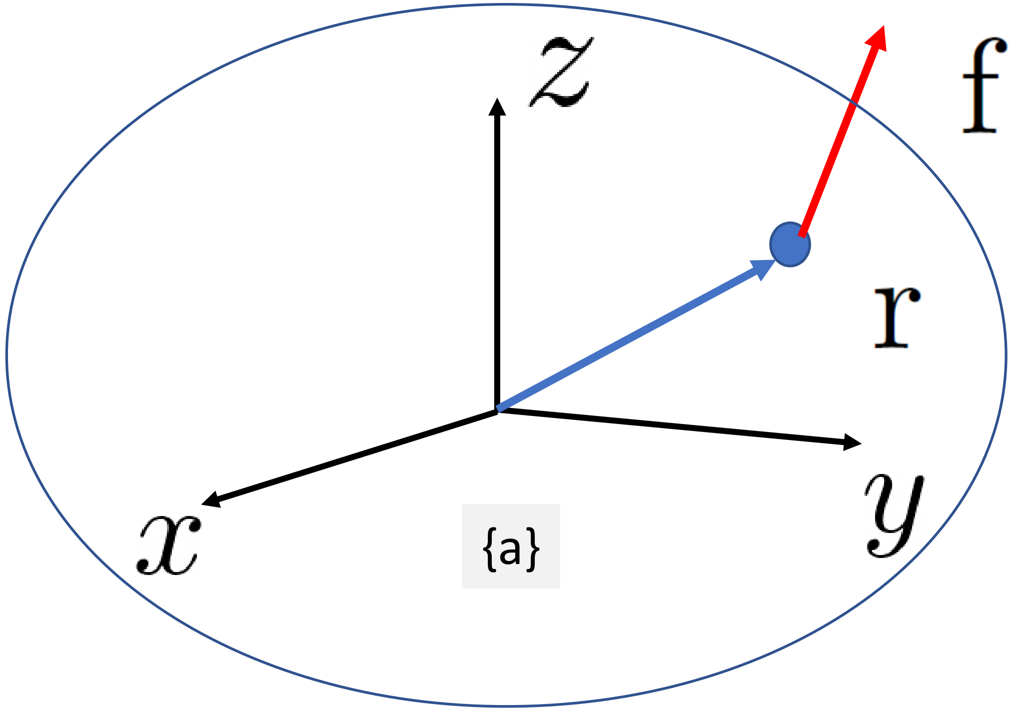


$$\mathbf{f} = \mathbf{f}_{\text{normal}} + \mathbf{f}_{\text{tangent}}$$

$$\mathbf{f}_{\text{normal}} = [0, 0, f_z]^T \quad f_z \geq 0$$

$$\mathbf{f}_{\text{tangent}} = [f_x, f_y, 0]^T$$

Recall Torque and Wrench



A rigid body

Point $r_a \in \mathbb{R}^3$

Force $f_a \in \mathbb{R}^3$

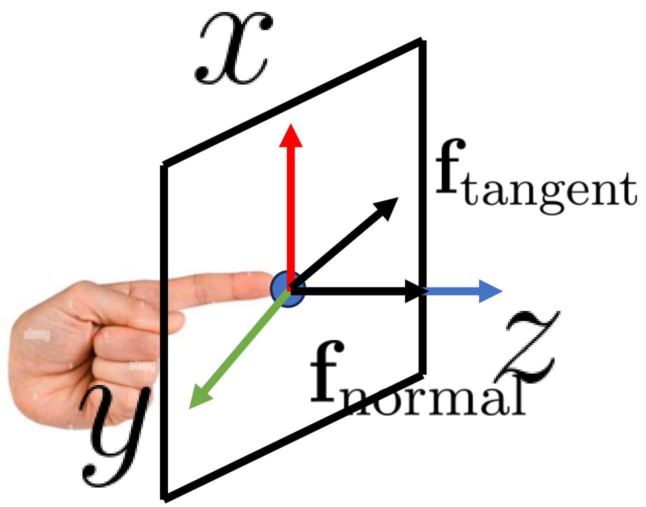
Torque or Moment

$$m_a \in \mathbb{R}^3$$

$$m_a = r_a \times f_a$$

Wrench $\mathcal{F}_a = \begin{bmatrix} m_a \\ f_a \end{bmatrix} \in \mathbb{R}^6$

Point-on-Plane Contact Models



Frictionless Point Contact:

$$\mathcal{F} = \{\mathbf{f}_{\text{normal}} | f_z \geq 0\}$$

Admissible forces (i.e. forces that don't lead to slipping)

Friction Point Contact:

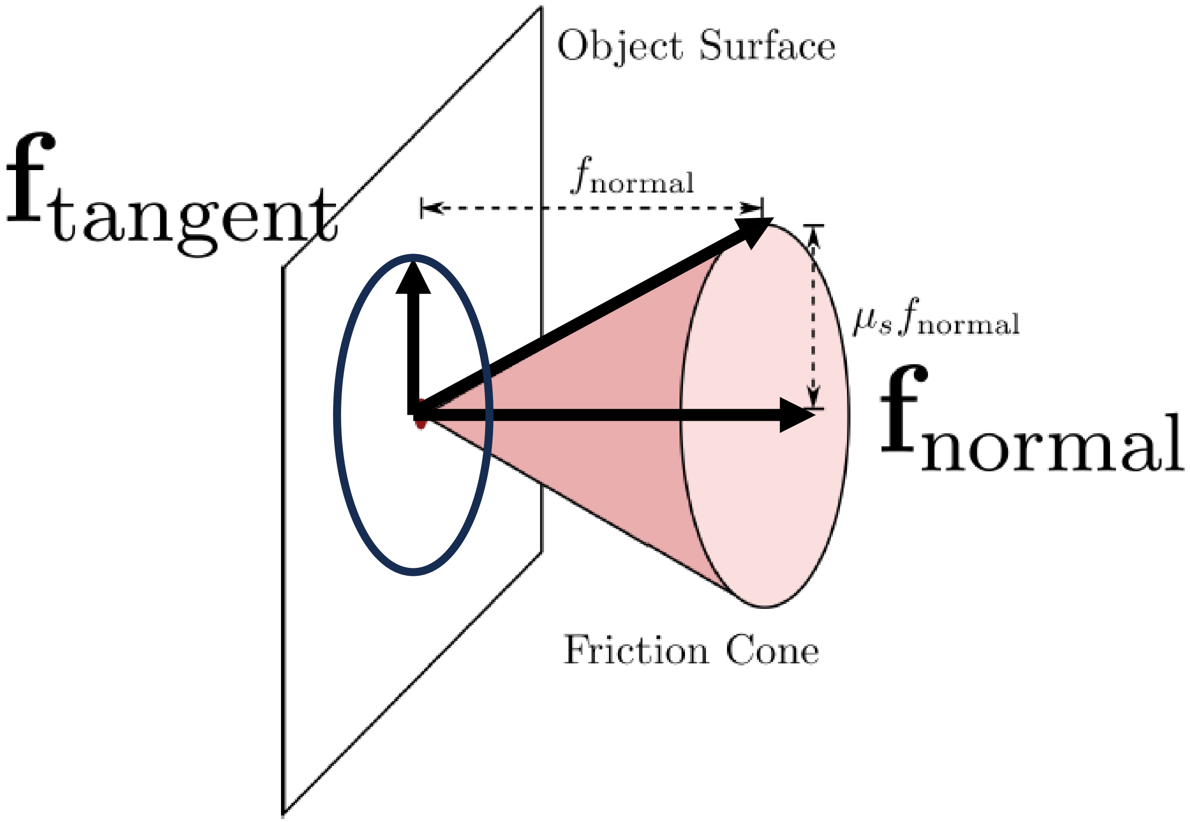
$$\mathcal{F} = \{\mathbf{f} | \|\mathbf{f}_{\text{tangent}}\| \leq \mu_s \|\mathbf{f}_{\text{normal}}\|, f_z \geq 0\}$$

μ_s static friction coefficient

Soft-finger Contact Model

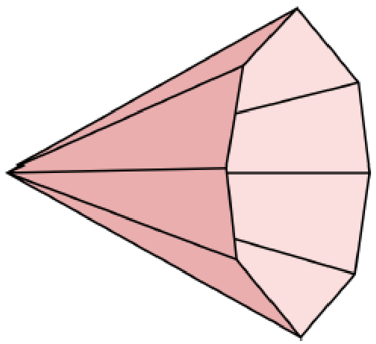
$$\mathcal{F} = \{(\mathbf{f}, \tau_{\text{normal}}) | \|\mathbf{f}_{\text{tangent}}\| \leq \mu_s \|\mathbf{f}_{\text{normal}}\|, f_z \geq 0, |\tau_{\text{normal}}| \leq \gamma f_z\}$$

Friction Cone



$$\mathcal{F} = \{\mathbf{f} \mid \|\mathbf{f}_{\text{tangent}}\| \leq \mu_s \|\mathbf{f}_{\text{normal}}\|, f_z \geq 0\}$$

$$\tan(\theta) = \mu_s$$



A pyramidal inner-approximation of the friction cone

$$\{f_{i,1}, f_{i,2}, \cdots f_{i,m}\}$$

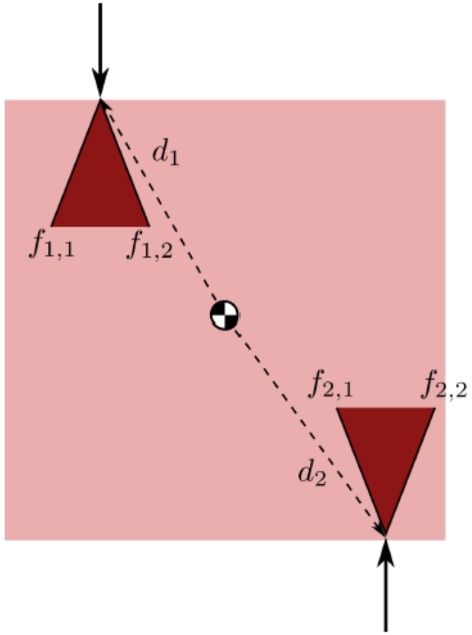
$$f_i = \sum_{j=1}^{m} \alpha_{i,j} f_{i,j}, \quad \alpha_{i,j} \geq 0$$

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

Grasp Wrench Space

- Wrench: force and torque $\boldsymbol{w} = \begin{bmatrix} \boldsymbol{f} \\ \boldsymbol{\tau} \end{bmatrix} \in \mathbb{R}^6$

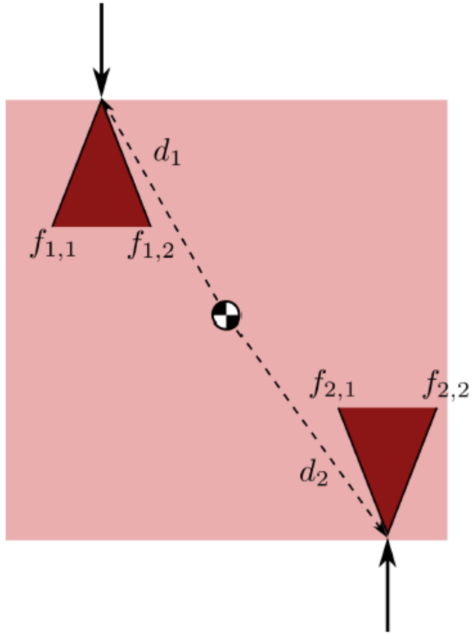
- Each contact point applies a wrench to the object



$$\boldsymbol{w}_i = \begin{bmatrix} \boldsymbol{f}_i \\ \lambda(\boldsymbol{d}_i \times \boldsymbol{f}_i) \end{bmatrix}$$

$$\omega_i = \begin{bmatrix} I \\ \lambda[\mathbf{d}_i] \end{bmatrix} \mathbf{f}_i \qquad \omega_i = G_i \mathbf{f}_i$$

Grasp Wrench Space



Total wrench on the object

k contact points

$$w = \sum_{i=1}^{k} G_i f_i = G \begin{bmatrix} f_1 \\ \vdots \\ f_k \end{bmatrix}, \quad G = \begin{bmatrix} G_1 & \dots & G_k \end{bmatrix}$$

grasp map

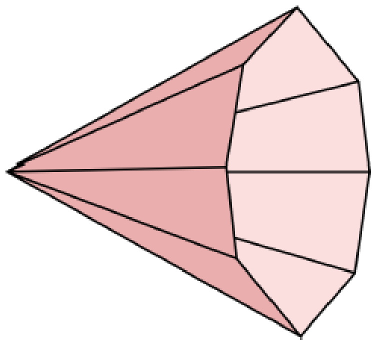
Grasp Wrench Space

- The grasp wrench space W for a grasp with k contact points is the set of all possible wrenches **w** that can be applied to the object through admissible forces:

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

- If the grasp wrench space is large, the grasp can compensate for a bigger set of external wrenches that might be applied to the object, leading to a more robust grasp

Grasp Wrench Space



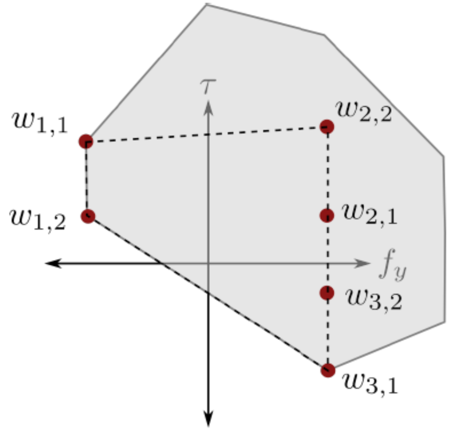
$$\{f_{i,1}, f_{i,2}, \dots f_{i,m}\}$$

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

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

$$\mathcal{W} = \{w \mid w = \sum_{i=1}^{k} w_i, \quad w_i = \sum_{j=1}^{m} \alpha_{i,j} w_{i,j}, \quad w_{i,j} = \begin{bmatrix} f_{i,j} \\ \lambda(d_i \times f_{i,j}) \end{bmatrix},$$

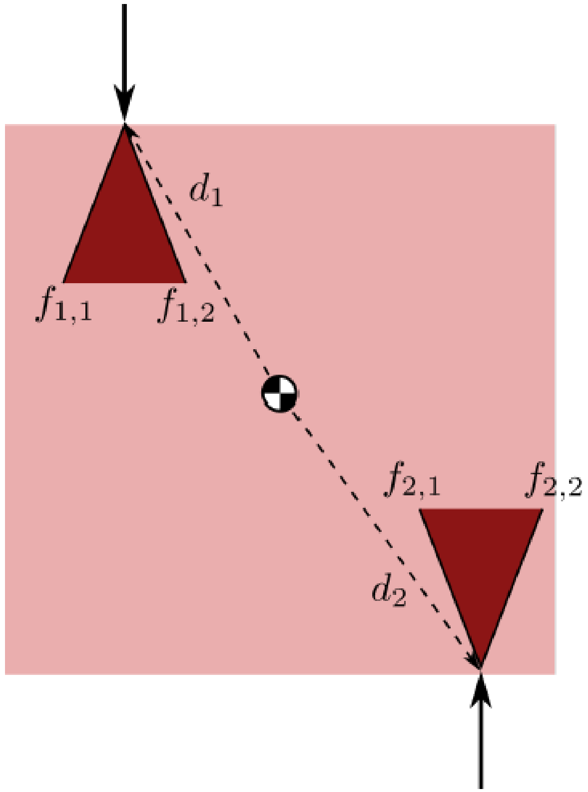
$$\sum_{j=1}^{m} \alpha_{i,j} \leq 1, \quad \alpha_{i,j} \geq 0\}.$$

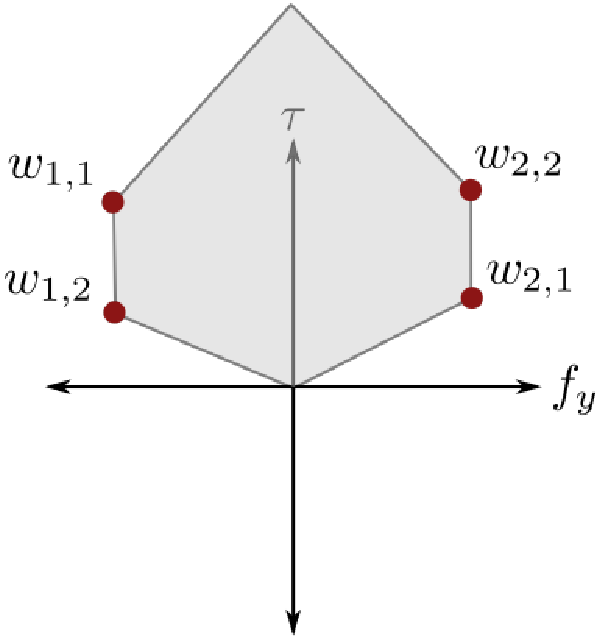


Grasp Wrench Hull

$$\tilde{\mathcal{W}} = \{w \mid w = \sum_{i=1}^{k} \sum_{j=1}^{m} \alpha_{i,j} w_{i,j}, \quad w_{i,j} = \begin{bmatrix} f_{i,j} \\ \lambda(d_i \times f_{i,j}) \end{bmatrix}, \quad \sum_{i=1}^{k} \sum_{j=1}^{m} \alpha_{i,j} = 1, \quad \alpha_{i,j} \geq 0\}$$

Grasp Wrench Space





ignoring the horizontal force components f_x

Force Closure Grasp

- A grasp is a force closure grasp if for any external wrench **w** there exist contact forces $\{f_i\}_{i=1}^{k}$ such that

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

Or

$$-w \in \mathcal{W}.$$

resist any external wrench

The grasp wrench space needs to be $\mathcal{W} = \mathbb{R}^n$

For 2D objects n = 3 and for 3D n = 6

Force Closure Grasp

Grasp Wrench Hull

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

- Theorem: In an n-dimensional vector space with

$$\mathcal{W} := \{\boldsymbol{w} \mid \boldsymbol{w} = \sum_{k=1}^{N} \beta_k \boldsymbol{w}_k, \quad \beta_k \geq 0\},$$

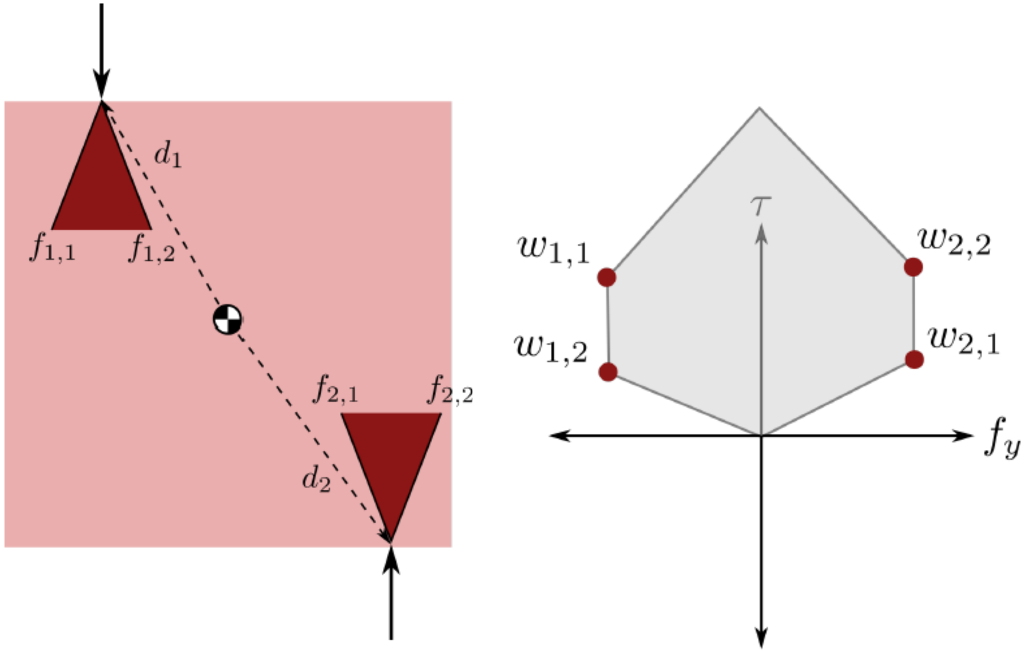
$\mathcal{W} = \mathbb{R}^n$ *if and only if the set* $\{\boldsymbol{w}_k\}_{k=1}^{N}$ *contains at least* $n+1$ *vectors,* n *of the vectors are linearly independent, and there exists scalars* $\beta_k > 0$ *such that:*

$$\sum_{k=1}^{N} \beta_k \boldsymbol{w}_k = 0.$$

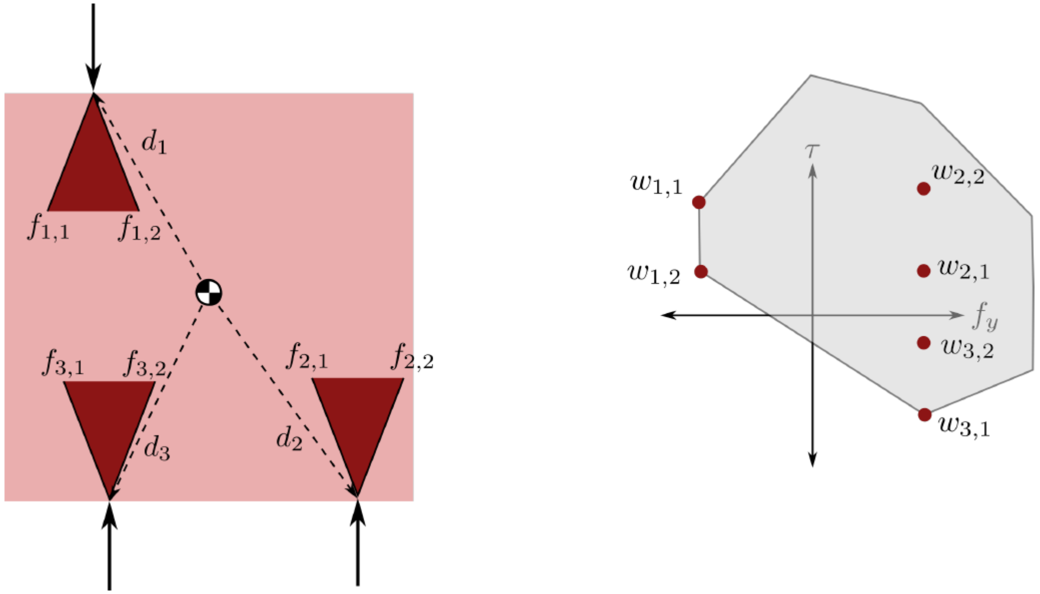
grasp wrench space W must contain the origin in its interior

Force Closure Grasp

n = 3



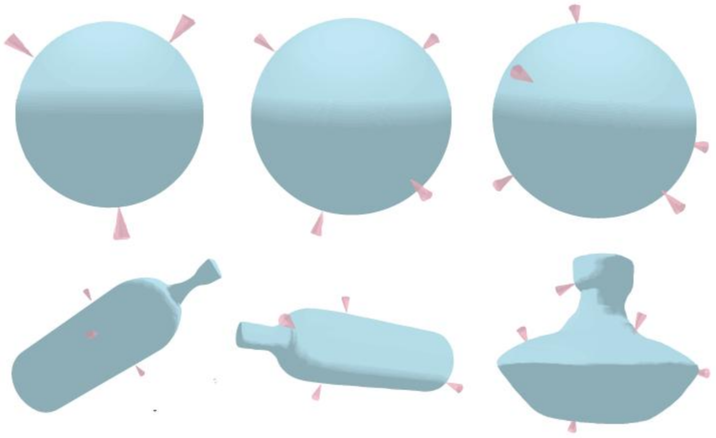
Not force closure



force closure

Optimization to find force closure grasps

- Find contact points $\mathbf{x}_1, \ldots, \mathbf{x}_k$, and contact forces $\mathbf{f}_1, \ldots, \mathbf{f}_k$



$$GG' \succeq \epsilon I_{6\times 6},$$

G is full rank

$$Gf = 0,$$

grasp wrench hull contains the origin in its interior

$$f_i^T c_i > \frac{1}{\sqrt{\mu^2+1}}|f_i|,$$

Friction cone constraint

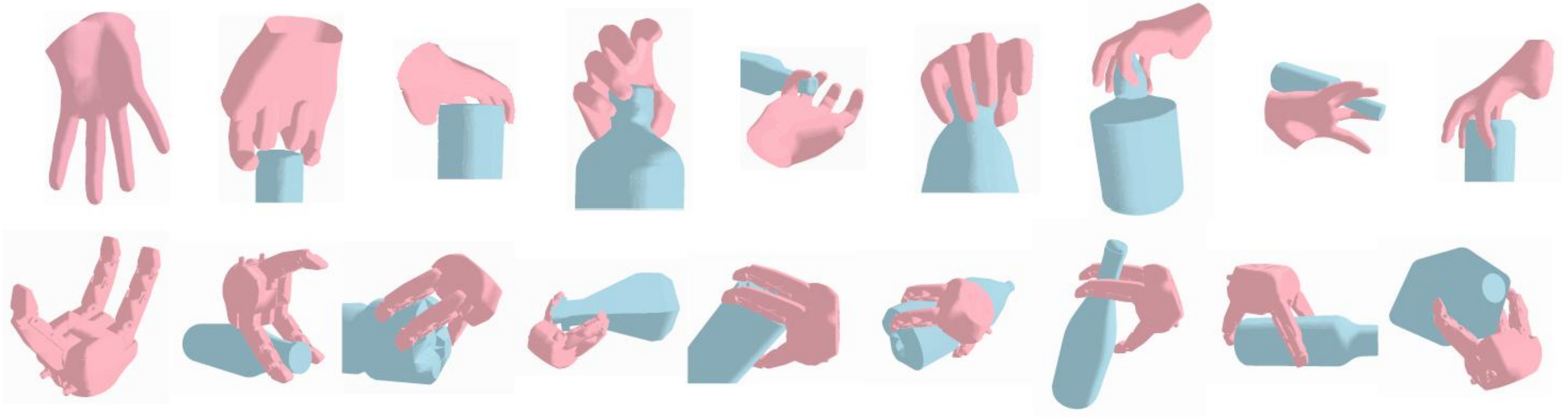
$$x_i \in S,$$

Point on object surface

$$G = \begin{bmatrix} I_{3\times 3} & I_{3\times 3} & \ldots & I_{3\times 3} \\ \lfloor x_1 \rfloor_\times & \lfloor x_2 \rfloor_\times & \ldots & \lfloor x_n \rfloor_\times \end{bmatrix}$$

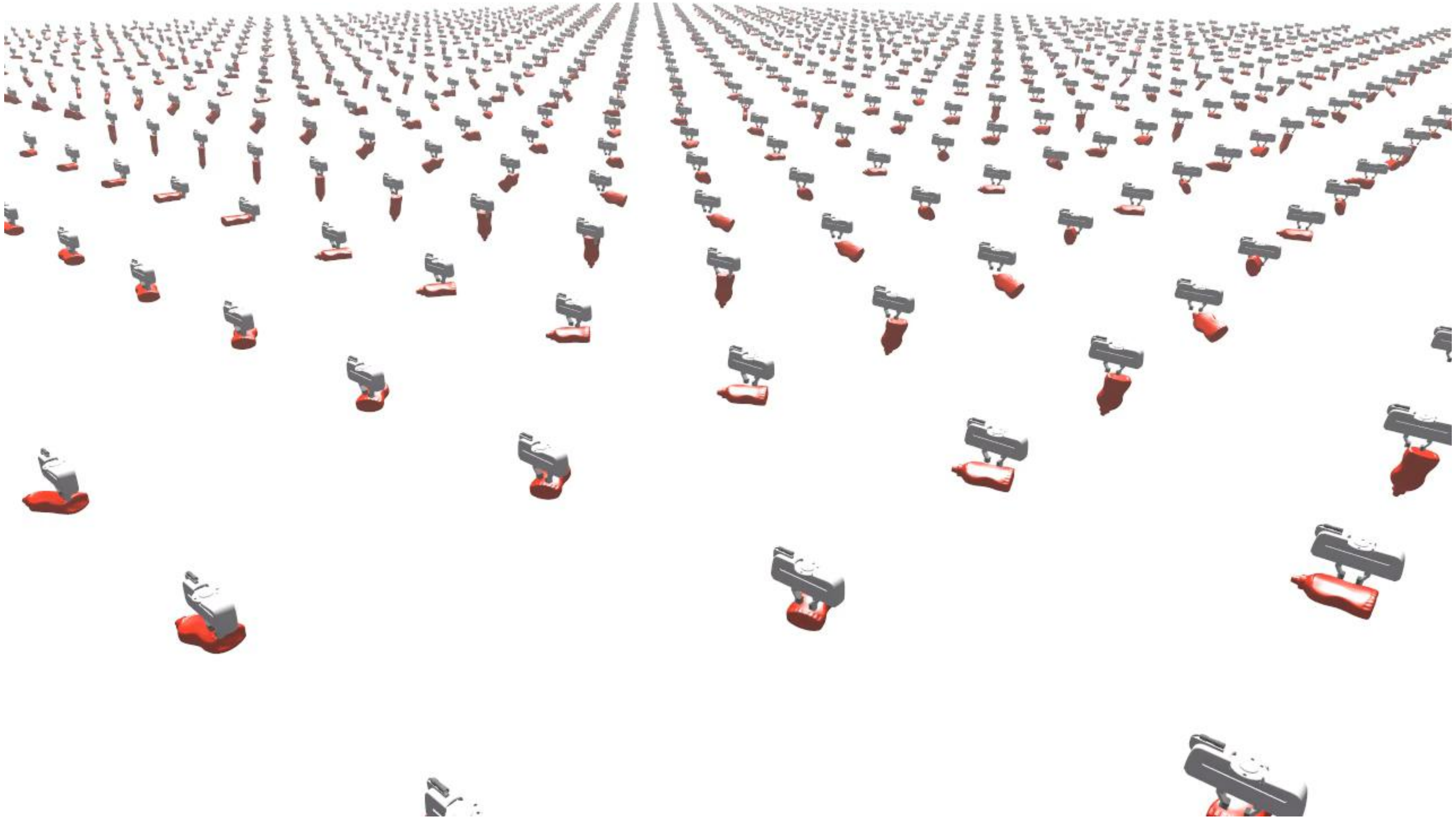
[1] Synthesis and Optimization of Force Closure Grasps via Sequential Semidefinite Programming. Hongkai Dai, Anirudha Majumdar and Russ Tedrake, 2015
[2] Synthesizing Diverse and Physically Stable Grasps With Arbitrary Hand Structures Using Differentiable Force Closure Estimator. Tengyu Liu , Zeyu Liu, Ziyuan Jiao , Yixin Zhu , and Song-Chun Zhu, 2022

Optimization to find force closure grasps



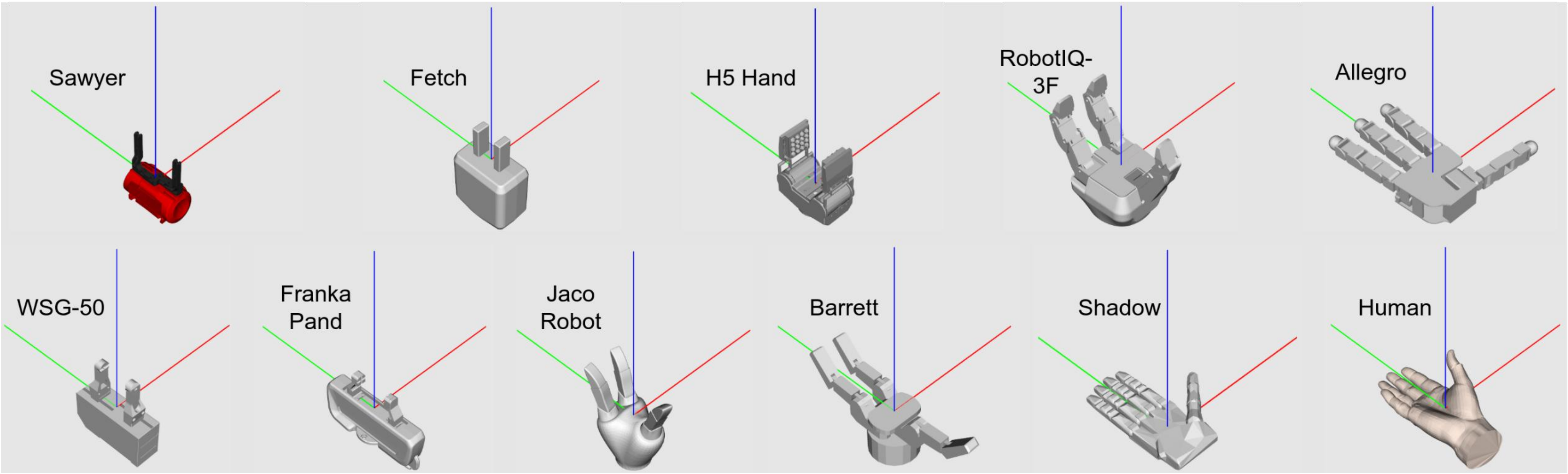
Synthesizing Diverse and Physically Stable Grasps With Arbitrary Hand Structures Using Differentiable Force Closure Estimator. Tengyu Liu , Zeyu Liu, Ziyuan Jiao , Yixin Zhu , and Song-Chun Zhu, 2022

Use Physics Simulation for Grasp Planning



Eppner-Mousavian-Fox, ISRR'19

MultiGripperGrasp

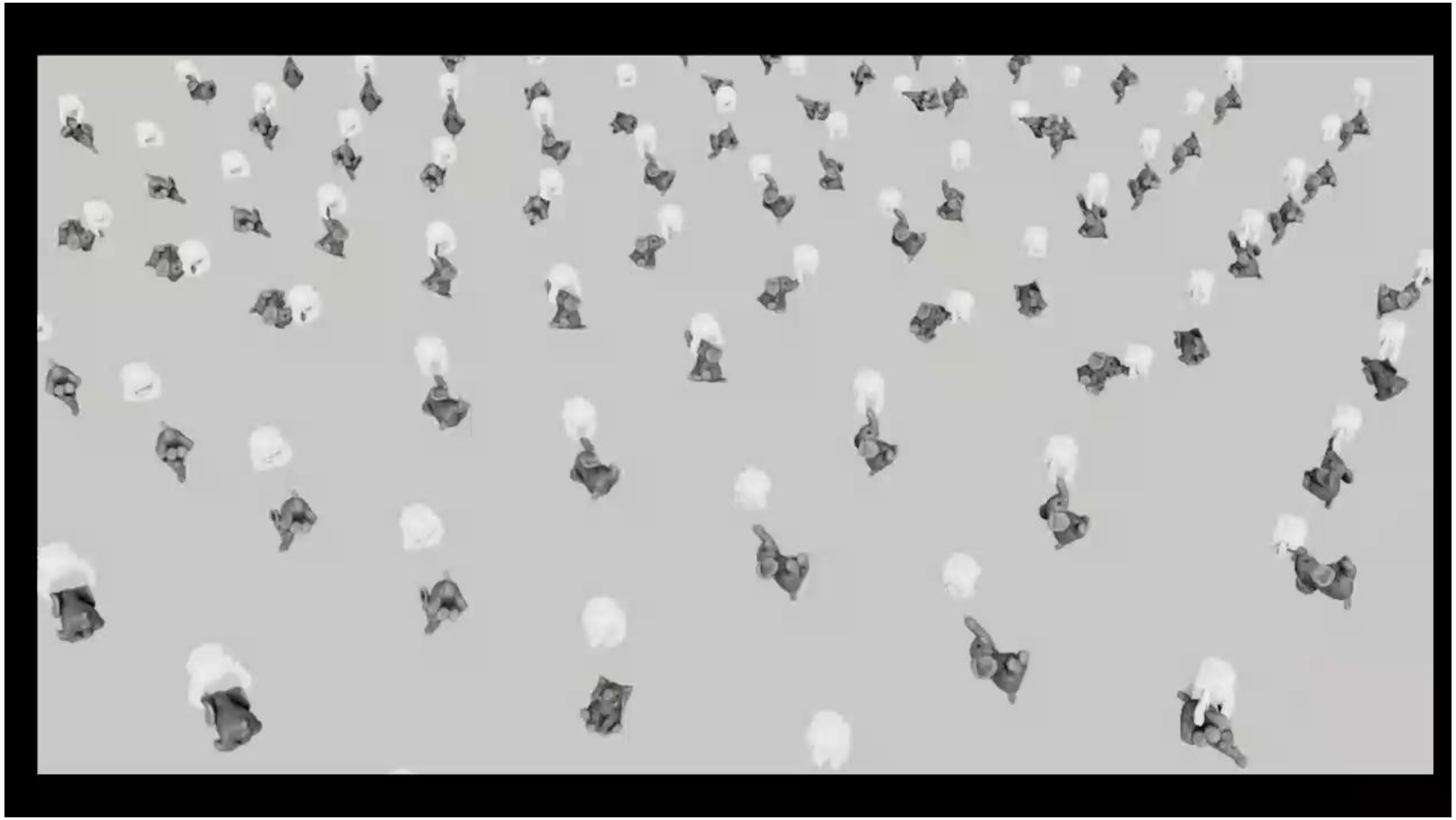


- 11 grippers (aligned with palm directions)
  - 2-finger grippers: Fetch, Franka Panda, WSG50, Sawyer, H5 Hand
  - 3-finger grippers: Barrett, Robotiq-3F, Jaco Robot
  - 4-finger grippers: Allegro
  - 5 finger grippers: Shadow, Human Hand

MultiGripperGrasp: A Dataset for Robotic Grasping from Parallel Jaw Grippers to Dexterous Hands. Luis Felipe Casas Murrilo*, Ninad Khargonkar*, Balakrishnan Prabhakaran, Yu Xiang (*equal contribution). In IROS, 2024.

MultiGripperGrasp

- Generate initial grasps using GraspIt! Ranking grasps in Isaac Sim

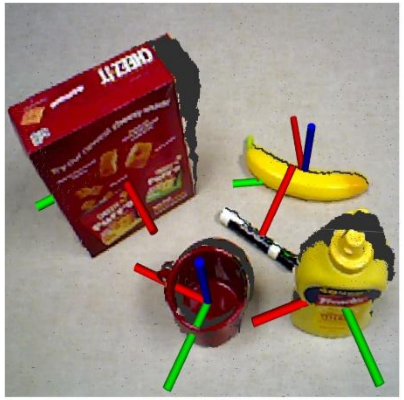


MultiGripperGrasp: A Dataset for Robotic Grasping from Parallel Jaw Grippers to Dexterous Hands. Luis Felipe Casas Murrilo*, Ninad Khargonkar*, Balakrishnan Prabhakaran, Yu Xiang (*equal contribution). In IROS, 2024.

Model-based Grasping vs Model-free Grasping

SceneReplica, ICRA'24: https://irvlutd.github.io/SceneReplica/

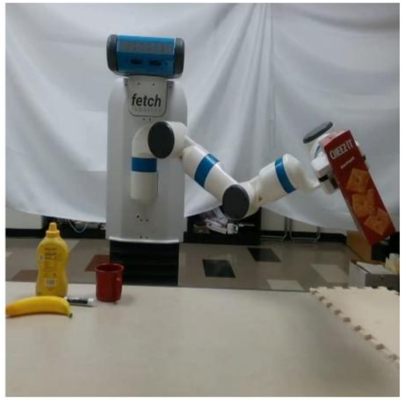

Input real world scene


6D Pose Estimation

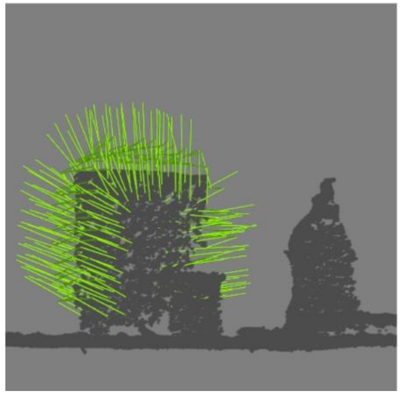

Offline Grasp Database

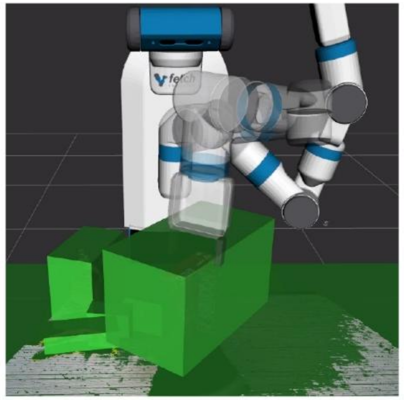

Motion Planning Setup


Grasping & Lifting

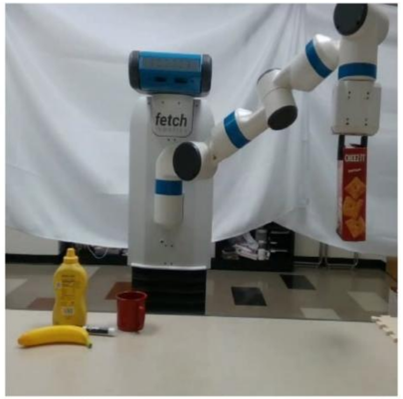

Moving arm for Dropoff


Unseen Object Segmentation

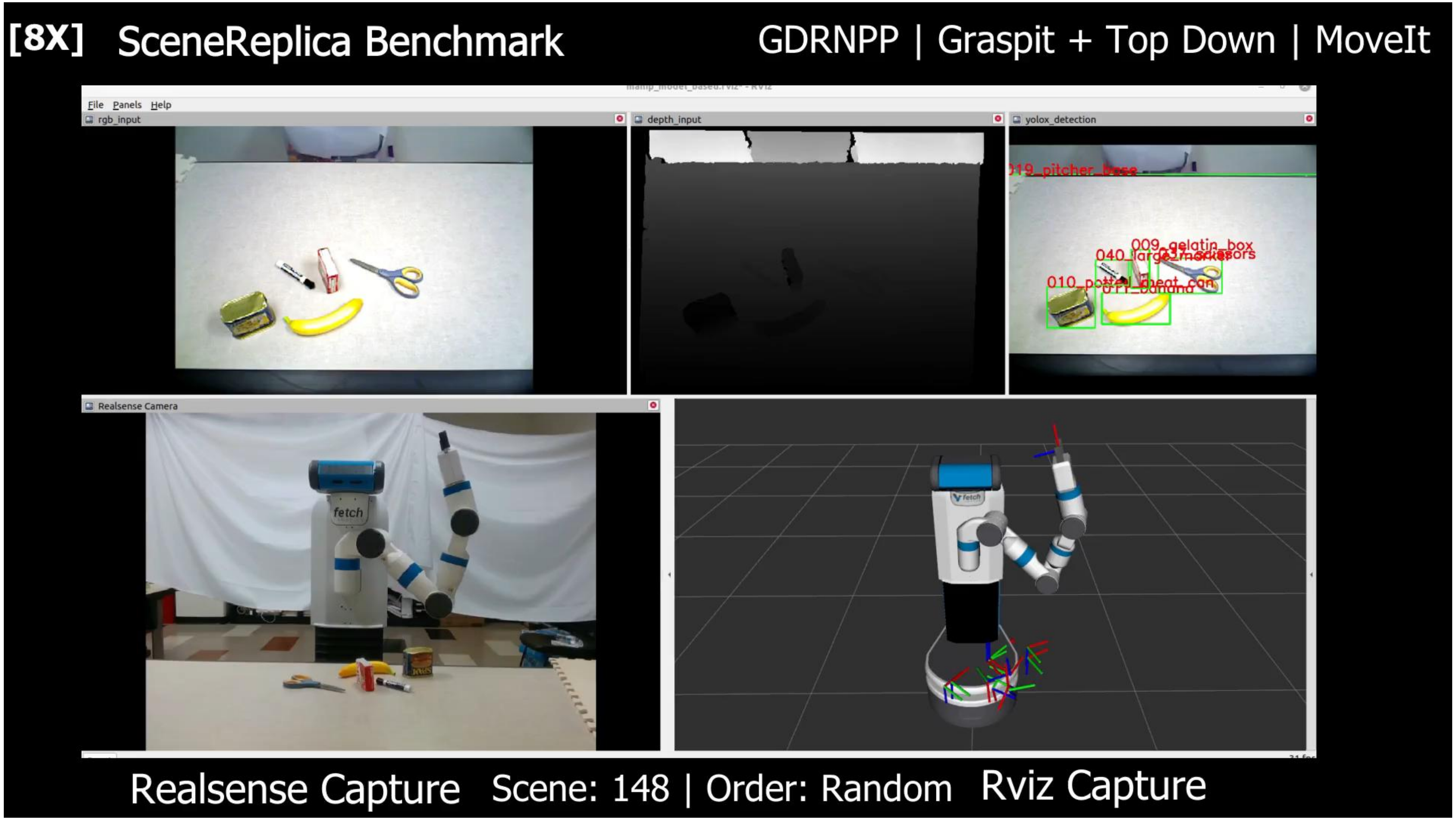

Model-free Grasp Planning


Motion Planning Setup

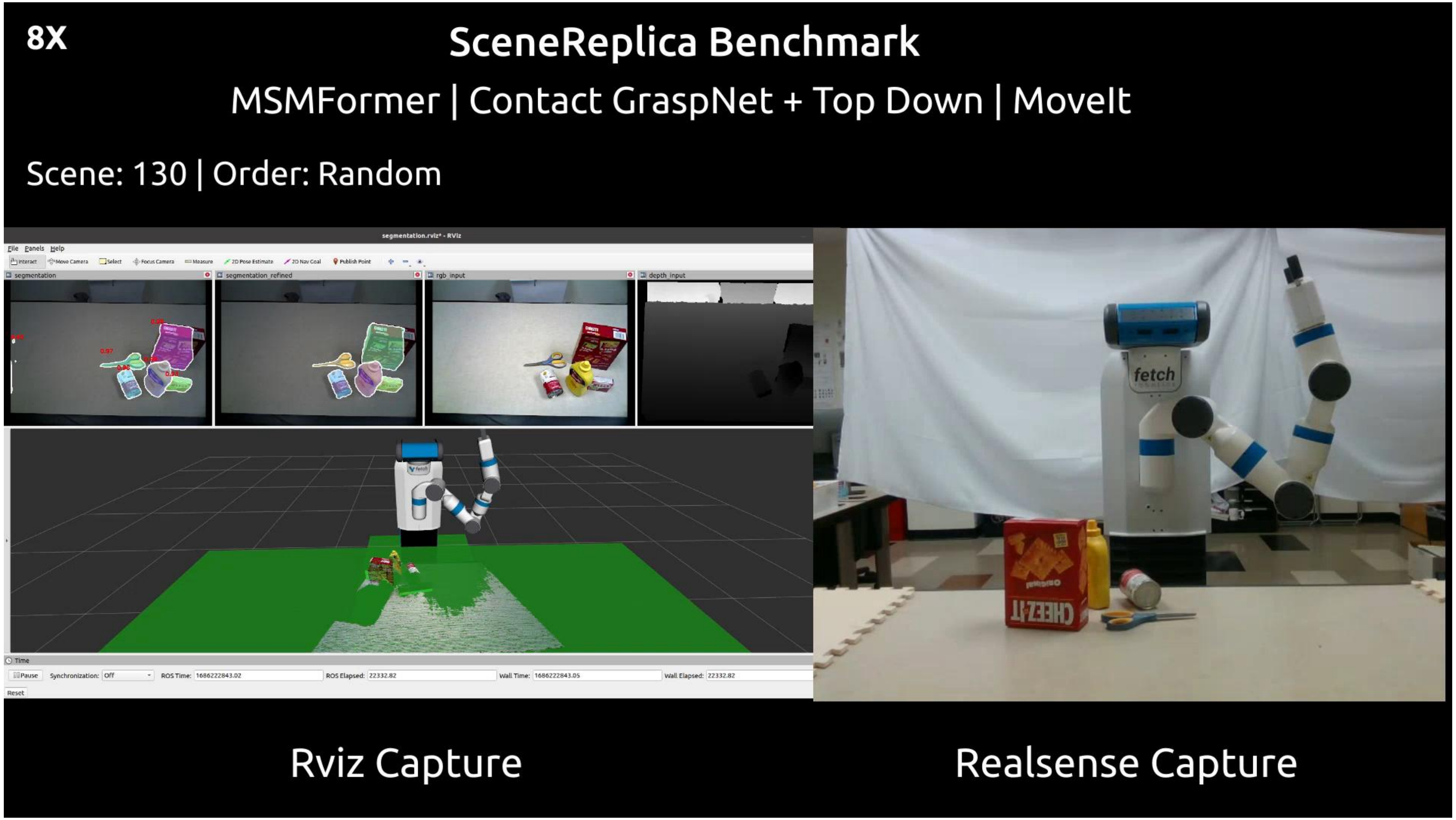

Grasping & Lifting


Moving arm for Dropoff

Model-based Grasping Example



Model-free Grasping Example



Summary

- Point-on-Plane Contact Models
- Friction cone
- Grasp Wrench Space
- Force Closure Grasp
- Optimization to find force closure grasps

Further Reading

[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

[6] SceneReplica: https://irvlutd.github.io/SceneReplica/