Intro to Robotic Grasping

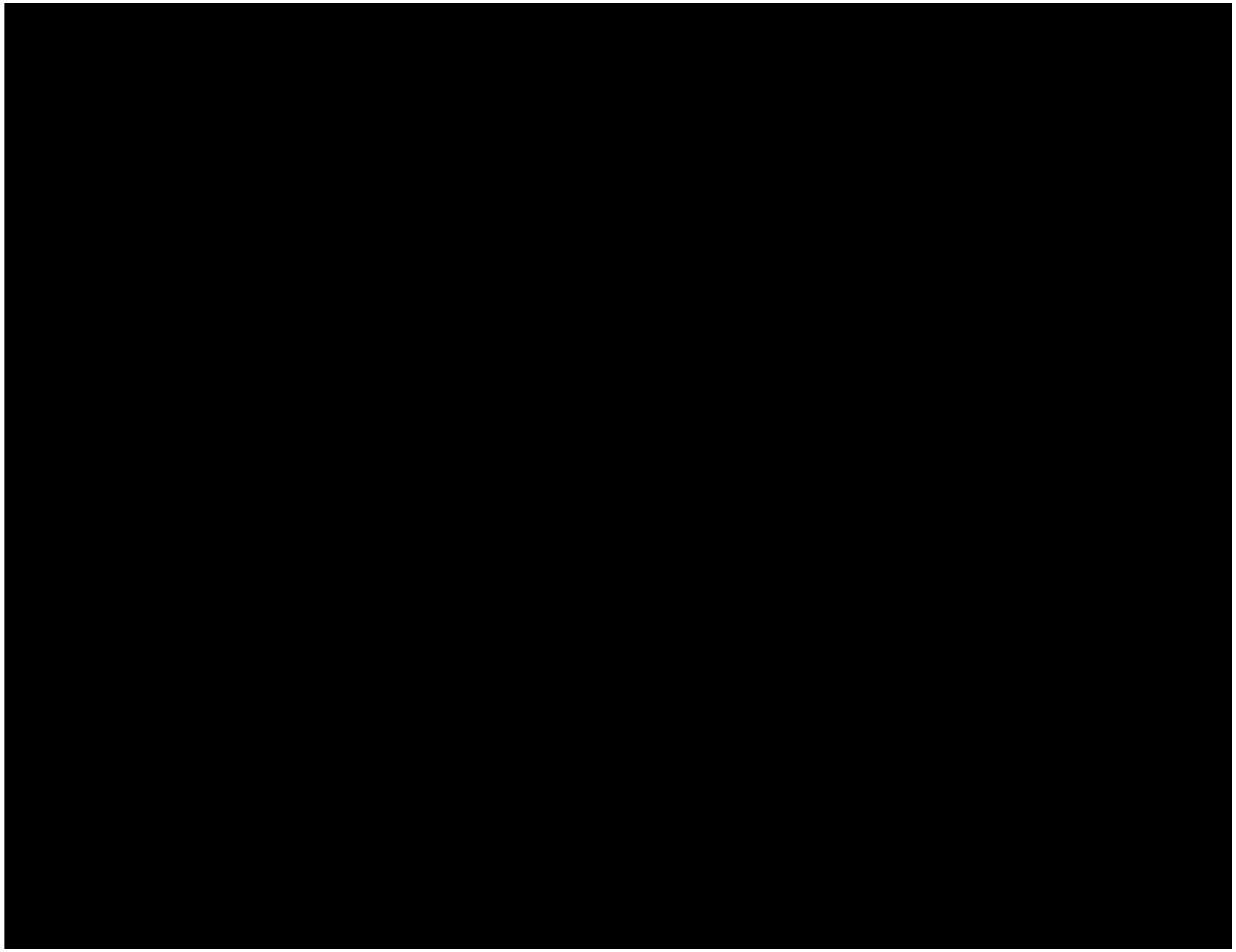
Instructor: Chris Mavrogiannis

TAs: Kay Ke, Gilwoo Lee, Matt Schmittle

Logistics

- Lab 3
    - Deadline Friday **March 6th**
    - Demo Thursday **March 5th** (recitation slots)
    - **Extra Credit important for final project**
- Final Project
    - Released
    - Demo Thursday **March 12th** (recitation slots)
    - Short writeup due **Monday 16th**

Manipulation



Julia Child slicing potato —example from Matt Mason's 16-741 class at CMU

Manipulation

https://www.youtube.com/watch?v=l9U8X6I1vow

https://sites.google.com/view/kpam

Lucas Manuelli*, Wei Gao*, Peter Florence, Russ Tedrake. kPAM: KeyPoint Affordances for Category-Level Robotic Manipulation. In International Symposium on Robotics Research (ISRR), Hanoi, Vietnam, October 2019

Manipulation

Definition 1. Manipulation refers to the activities performed by hands.

Definition 2. Manipulation is when an agent moves things other than itself.

Definition 3. Manipulation is when an agent moves things other than itself through selective contact.

Definition 4. Manipulation is pick-and-place manipulation plus in-hand manipulation plus mechanical assembly plus. . . .

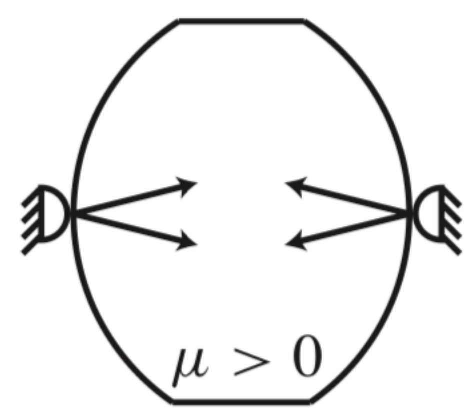
Definition 5. Manipulation refers to an agent's control of its environment through selective contact.

Toward Robotic Manipulation Matthew T. Mason Annual Review of Control, Robotics, and Autonomous Systems 2018 1:1, 1-28

Special Case: Grasping

- Special class of manipulation (others include caging, nonprehensile manipulation, etc)
- Exerting force/moment on object via a set of **contacts** to keep it in stable equilibrium or rearrange it
- Often quasistatic

Form closure does not imply force closure



Force closure does not imply form closure

Special Case: Caging

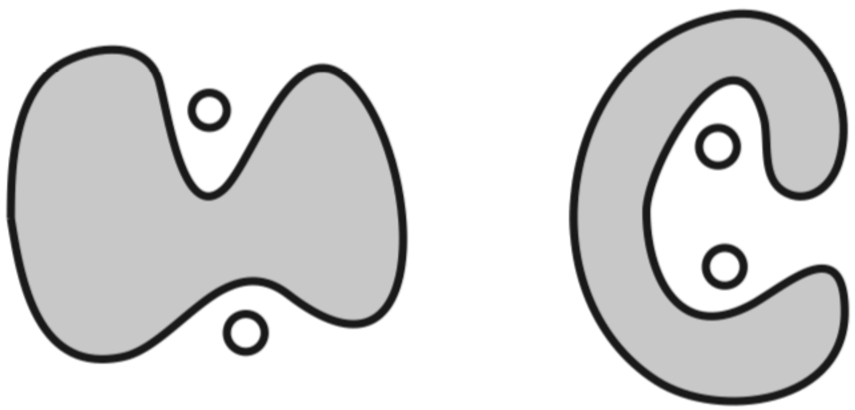


Fig. 2. Examples of squeezing (left) and stretching (right) caging configurations.

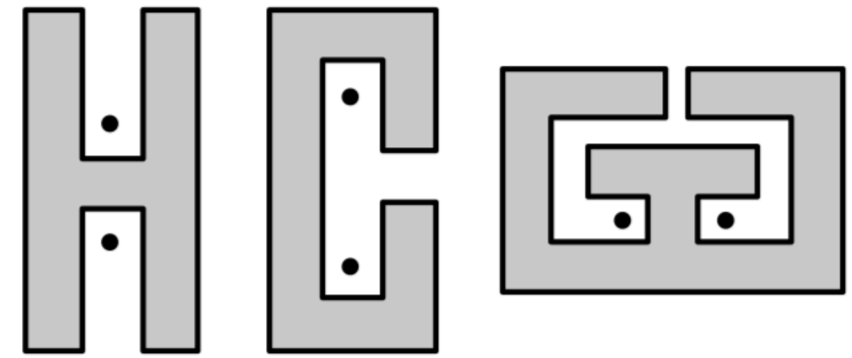


Fig. 1. Examples of (a) squeezing caging, (b) stretching caging (c), both.

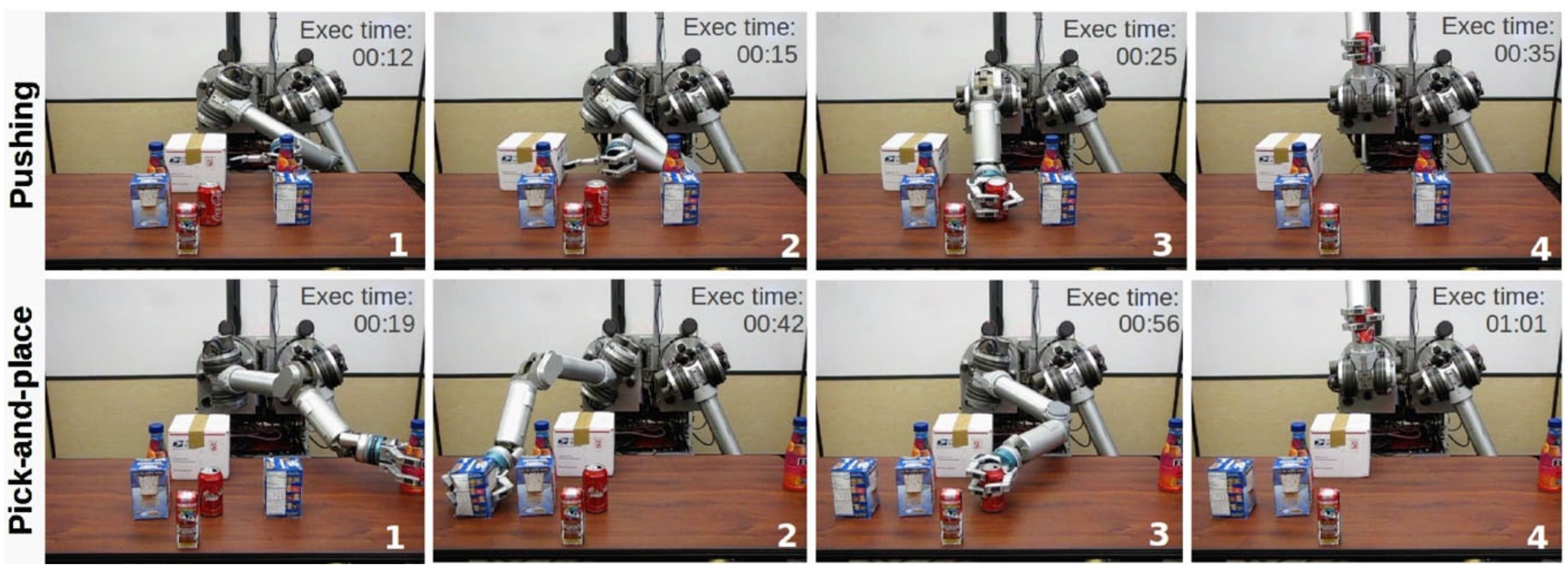
- To cage an object is to arrange obstacles so that all motions of the mobile body are bounded.
- An object is caged if and only if the manipulator is unable to escape from the object while preserving its shape.

Rodriguez, A., Mason, M. T., & Ferry, S. (2012). From caging to grasping. The International Journal of Robotics Research, 31(7), 886–900. https://doi.org/10.1177/0278364912442972

A. Rodriguez, M. Mason, “Two Finger Caging: Squeezing and Stretching”, WAFR '08

Special Case: Nonprehensile Manipulation

"The environment is your friend"



https://youtu.be/QLvgEDFE68Y

https://youtu.be/tVDO8QMuYhc

Chavan-Dafle, N., Holladay, R., & Rodriguez, A. (2020). Planar in-hand manipulation via motion cones. The International Journal of Robotics Research, 39(2–3), 163–182. https://doi.org/10.1177/0278364919880257

A Planning Framework for Non-Prehensile Manipulation under Clutter and Uncertainty. M.R. Dogar and S.S. Srinivasa. Autonomous Robots, 33(3), 2012.

The Cutkosky Grasp Taxonomy

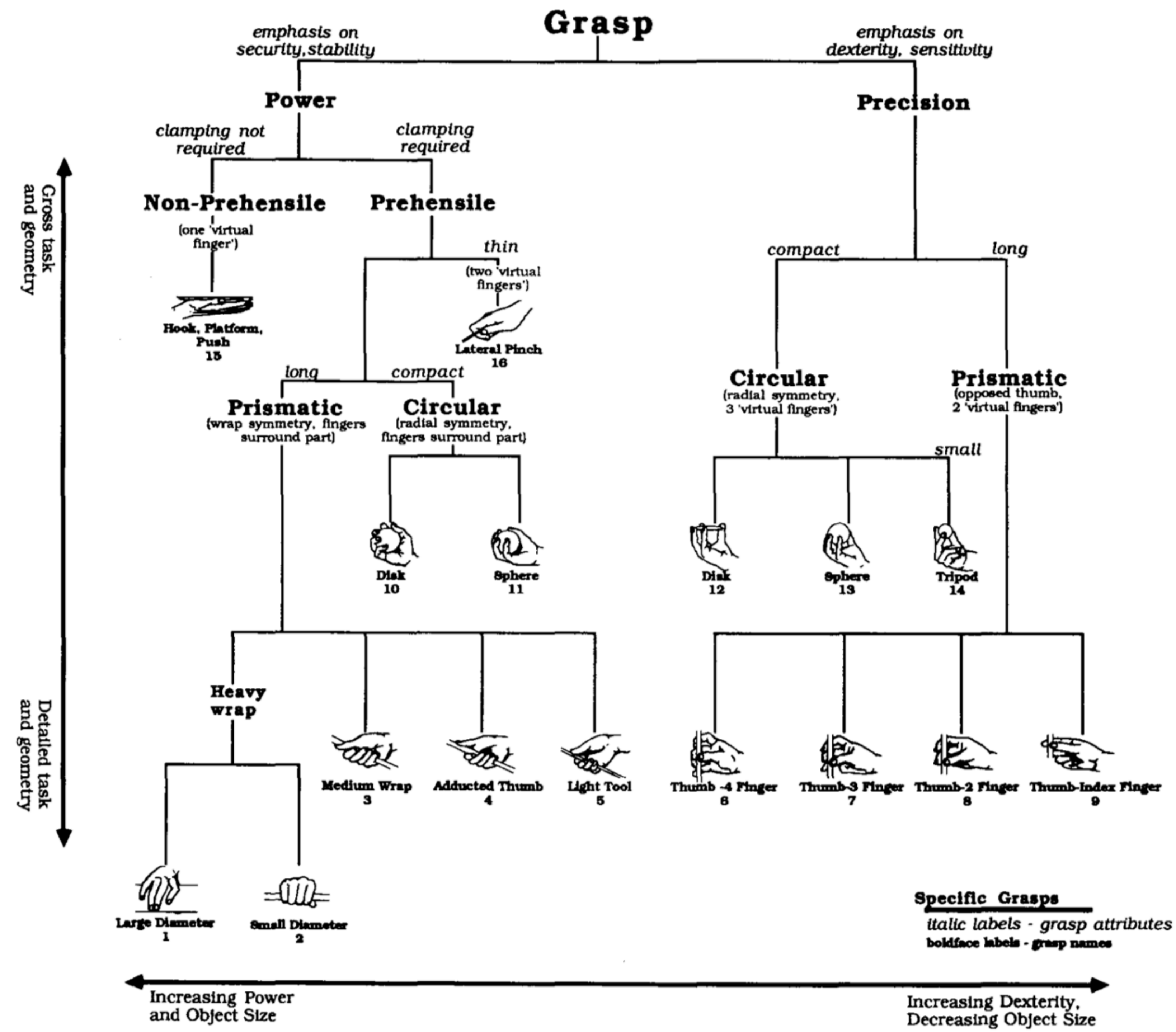


Fig. 4. A partial taxonomy of manufacturing grasps, modified from a taxonomy presented in [4]. The drawings of hands were provided by M. J. Dowling and are reprinted with permission of the Robotics Institute, Carnegie-Mellon University.

M. R. Cutkosky, "On grasp choice, grasp models, and the design of hands for manufacturing tasks," in *IEEE Transactions on Robotics and Automation*, vol. 5, no. 3, pp. 269-279, June 1989. doi: 10.1109/70.34763

Robotic Grasping

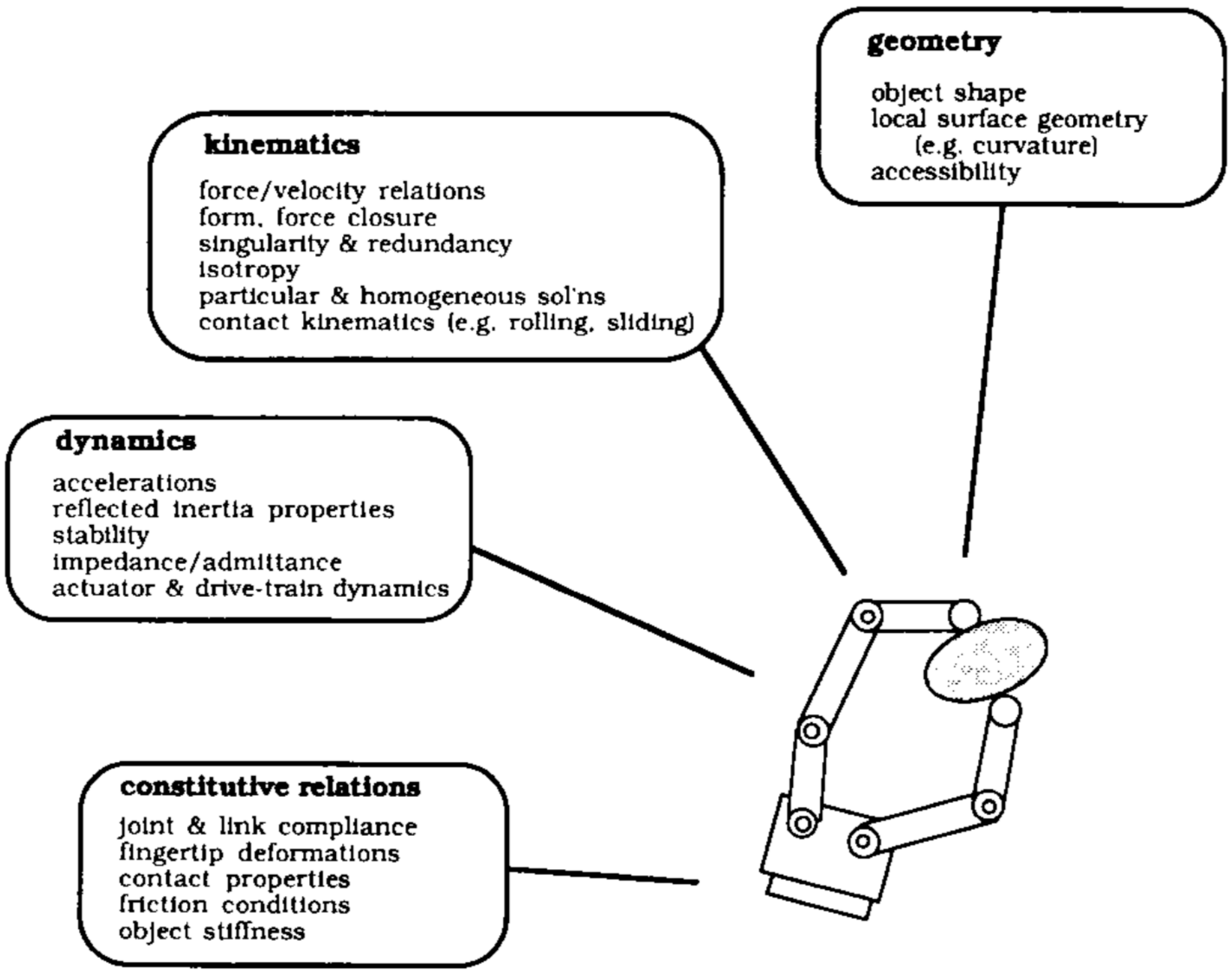
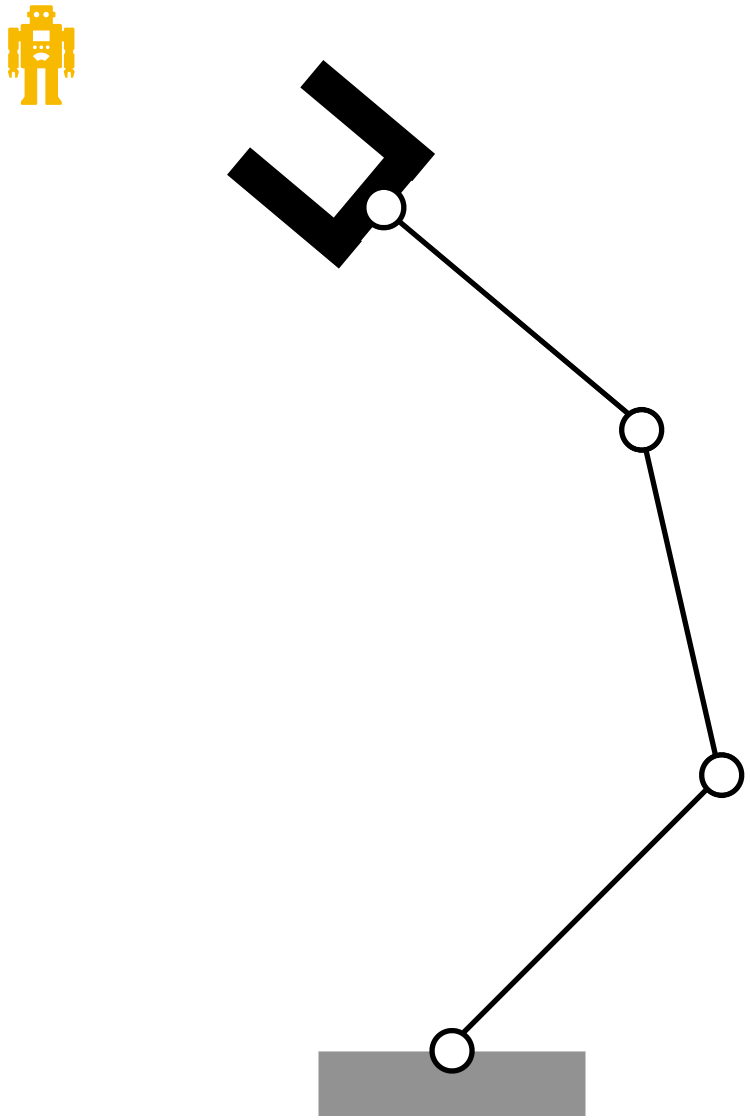


Fig. 1. Issues in analytic modeling of grasping and manipulation.

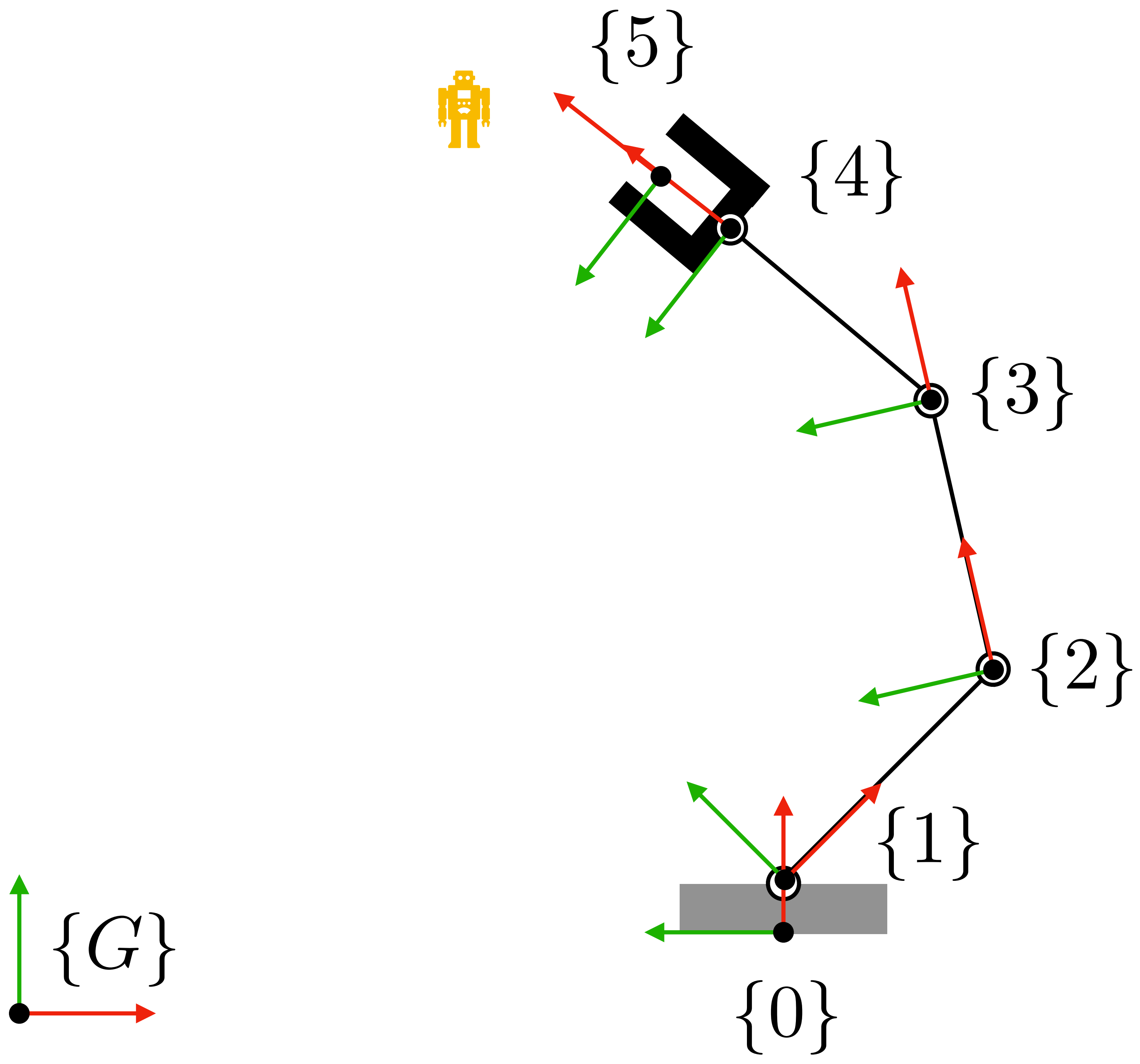
M. R. Cutkosky, "On grasp choice, grasp models, and the design of hands for manufacturing tasks," in *IEEE Transactions on Robotics and Automation*, vol. 5, no. 3, pp. 269-279, June 1989. doi: 10.1109/70.34763

Serial Manipulators

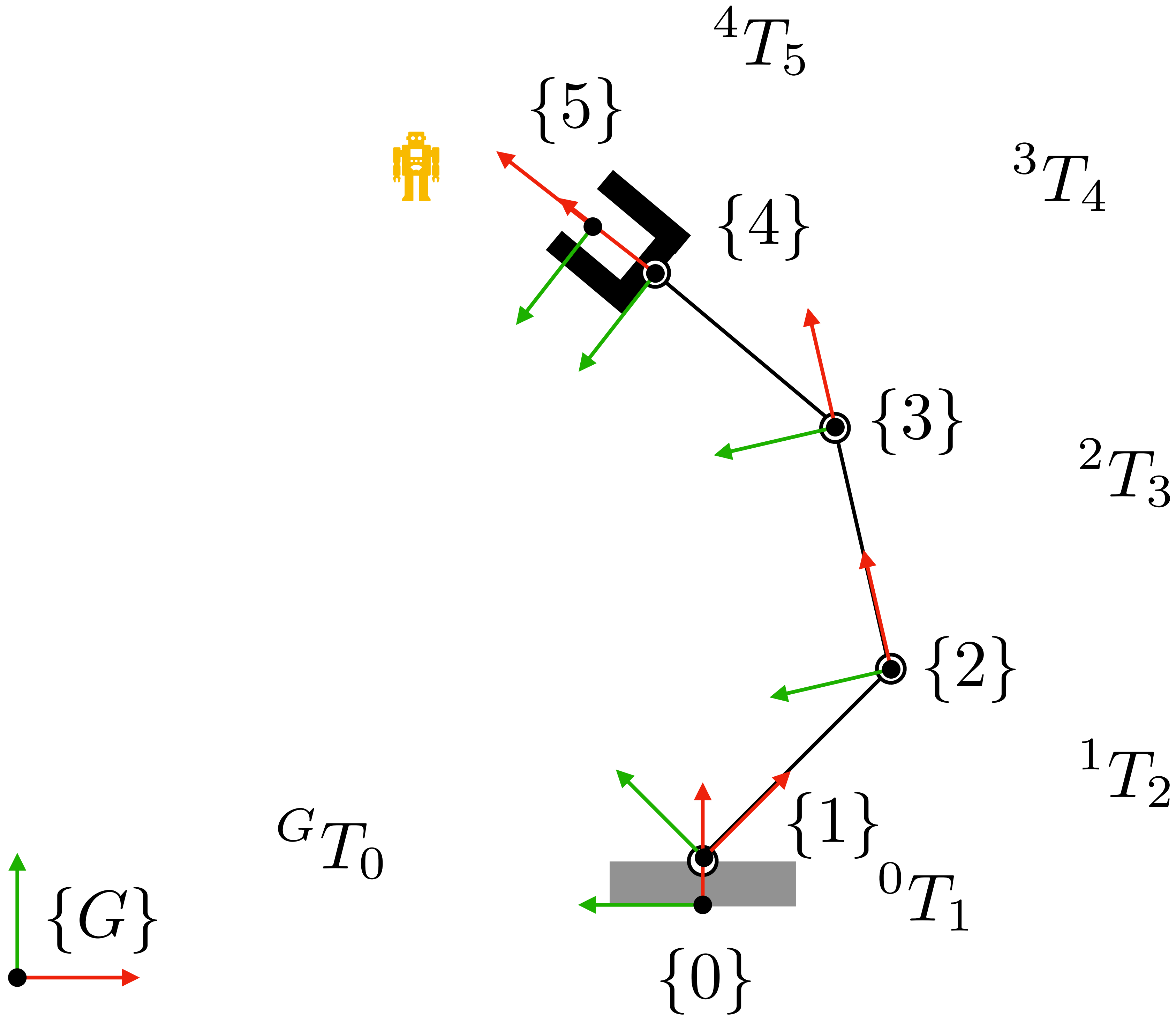
Serial-Manipulator Kinematics



Kinematics



Homogeneous Transform

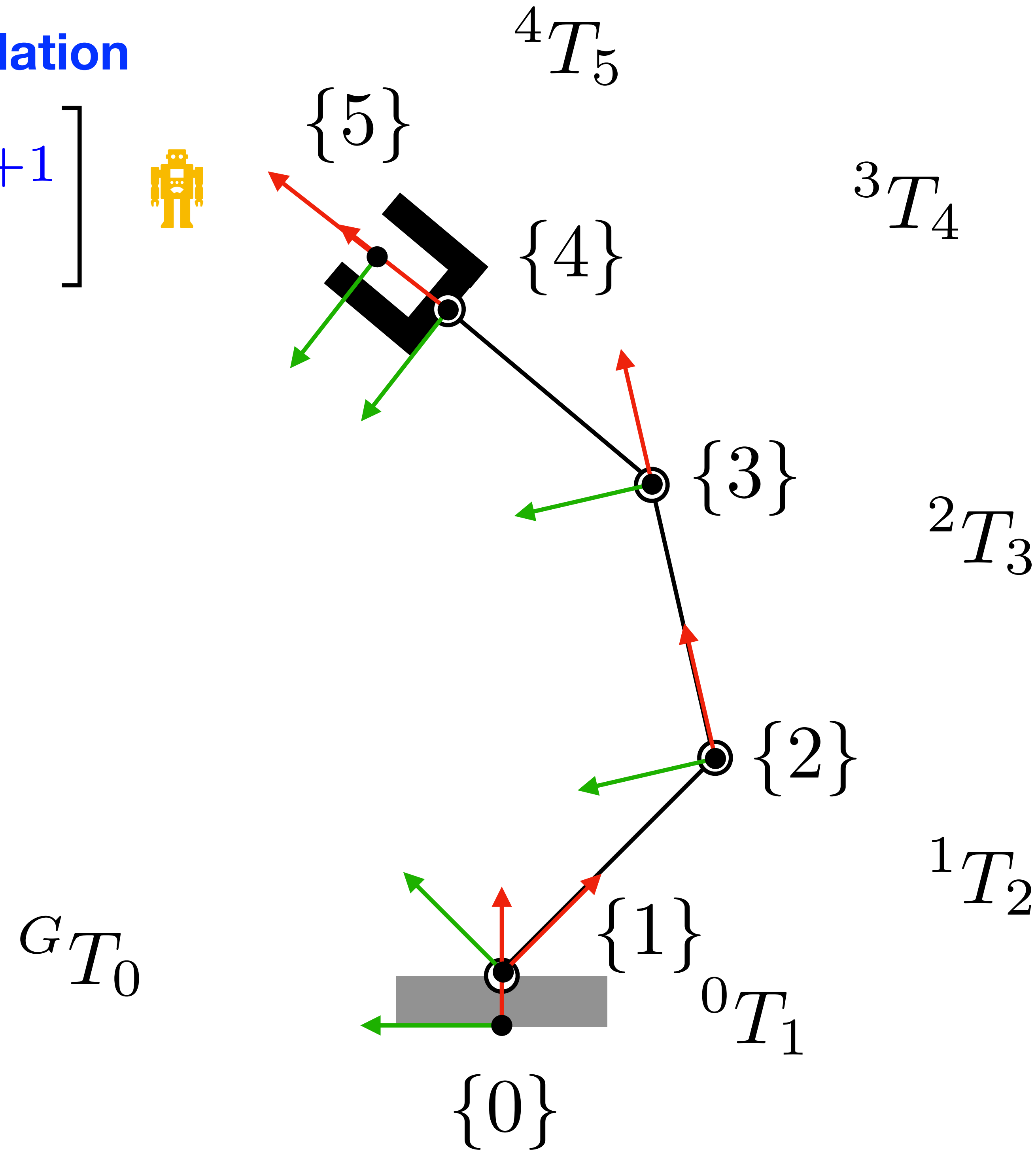


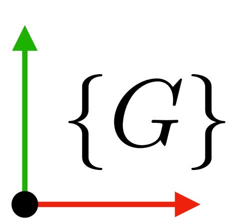
Homogeneous Transform

Rotation **Translation**

$$ {}^{i}T_{i+1} = \begin{bmatrix} {}^{i}R_{i+1} & {}^{i}d_{i+1} \\ \mathbf{0} & 1 \end{bmatrix} $$

2D, 3D, same formulation



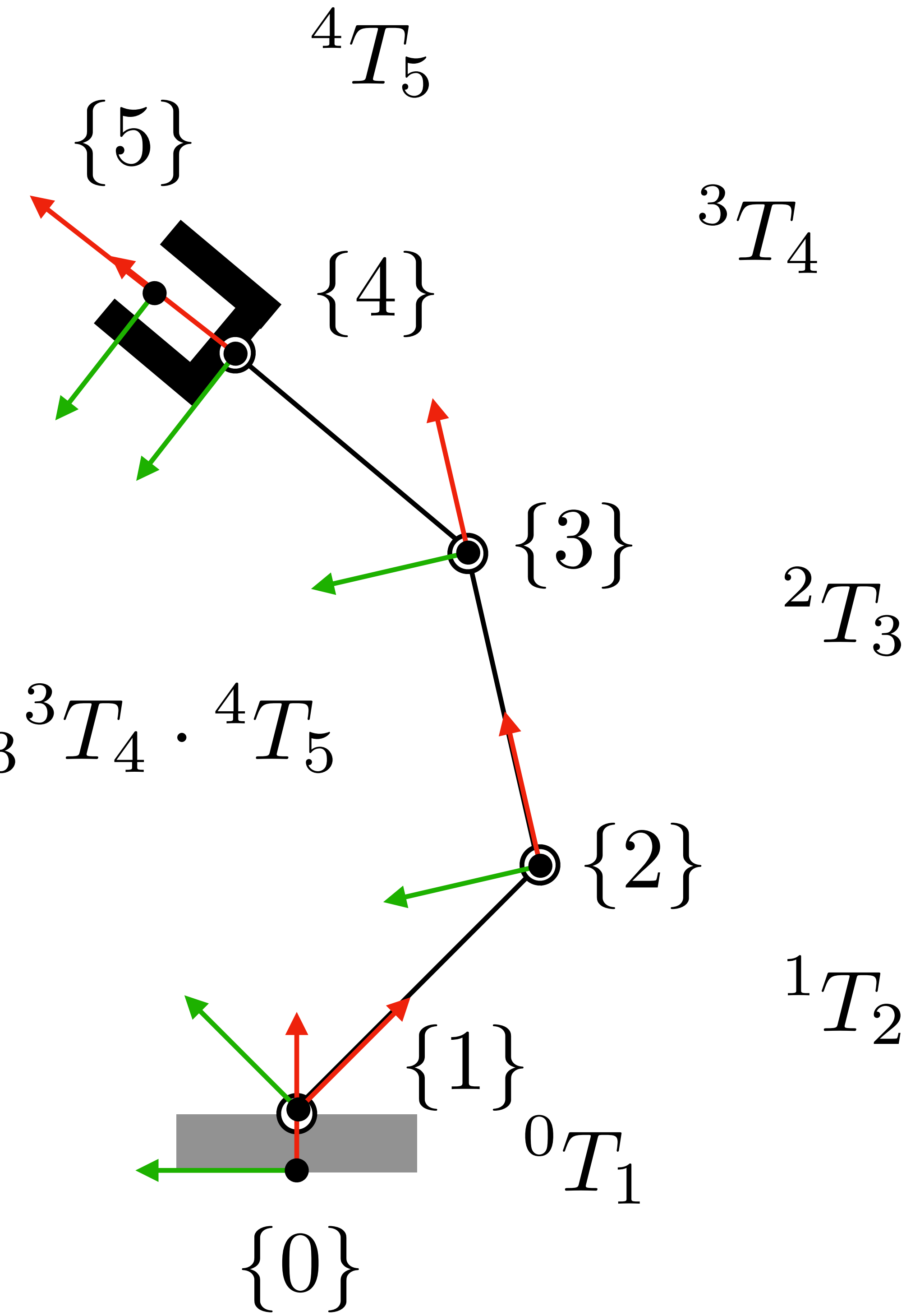


Synthesis of Transforms

Rotation **Translation**

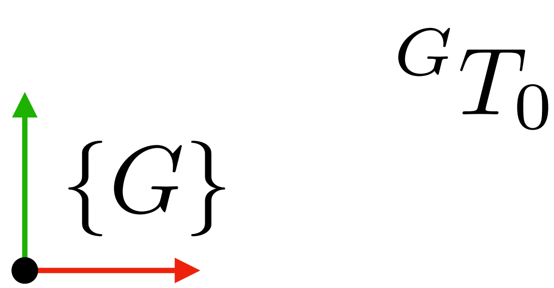
$$ {}^{i}T_{i+1} = \begin{bmatrix} {}^{i}R_{i+1} & {}^{i}d_{i+1} \\ \mathbf{0} & 1 \end{bmatrix} $$

2D, 3D, same formulation

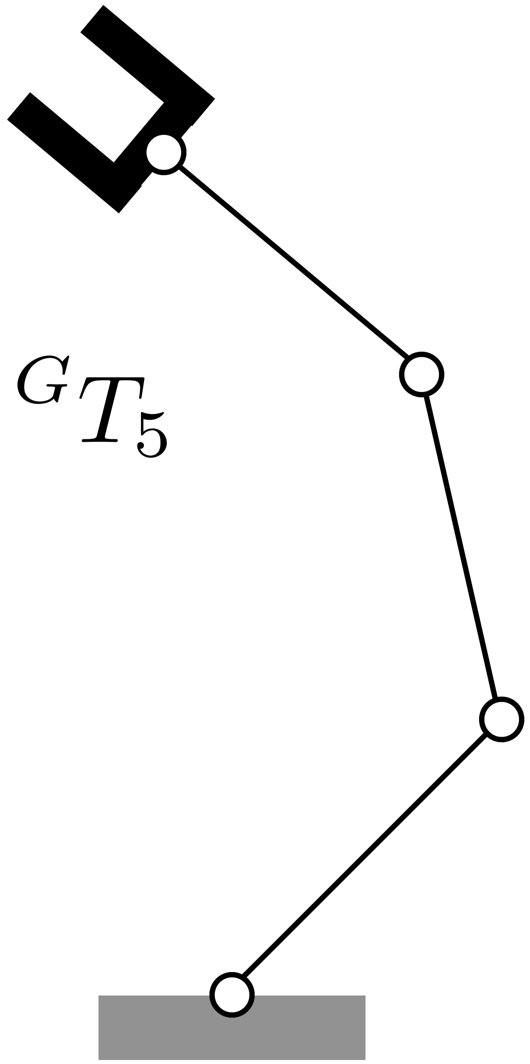


$$ {}^{G}T_5 = {}^{G}T_0 \cdot {}^{0}T_1 \cdot {}^{1}T_2 \cdot {}^{2}T_3 {}^{3}T_4 \cdot {}^{4}T_5 $$

Forward kinematics

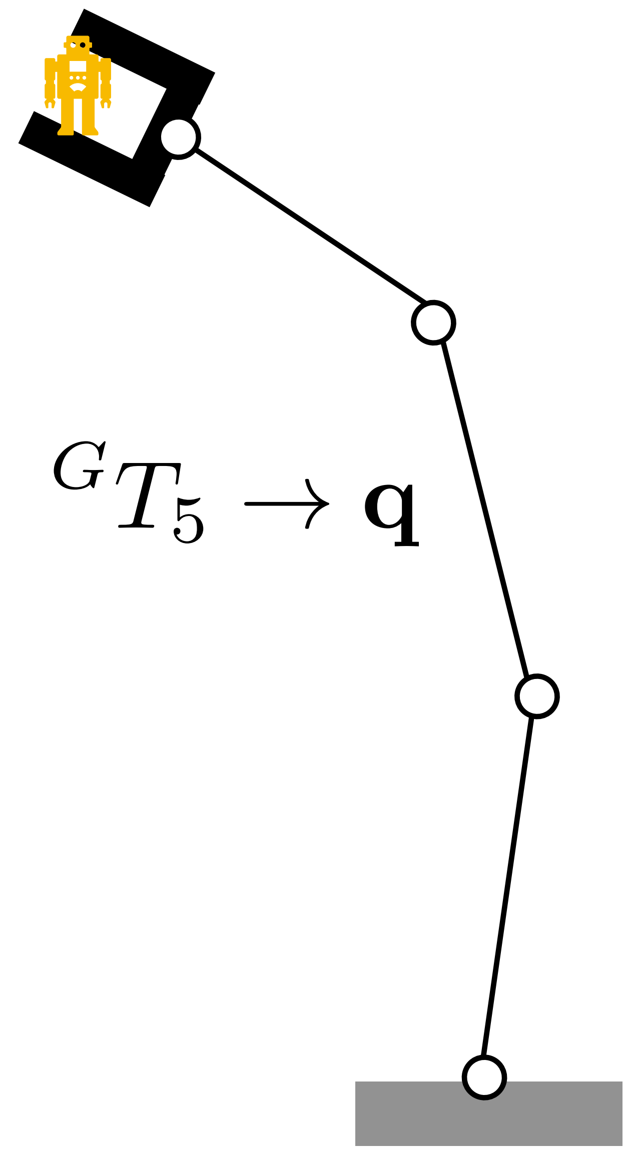


Forward Kinematics



$$\mathbf{q} \rightarrow {}^{G}T_{5}$$

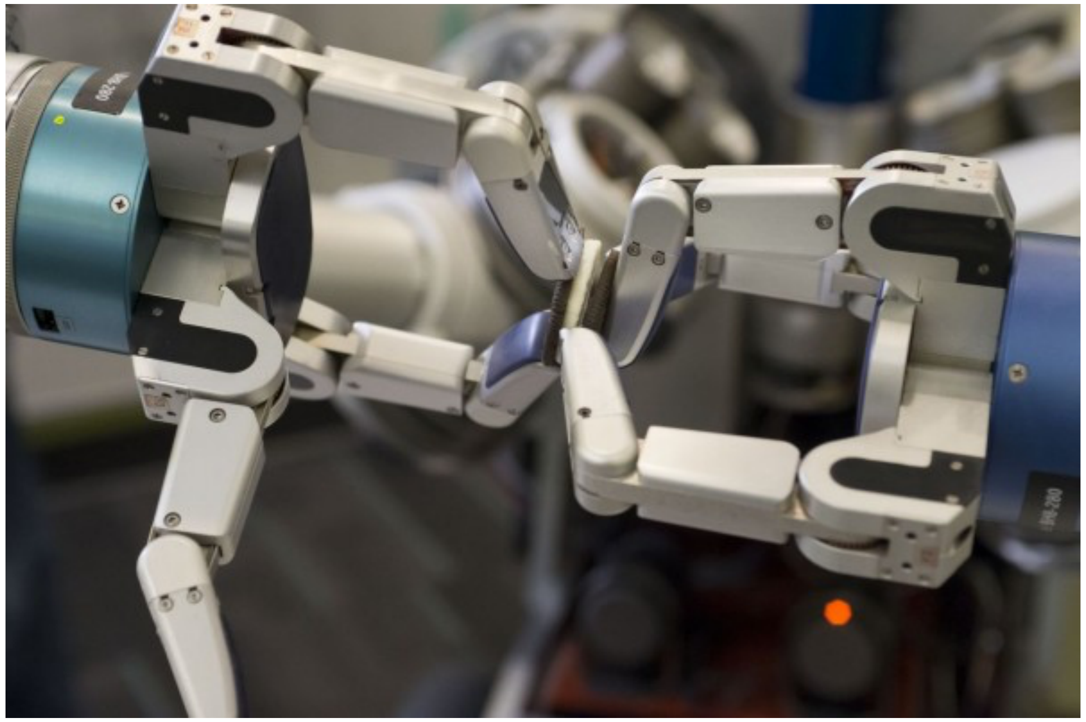
Inverse Kinematics



Robot Hands

Multifingered Rigid Hands

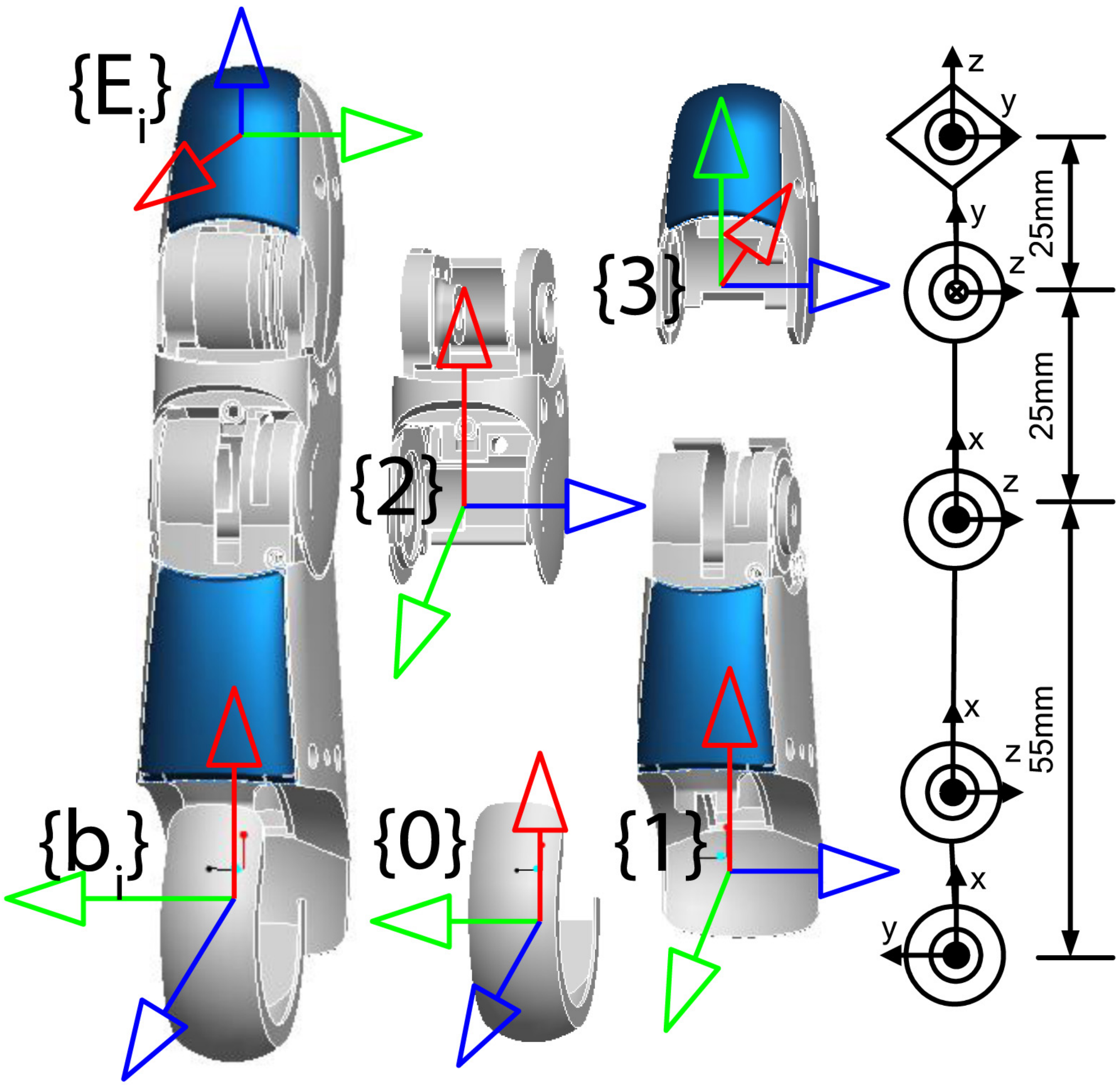
Shadow Dexterous Hand,
Shadow Robot Company



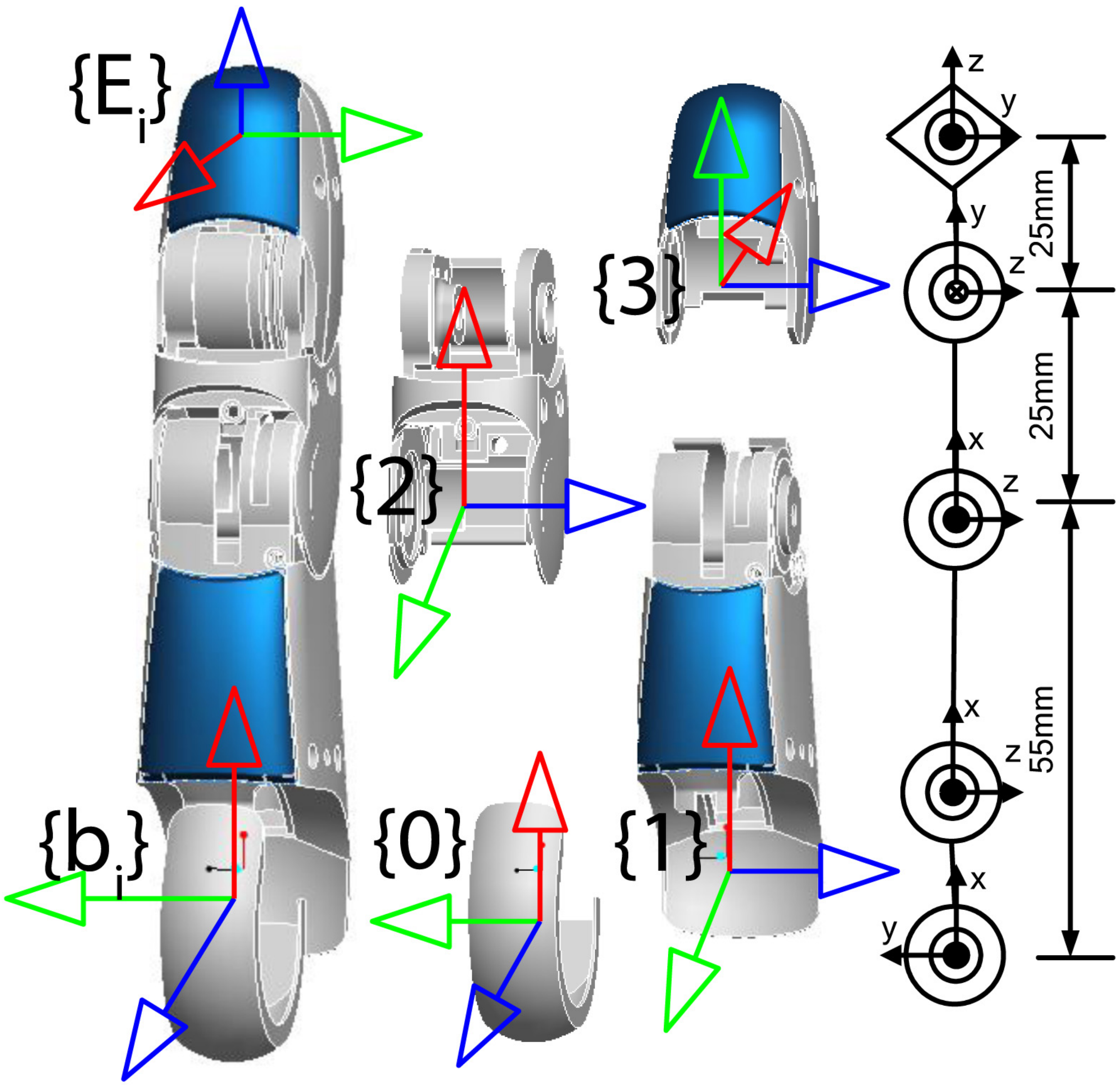
(Barrett Hand) HERB

DLR/HIT II

Example: DLR/HIT II



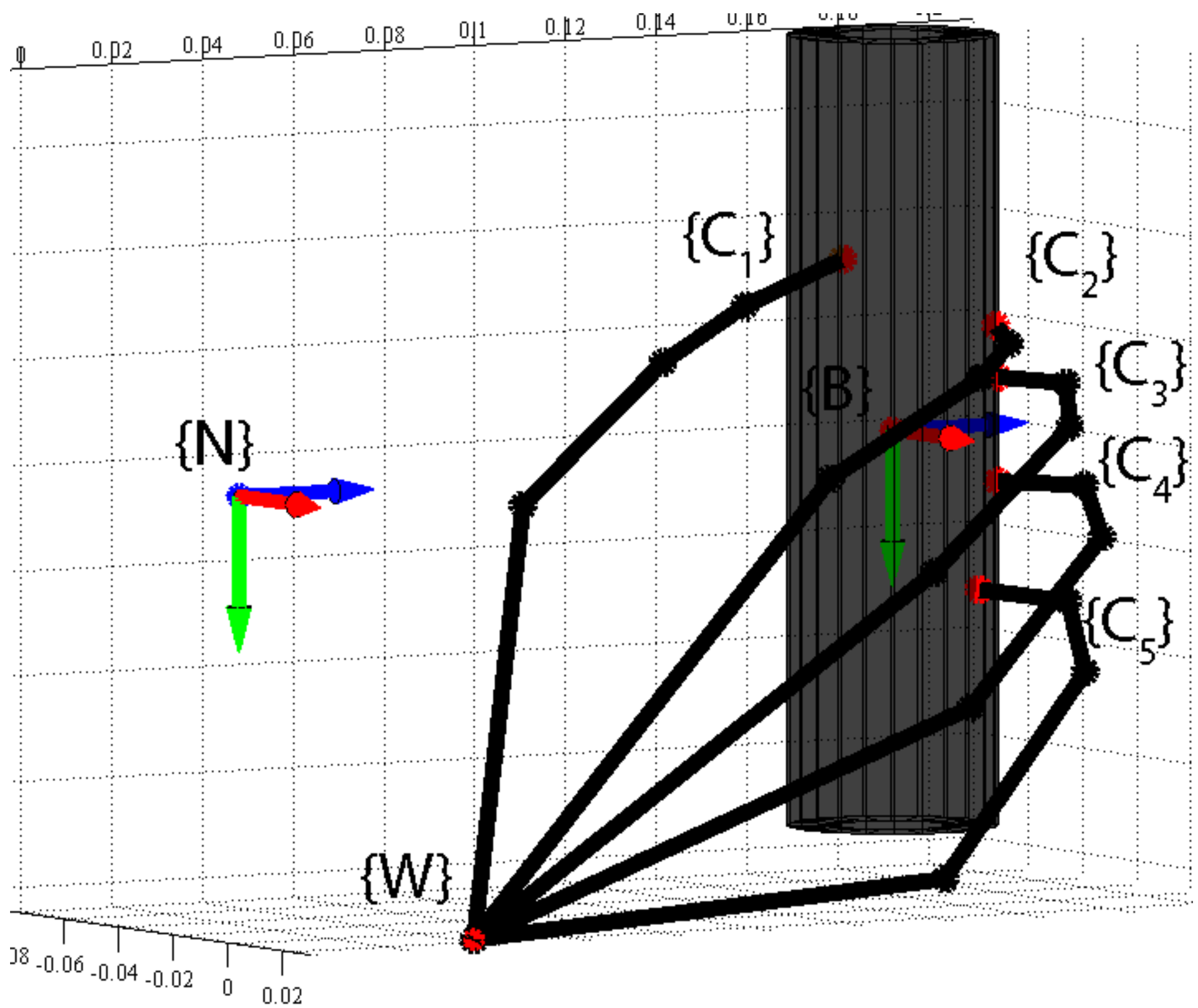
(Modified) Denavit-Hartenberg Notation



j	α_{j-1}	a_{j-1}	d_j	θ_j
0	0	0	0	q_0
1	$90°$	0	0	q_1
2	0	55	0	q_2
3	0	25	0	$q_3 - 90°$
E_i	$-90°$	0	25	$180°$

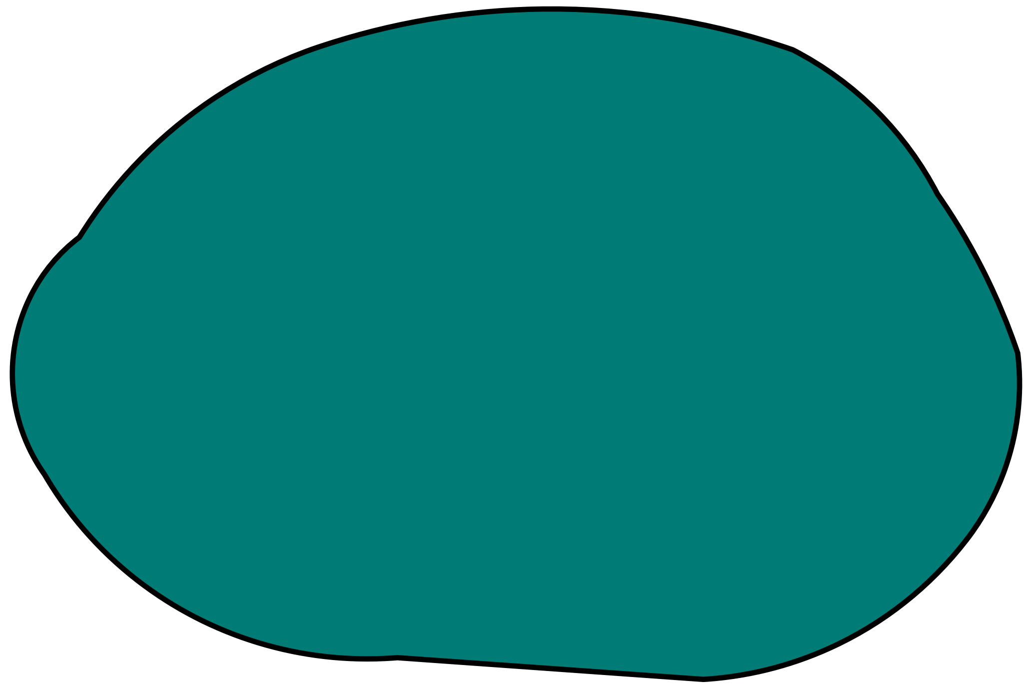
John J. Craig. 1989. Introduction to Robotics: Mechanics and Control (2nd. ed.). Addison-Wesley Longman Publishing Co., Inc., USA.

DLR/HIT II Forward Kinematics



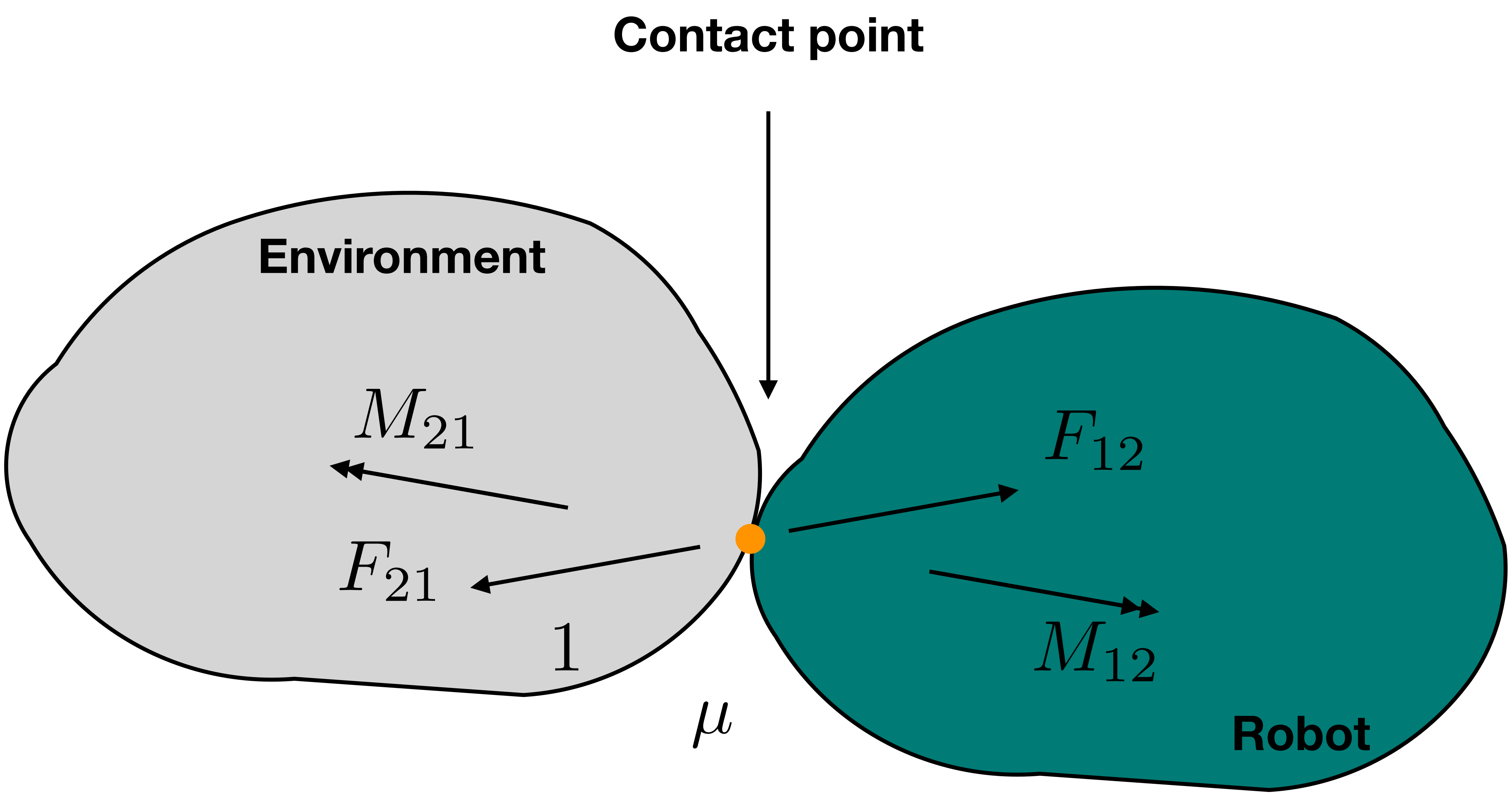
Contact

Rigid Body Assumption

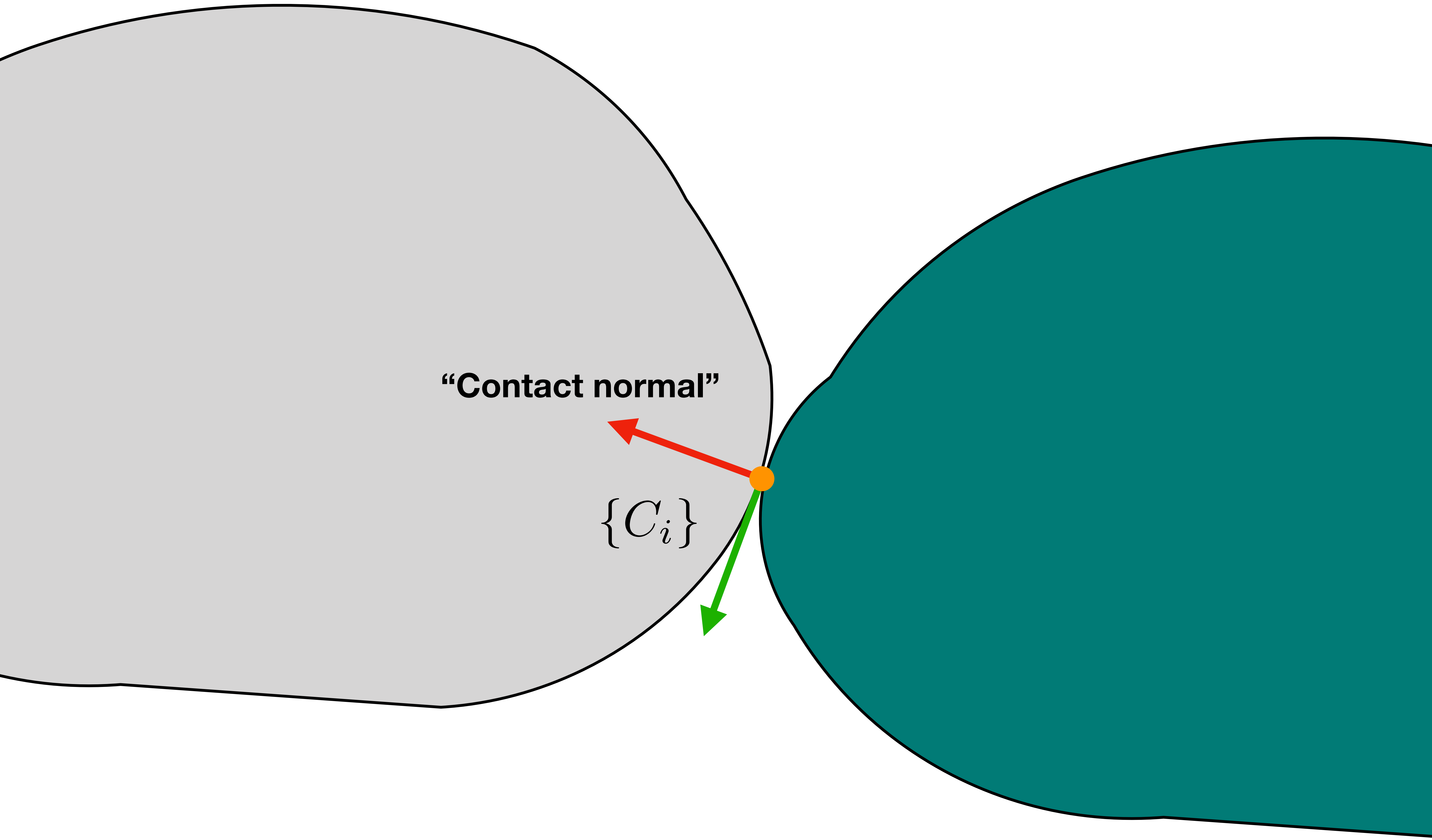


- Neglect deformations.
- Distance between any points of body constant.
- Simplifies analysis, practically valid for a number of problems.

Contact



Zoom In



Contact Modeling

Point Contact without Friction

- Transmission: Only normal velocity/force.
- Frictional forces/moments negligible; contact patch small, surfaces slippery.

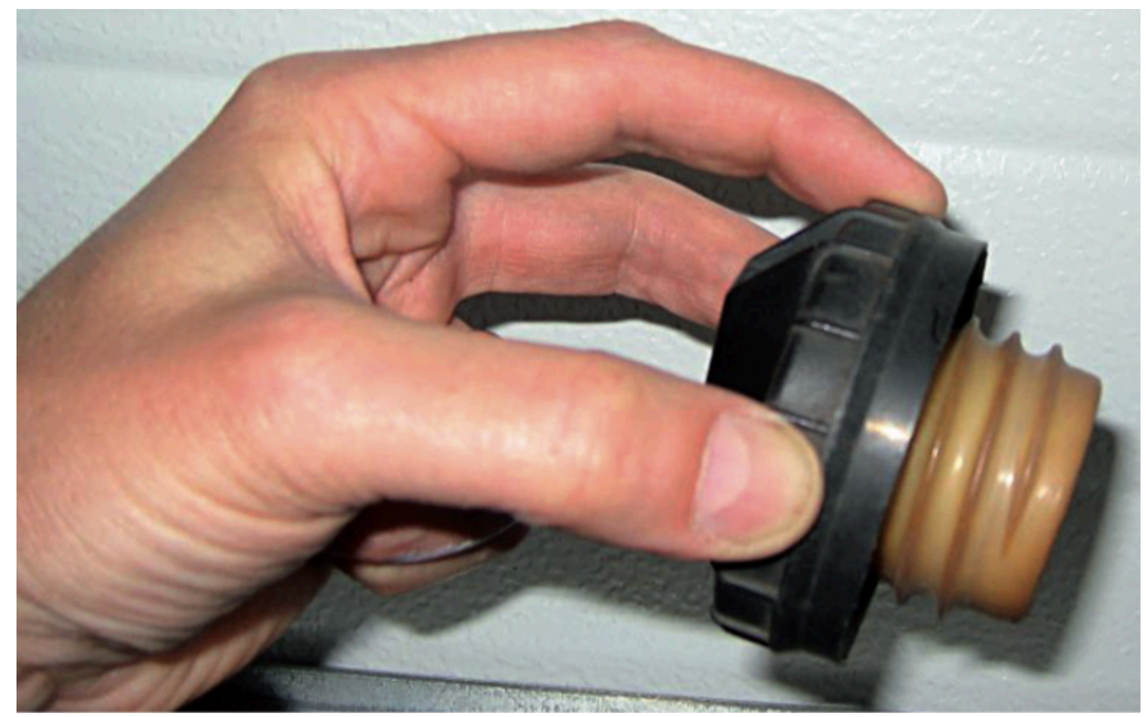
Hard Finger

- Transmission: Only translational velocity/force.
- Useful: Significant friction at contact but contact patch small.

Soft Finger

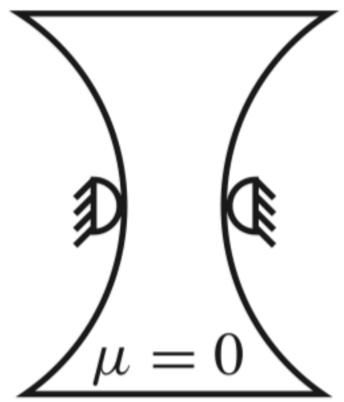
- Transmission: translational velocity/force + rotational velocity/moment around contact normal.
- Useful: when contact patch is large and friction significant.

Closure Grasps

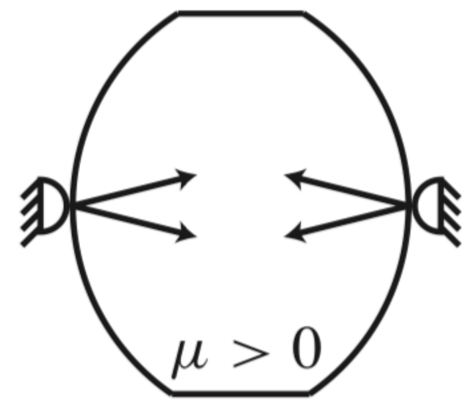


Figures from Bruno Siciliano and Oussama Khatib. 2016. Springer Handbook of Robotics (2nd. ed.). Springer Publishing Company, Incorporated.

Closure Grasps



Form closure does not imply force closure



Force closure does not imply form closure

Figure from Matt Mason

Form Closure

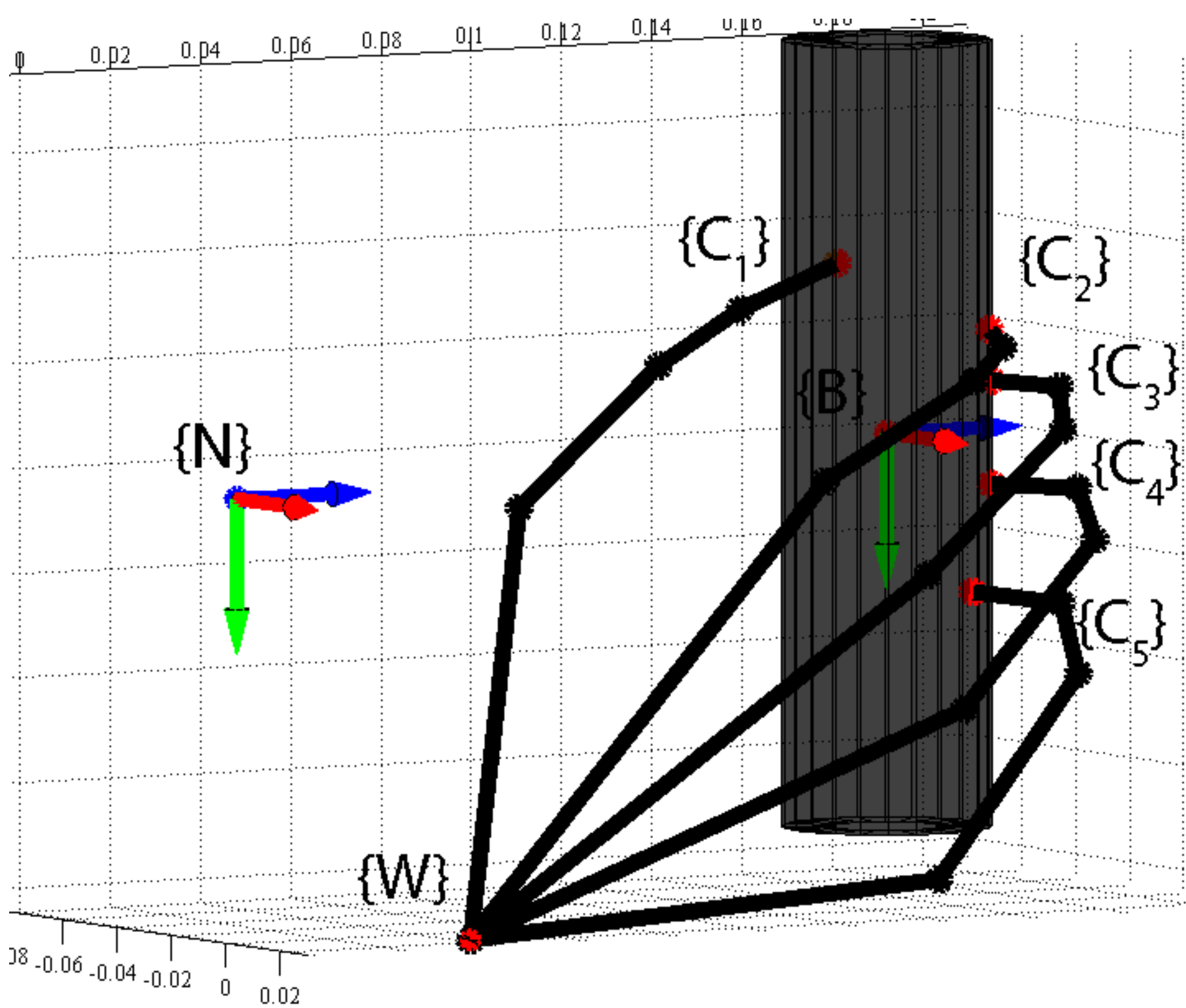
- Fingers and palm wrap around object forming a *cage*.
- Impossible to move the object, even infinitesimally.
- *Power Grasp*.
- Guarantees maintenance of contact (links rigid, joint actuators strong)

Force Closure

- Under any external wrench, contact forces exist that satisfy object equilibrium conditions.
- Hand to squeeze arbitrarily tight to compensate for external wrenches, through friction.
- *Precision Grasp*.

Analysis

Grasp Analysis



Kinematics

$$^{G}T_{C_i}$$

Force at contact (HF)

$$^{C_i}f_i$$

Wrench to object's CoM

$$\underset{6\text{x}1}{\mathbf{g}} = \underset{6\text{x}15}{\boldsymbol{G}}\ {}^{C}\underset{15\text{x}1}{\boldsymbol{f}}$$

Grasp Matrix

Force Closure

External wrench

2 Conditions

-Object at equilibrium

-No sliding at contacts

$$\mathbf{g} = -\boldsymbol{w}$$

$$\sqrt{{}^{C}f_{t,i}^{2} + {}^{C}f_{o,i}^{2}} \leq \mu {}^{C}f_{n,i}$$

$$\mathcal{F}_i = \{ {}^{C}\boldsymbol{f}_i = \begin{bmatrix} {}^{C}f_{n,i} & {}^{C}f_{t,i} & {}^{C}f_{o,i} \end{bmatrix}^T \in \mathbb{R}^3 | \sqrt{{}^{C}f_{t,i}^{2} + {}^{C}f_{o,i}^{2}} \leq \mu \, {}^{C}f_{n,i} \}$$

Friction cone

Synthesis

Grasp Synthesis

$$\mathbf{f}^* = \arg\min_{\mathbf{f}} Q(\mathbf{f}, \mathbf{q})$$

s.t. $\mathbf{g} + \mathbf{w} = 0$ **(equilibrium)**

$^{C_i}\mathbf{f}_i \in \mathcal{F}_i$ **(friction cone)**

$NT_{C_i} - NT_{O_i} = 0$ **(kinematics)**

$\mathbf{f}_i \in \mathcal{F}_i^{motor}$ **(force constraints)**

$q_i \in \mathcal{Q}_i$ **(joint limits)**

Grasp Quality Measures

Categories
- Contact forces
- Hand configuration
- Grasp Robustness

...

Examples
- Normal force magnitudes
- Manipulability
- Task-specificity

...

Máximo A. Roa and Raúl Suárez. 2015. Grasp quality measures: review and performance. Auton. Robots 38, 1 (January 2015), 65–88. DOI:https://doi.org/10.1007/s10514-014-9402-3

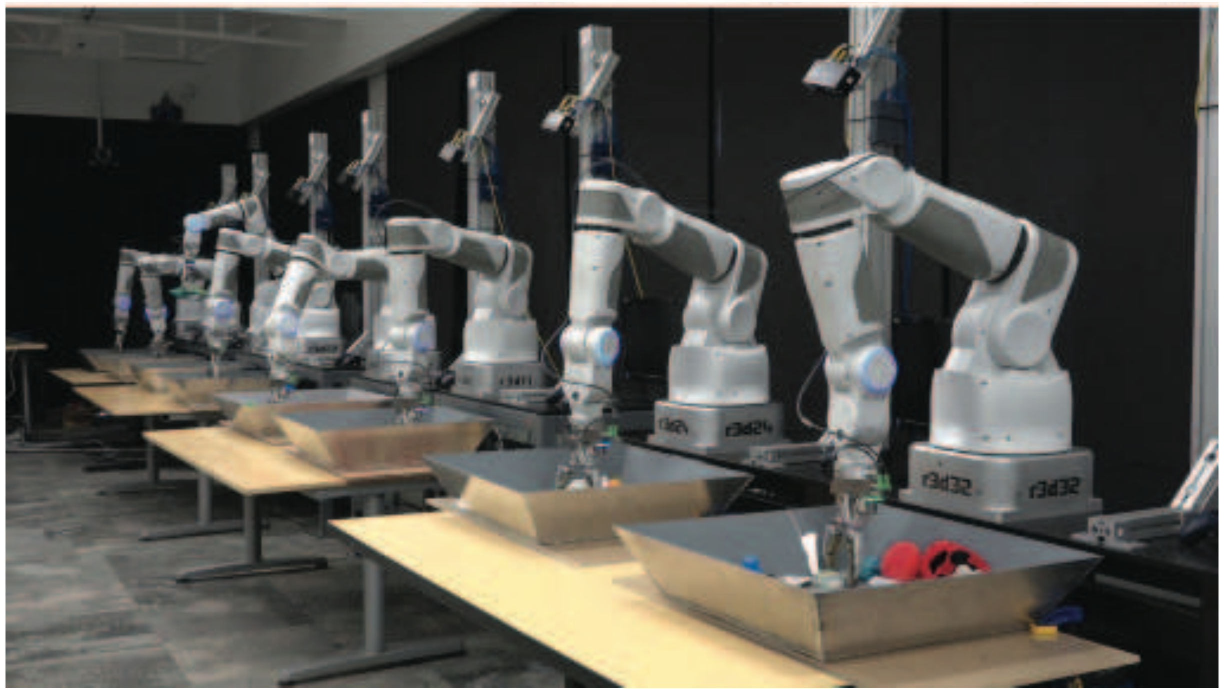
Recent trends: End-to-end Manipulation

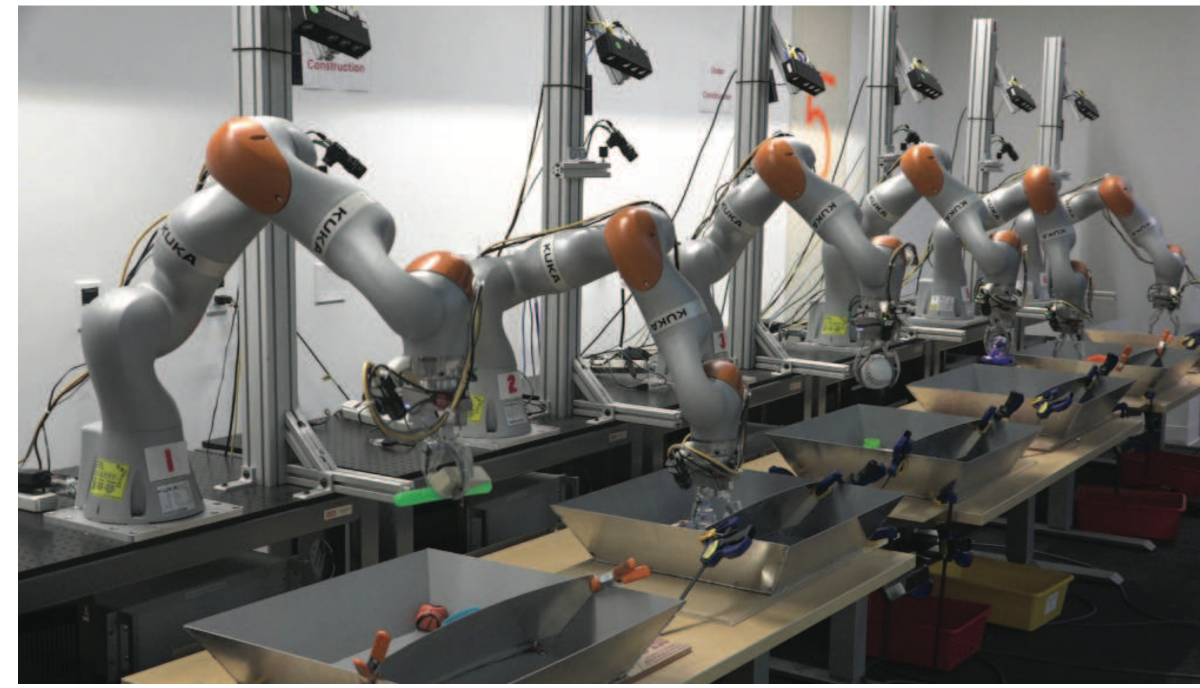
Deep Learning for Detecting Robotic Grasps

https://youtu.be/f9CuzqI1SkE

Lenz, I., Lee, H., & Saxena, A. (2015). Deep learning for detecting robotic grasps. The International Journal of Robotics Research, 34(4–5), 705–724. https://doi.org/10.1177/0278364914549607

Learning Hand-Eye Coordination for Robotic Grasping





The Google “arm farm”

https://youtu.be/cXaic_k80uM

Levine, S., Pastor, P., Krizhevsky, A., Ibarz, J., & Quillen, D. (2018). Learning hand-eye coordination for robotic grasping with deep learning and large-scale data collection. The International Journal of Robotics Research, 37(4–5), 421–436. https://doi.org/10.1177/0278364917710318

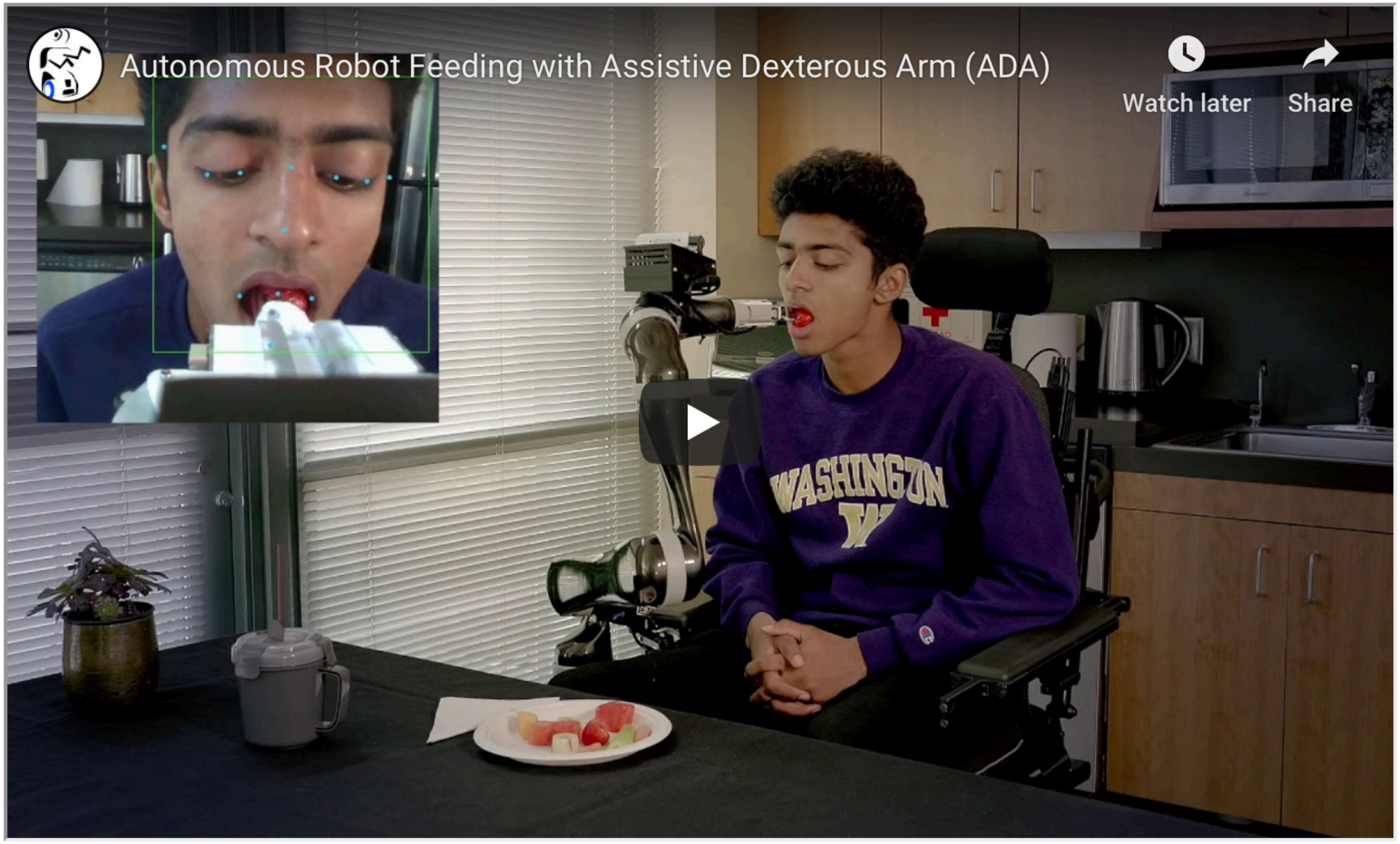
Dex-Net

https://youtu.be/GBiAxoWBNho

https://berkeleyautomation.github.io/dex-net

The Dexterity Network (Dex-Net) is a research project including code, datasets, and algorithms for generating datasets of synthetic point clouds, robot parallel-jaw grasps and metrics of grasp robustness based on physics for thousands of 3D object models to train machine learning-based methods to plan robot grasps. The broader goal of the Dex-Net project is to develop highly reliable robot grasping across a wide variety of rigid objects such as tools, household items, packaged goods, and industrial parts.

Assistive Feeding



https://www.youtube.com/watch?v=t2eO4CD-0WY

(Dr. Tapo Bhattacharjee will talk about ADA next week)

Next: Social Robot Navigation