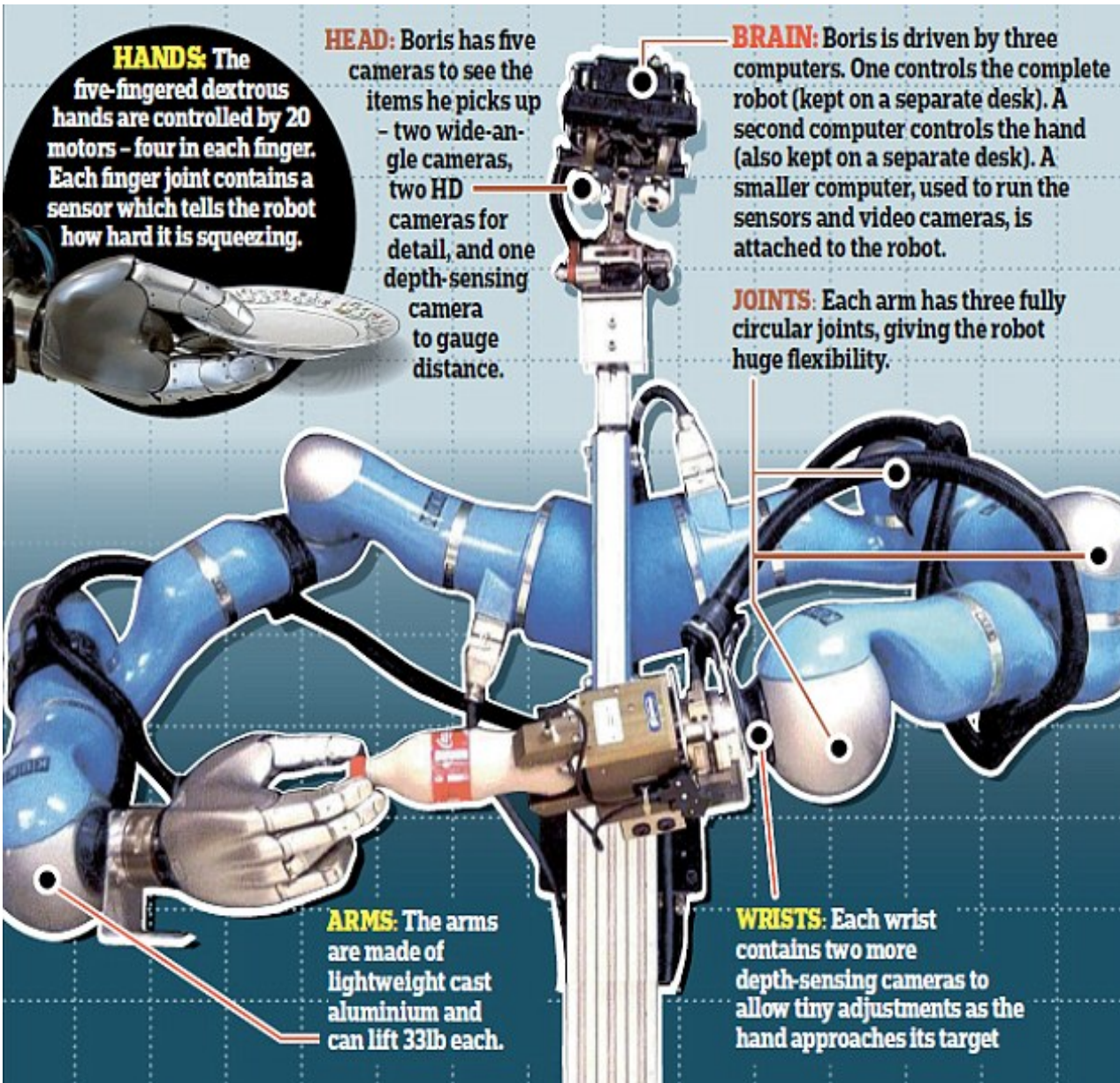


# Automated Design of Special Purpose Dexterous Manipulators

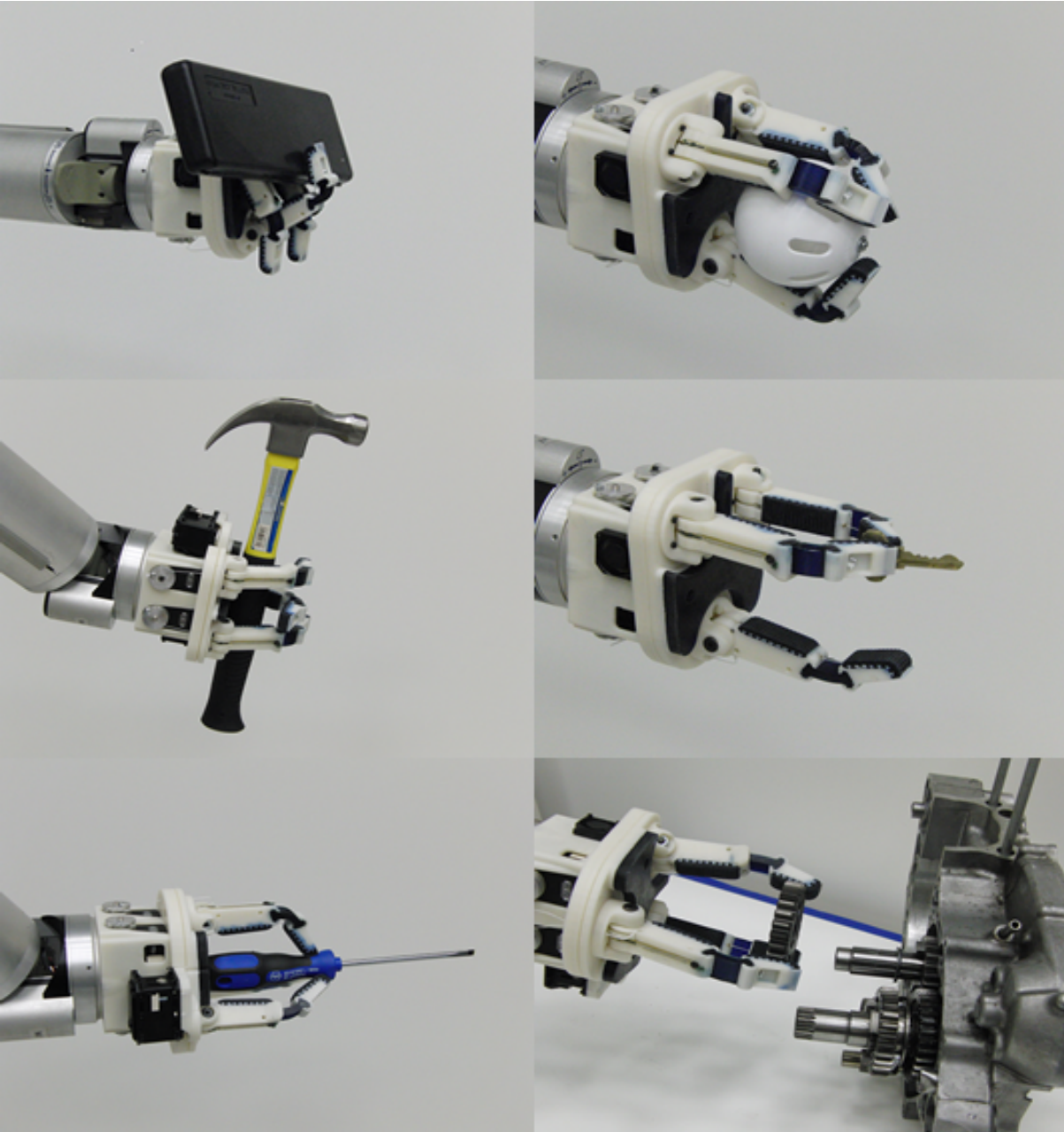
Christopher Hazard

# Motivation



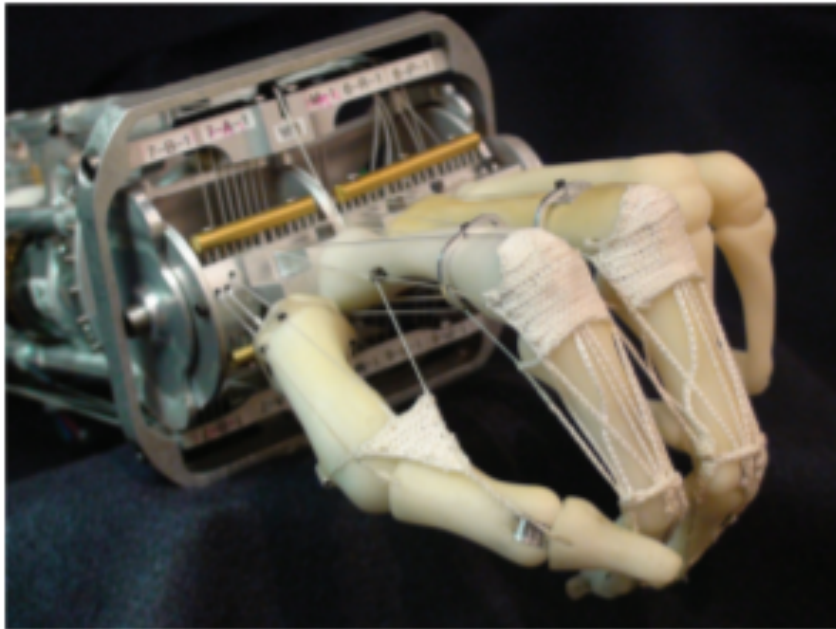


# Challenges

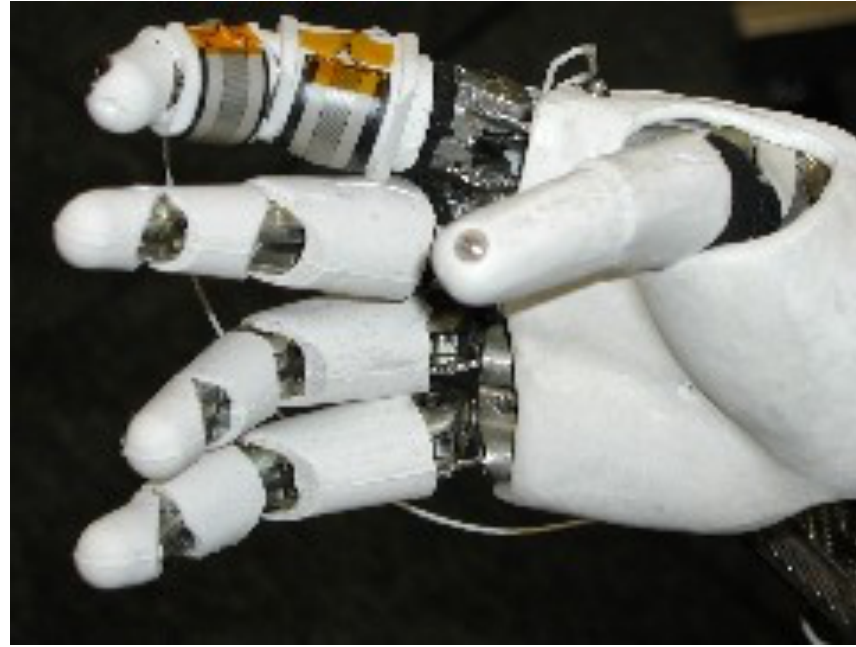


# Humanoid Hands

- Goal: mirror human hand
- Impressive capability
- Important limitations
- Very expensive
- Costly mechanical failures



ACT: anatomically correct testbed hand



NASA Robonaut Hand

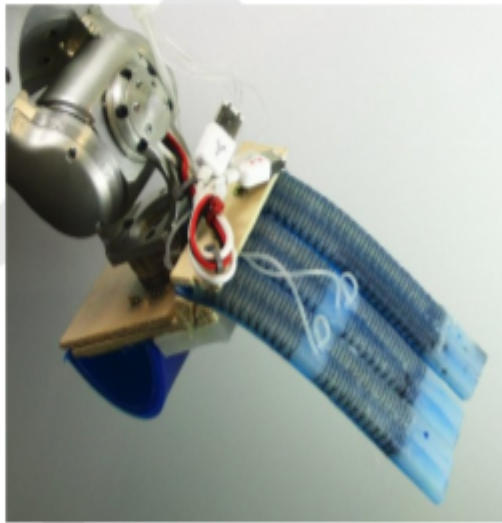
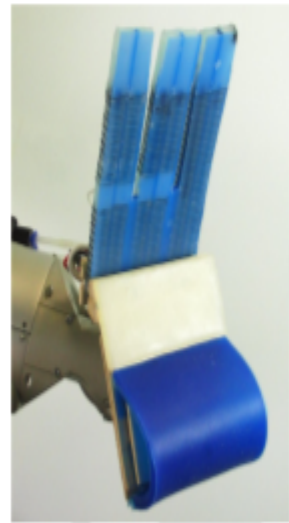


Shadow Dexterous

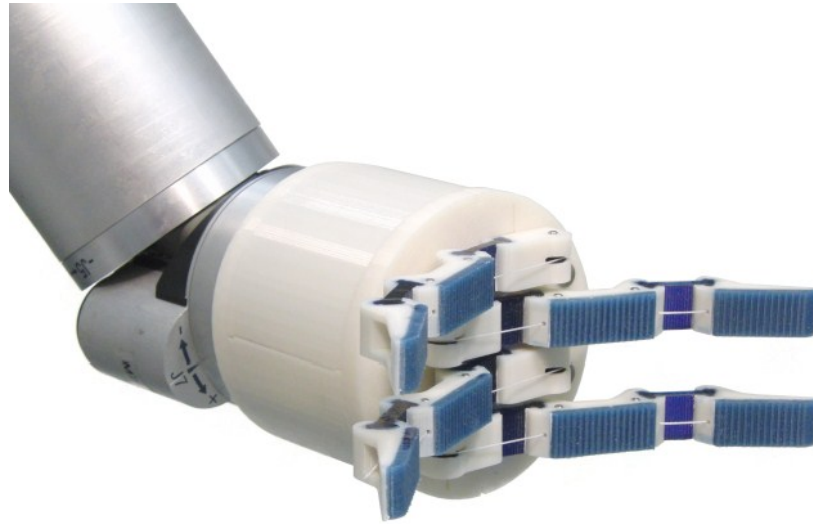
- [1] "The ACT hand: Design of the skeletal structure" Weghe 2004  
[2] "The robonaut hand: A dexterous robot hand for space" Lovchick 1999  
[3] Shadow Dexterous: <https://www.shadowrobot.com>



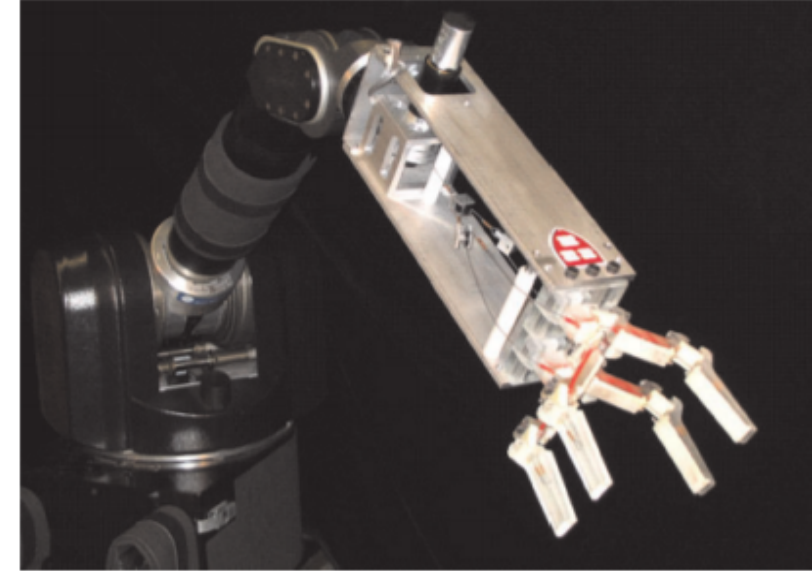
# Low Cost (Simplified) Hands



Pneumatic Hand (Diemel 2013)



3D printed Hand (Ma 2013)



SDM Hand (Dollar 2010)

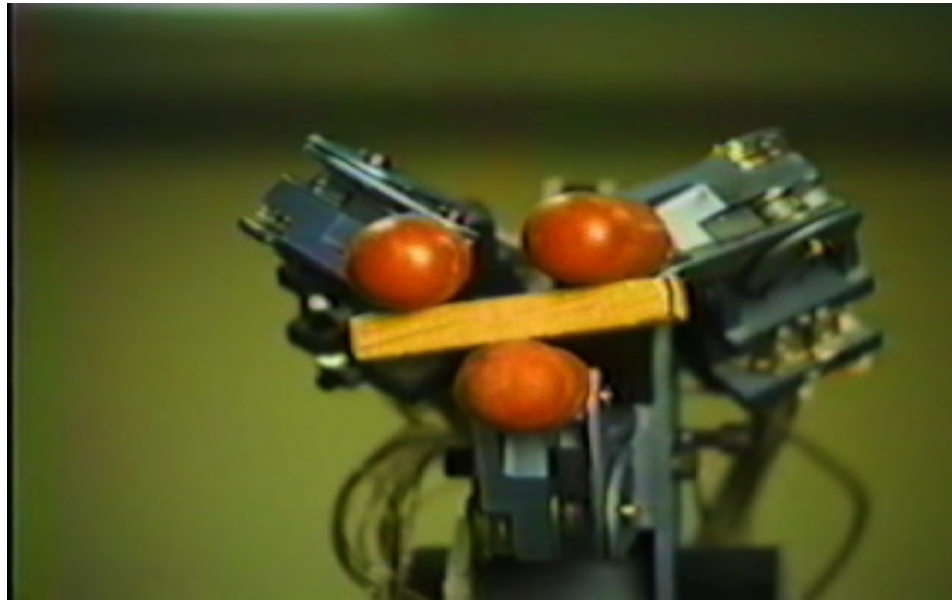
- underactuated designs
- 3d printable components
- cheap materials + simple construction
- soft/compliant components
- cheap embedded sensing

[1] "A modular, open-source 3D printed underactuated hand" Ma 2013

[2] "A compliant hand based on a novel pneumatic actuator" Deimel 2013

[3] "The highly adaptive SDM hand: Design and performance evaluation" Dollar 2010

# Design Parameter Optimization



Salisbury 1982: Stanford-JPL hand

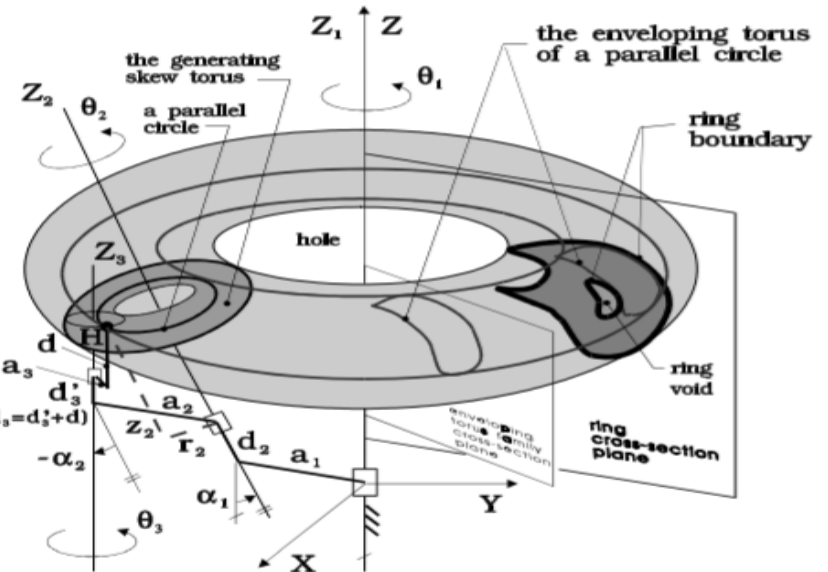
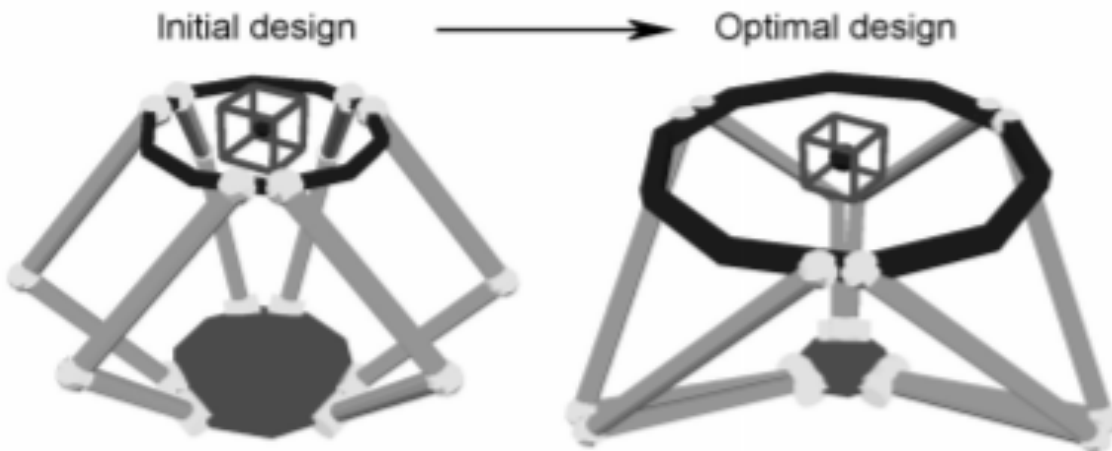


Fig. 2. Design parameters and workspace geometry for 3R manipulators.

Ceccarelli 2004: workspace optimization



Collard 2005: Manipulability Optimization

[1] "Articulated hands: Force control and kinematic issues" Salisbury 1982

[2] "A multi-objective optimum design of general 3R manipulators for prescribed workspace limits" Ceccarelli 2004

[3] "Contribution to the optimization of closed-loop multibody systems: Application to parallel manipulators" Collard 2005

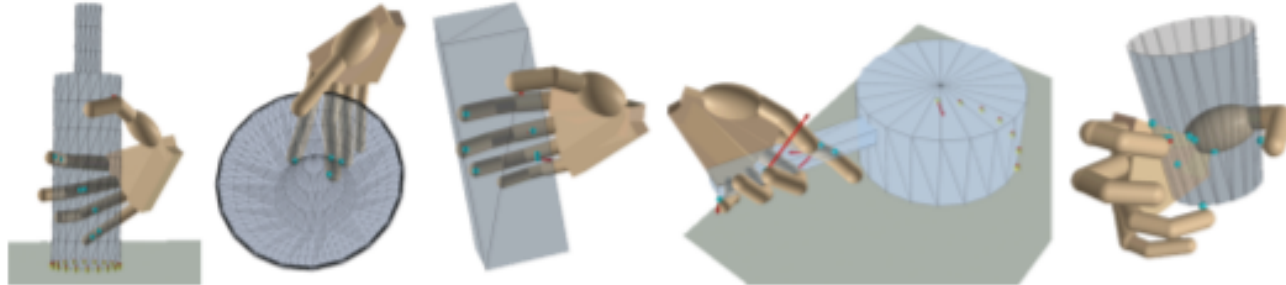
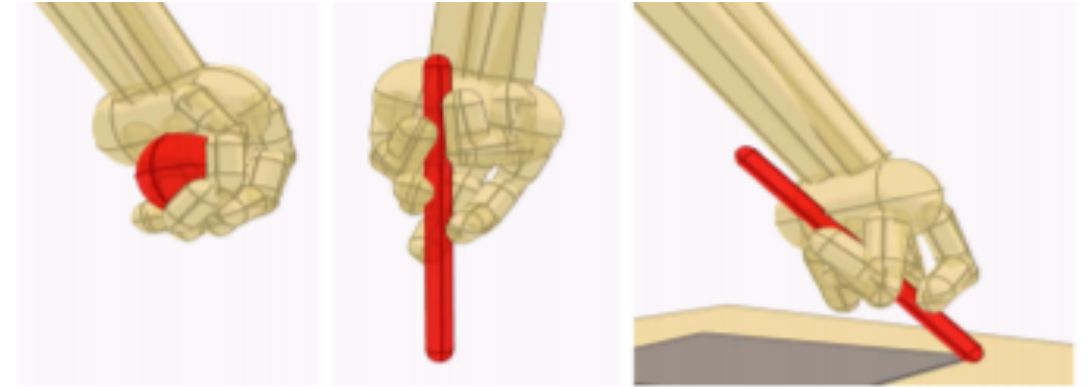
[4] "An optimization problem approach for designing both serial and parallel manipulators" Ceccarelli 2005



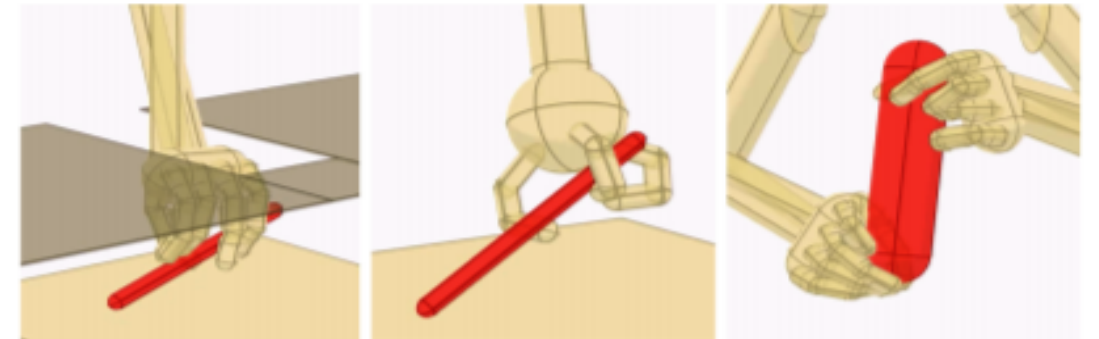
# Trajectory Optimization



Liu 2008



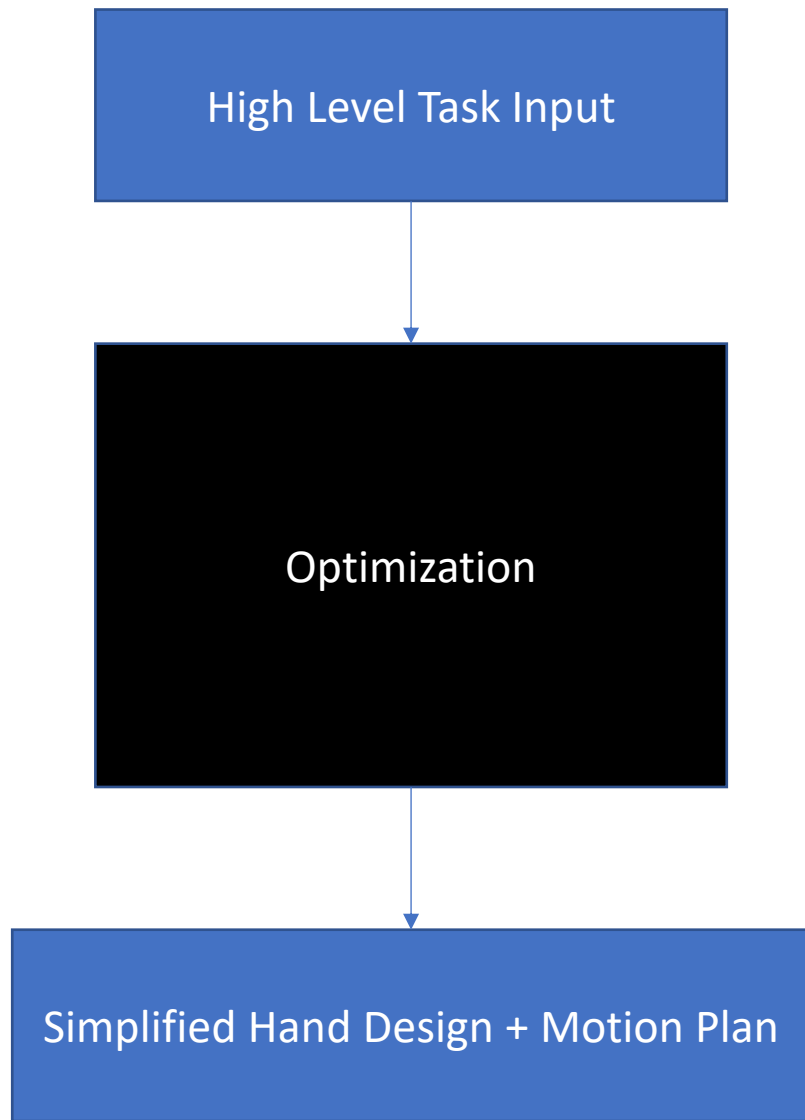
Ye 2012



Mordatch 2012

- [1] "Construction and animation of anatomically based human hand models" Albrecht 2003
- [2] "Synthesis of interactive hand manipulation." Liu 2008
- [3] "Dextrous manipulation from a grasping pose" liu 2009
- [4] "Synthesis of Detailed Hand Manipulations Using Contact Sampling" Ye 2012
- [5] "Contact-invariant optimization for hand manipulation." Mordatch 2012

# Our Work

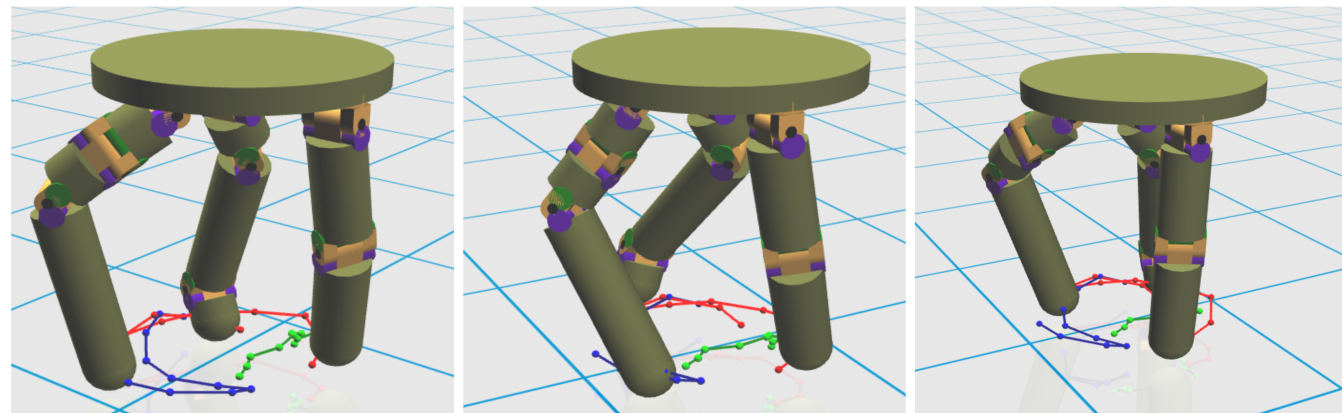




User Input:  
Initial contact points (not necessarily optimal),  
base trajectory, motion objectives

Step 1: Floating Contact Optimization

Step 1b: Floating De-fuzzification

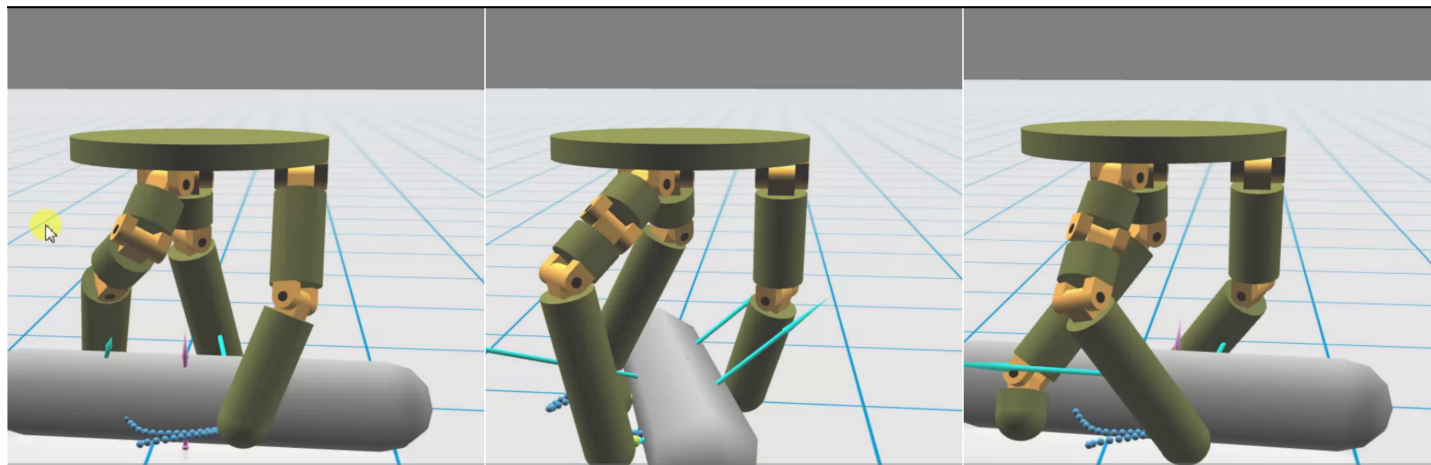


Optimized Mechanism and Poses

Step 2: Mechanism Synthesis Optimization

Step 3: "Whole Hand" Optimization

Mechanism and final motion plan (contacts, hand/object poses, forces)



Floating Motion Plan:  
Contacts, forces, object positions

# Step 1: Floating Contact Optimization

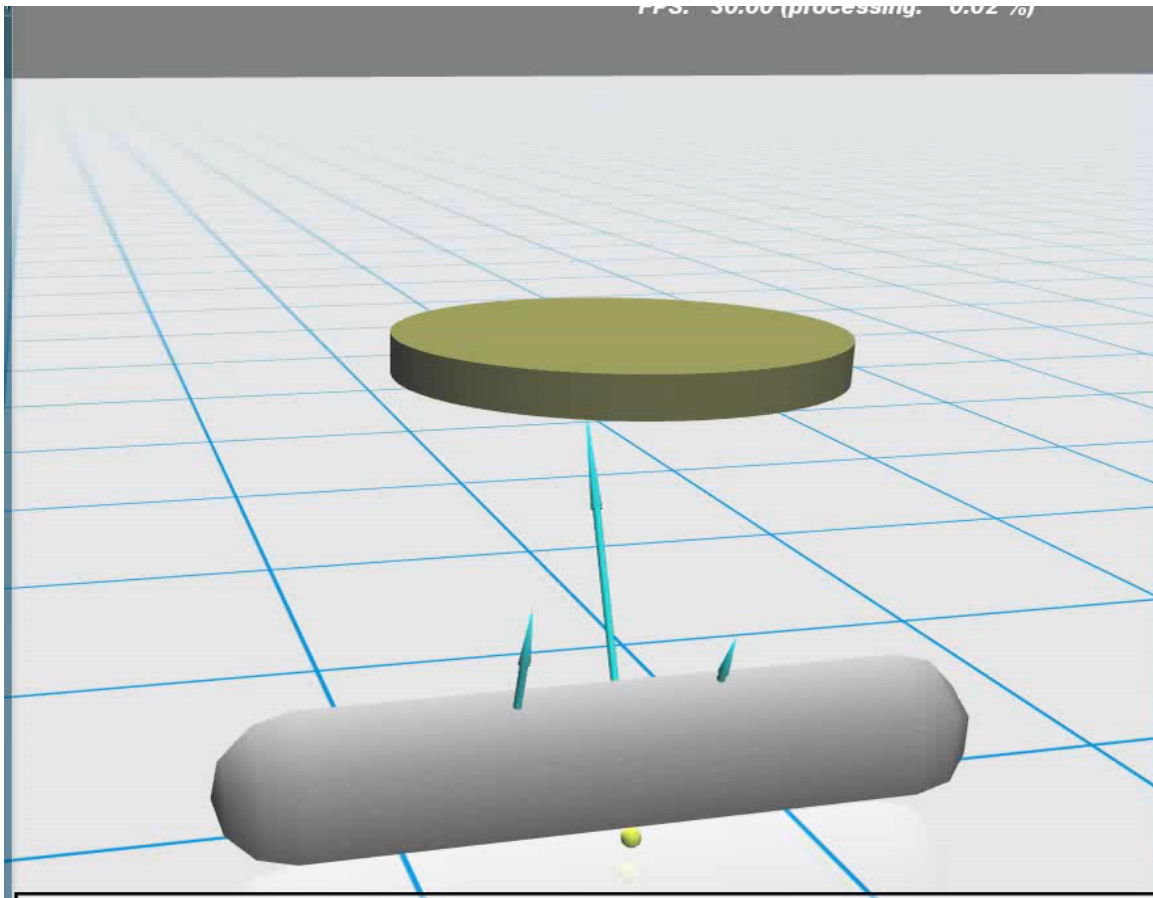
# Floating Contact Optimization

Input:

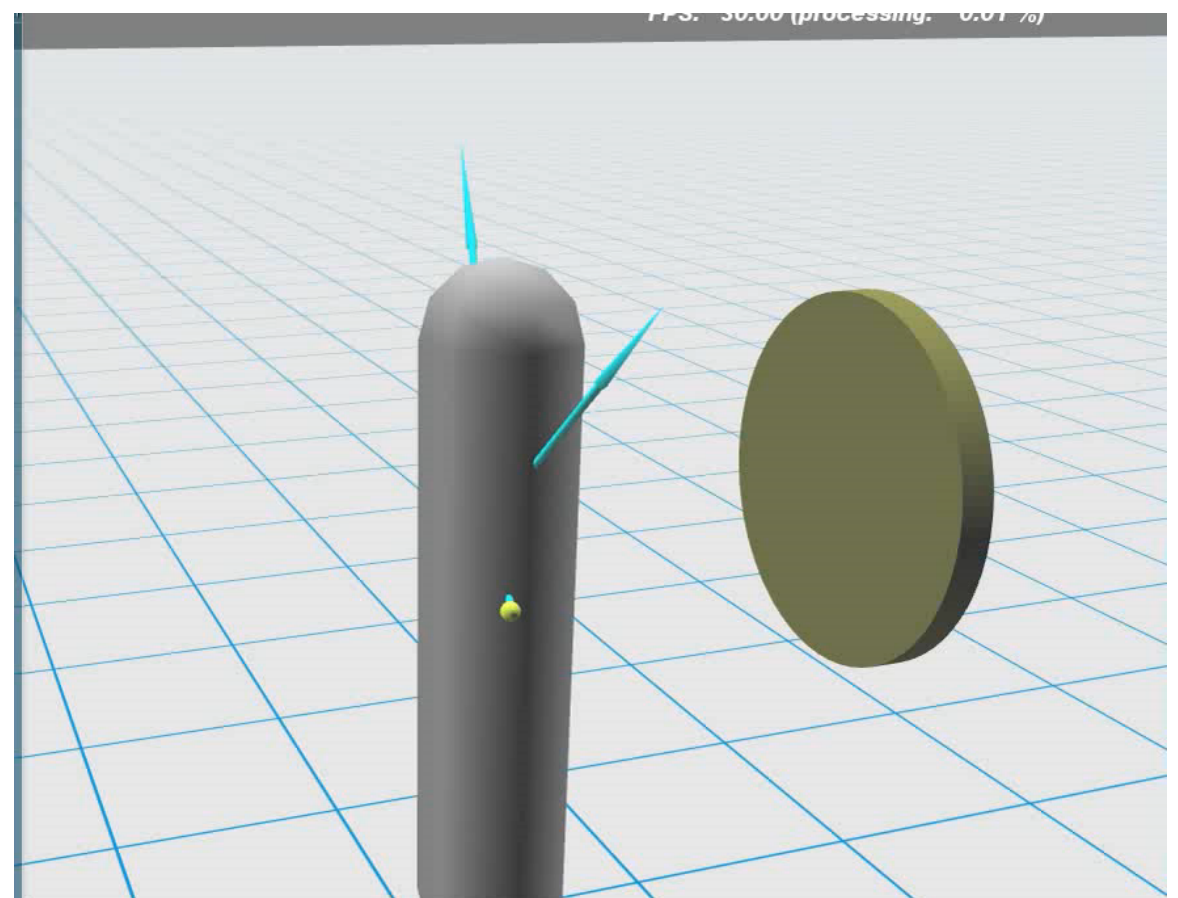
- Object goal poses
- Initial contact points

Output:

- Physically valid motion plan (contacts and forces)



Pick and Rotate



Vertical Flip



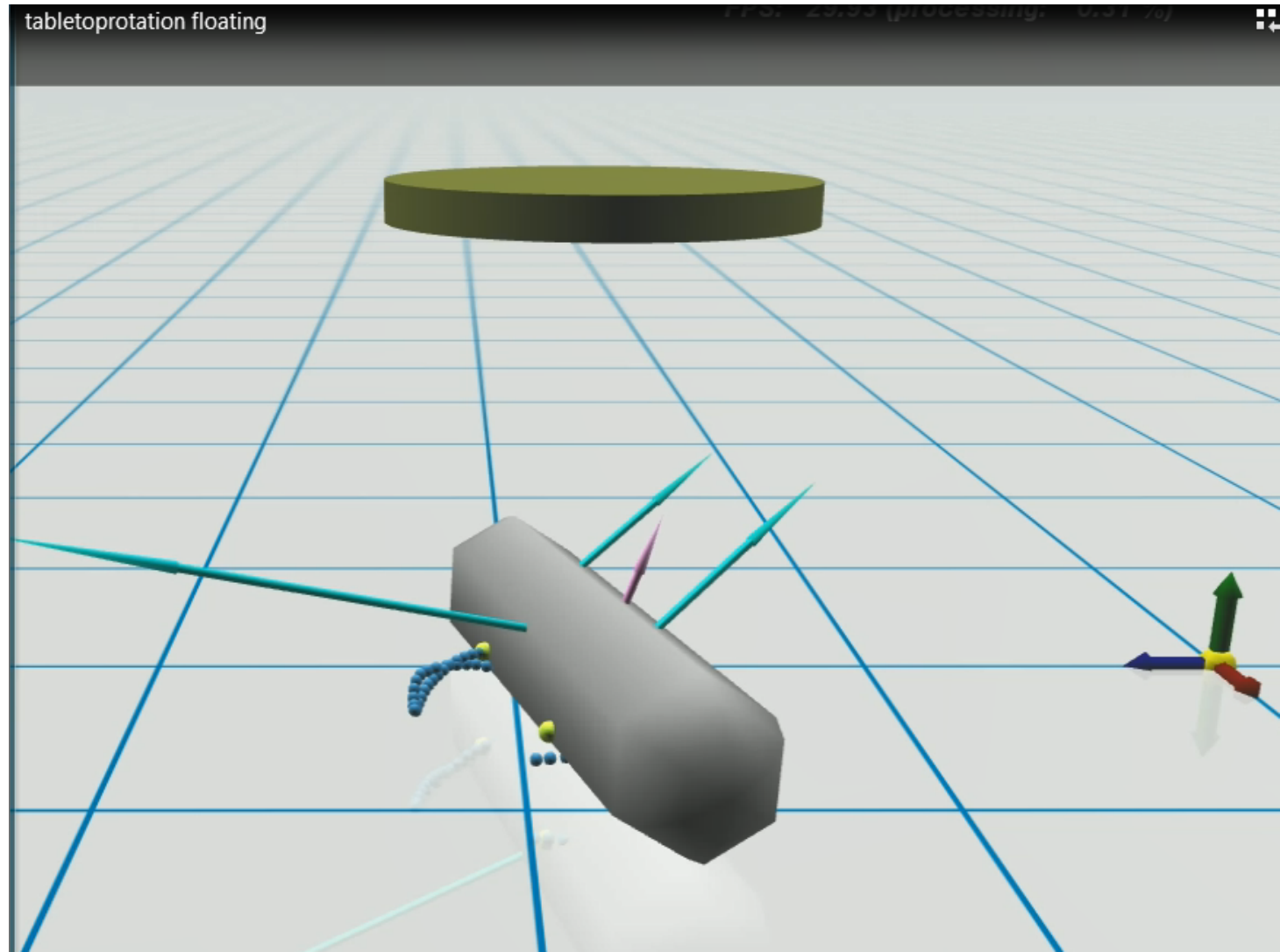
# Step 1: Floating Optimization Problem

$$\mathbf{S} = \underset{\mathbf{S}}{\operatorname{argmin}} \sum_t \sum_i w_i * L_i(t)$$

$$\text{s.t. } c_j \in [0, 1] \text{ for } 0 \leq t \leq T$$

$$\mathbf{S}_t = [\mathbf{x}_O \ \mathbf{f}_j \ \mathbf{r}_j \ c_j]$$

- $\mathbf{x}_O$  = object position + orientation
- $\mathbf{f}_j$  = contact force (contact j)
- $\mathbf{r}_j$  = contact position (contact j)
- $c_j$  = contact invariant term



# Step 1: Floating Optimization Objective Terms

- Task----specify goal of the manipulation
- Physics—force and torque balancing + friction cone constraints
- Contact Invariant terms—projection of contacts onto object surface
- Additional Regularization Terms—smooth out the motion

# Task Objective Terms

$$L_{task} = \frac{1}{k} \sum_k ||p(k) - p_{goal}(k)||^2 + quatdist(o(k), o_{goal}(k))^2$$

- Main objective type: object pose
- Quatdist: angular distance between 2 orientations

Alternative/additional objectives:

- End effector tracking between object and target points
- Additional perturbing forces

$$L_{eeTracking}(t) = \sum_i ||p_{ee}(t) - p_{target}(t)||^2$$



# Physics Terms

$$L_{physics}(t) = L_{linMomentum}(t) + L_{angMomentum}(t)$$

$$L_{linMomentum}(t) = \sum_i \underbrace{c_i(t)f_i}_{\text{Applied Force}} - \underbrace{m\ddot{x}}_{\text{Derivative of linear momentum}}$$

Applied Force      Derivative of linear momentum

$$L_{angMomentum}(t) = || \underbrace{\sum_i c_i(t) * (r_i \times f_{i,local})}_{\text{Applied Torque}} - \underbrace{(\omega \times (I_{object}^{local} \omega) + I\dot{\omega})}_{\text{Derivative of angular momentum}} ||^2$$

Applied Torque

Derivative of angular momentum

- $x$  = object position
- $f_j$  = contact force (contact j)
- $r_j$  = contact position (contact j)
- $c_j$  = contact invariant term

# Force and Contact Related Terms

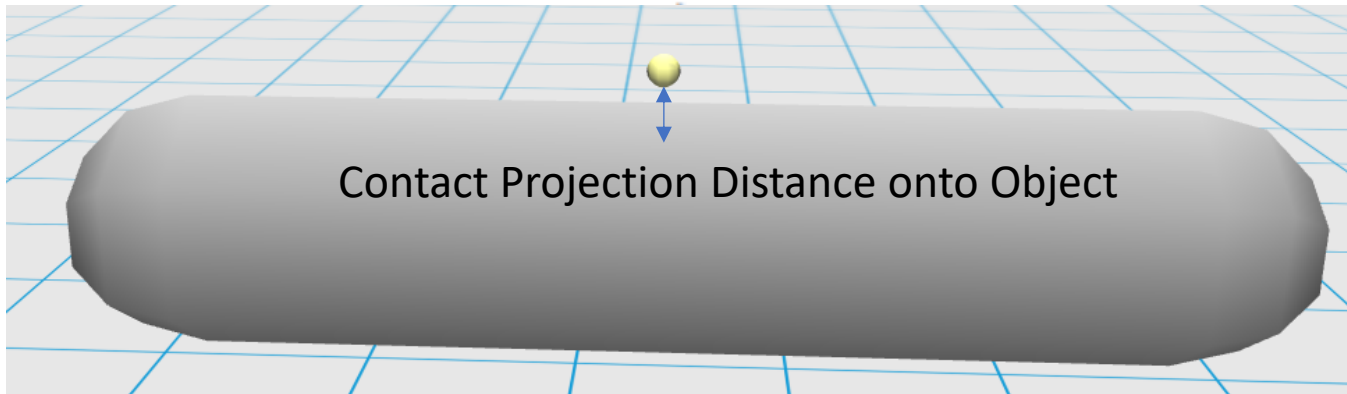
Force Related Costs

$$L_{forceReg}(t) = \sum_i \|c_i(t)f_i\|^2$$

$$L_{frictionCone}(t) = \sum_i c_i * \exp(\underbrace{\alpha(\|f_{i,local} - n * (f_i \cdot n_i)\|)}_{f_{tangent}} - \underbrace{\mu f_i \cdot n_i}_{f_{normal}})$$

Contact Invariant Related Costs

$$L_{ci\_object}(t) = \sum_i c_i \|r_{proj} - r_i\|^2$$



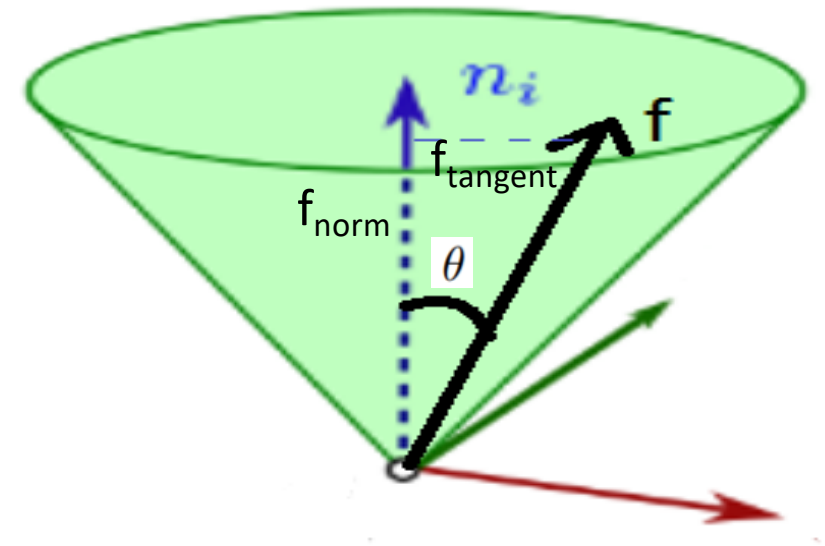
For contact i:

$f_i$  = contact force

$r_i$  = contact position (object local frame)

$n_i$  = object surface normal (local frame)

Alpha is a constant (sharpening factor)



$$f_{tangent} \leq \mu f_{normal} \text{ i.e.}$$

$$\theta = \tan^{-1} \frac{f_{tangent}}{f_{normal}} \leq \tan^{-1} \mu$$

# Additional Regularization Terms

$$L_{floatingContactAccel}(t) = \sum_i \underbrace{\|((r_i(t + t_{phys}) - 2 * r_i(t) + r_i(t - t_{phys}))/ (t_{phys} * t_{phys}))\|^2}_{\text{Acceleration of contact: finite differences}}$$

$$|L_{accelerationRegularization}(t) = \sum_i \ddot{x}^2$$

Object acceleration: finite differences

$$L_{angularAccelerationRegularization}(t) = \sum_i \underbrace{(\omega \times (I_{world}\omega) + I_{world}\dot{\omega}/t_{phys})^2}_{\text{Angular Momentum derivative}}$$

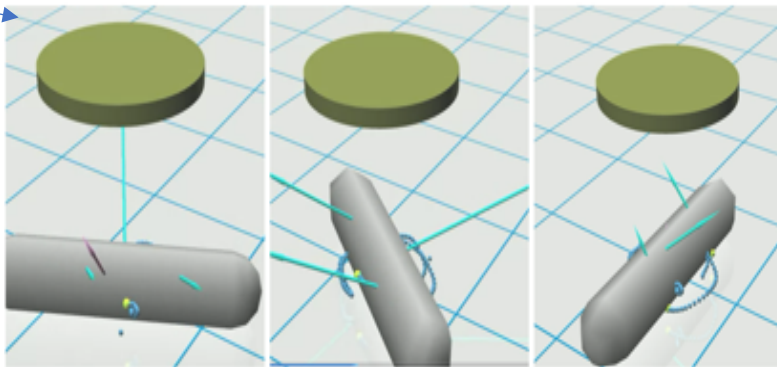
# Floating Post-Processing

- Continuous Contact Variables

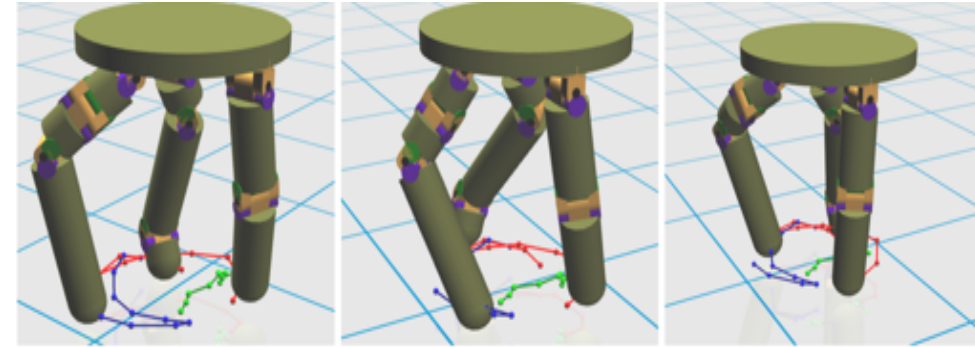
User Input:  
Initial contact points (not necessarily optimal),  
base trajectory, motion objectives

Step 1: Floating  
Contact Optimization

Step 1b: Floating De-  
fuzzification



Floating Motion Plan:  
Contacts, forces, object positions

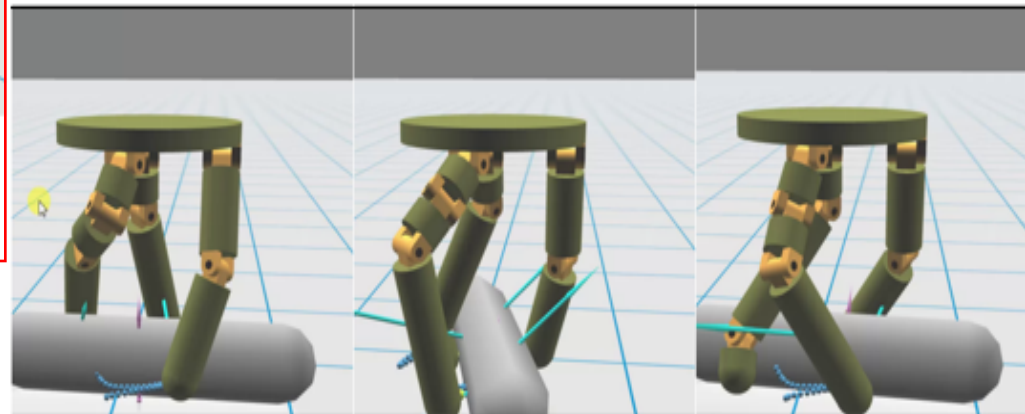


Optimized Mechanism and Poses

Step 2: Mechanism Synthesis Optimization

Step 3: "Whole Hand" Optimization

Mechanism and final motion plan (contacts, hand/object poses, forces)

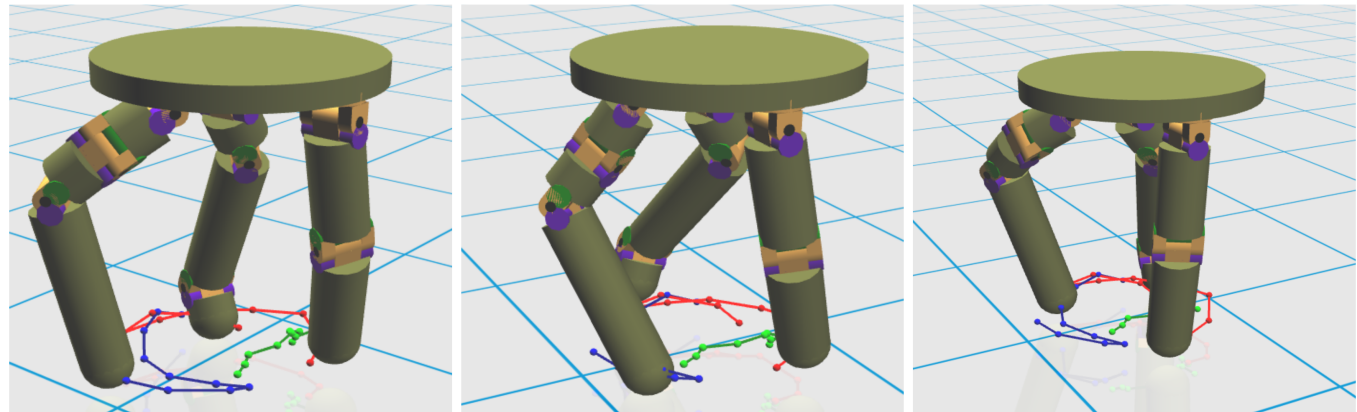
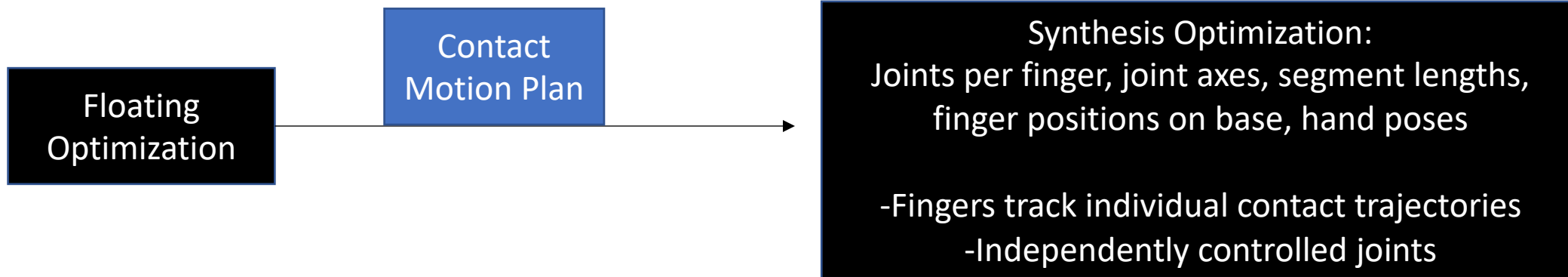


- Contact variables held fixed (binary)



# Step 2: Mechanism Synthesis

# Step 2: Mechanism Synthesis



Output: Optimized Mechanism + Poses

# Continuous Synthesis Optimization

$$\mathbf{M} = \underset{\mathbf{M}, \mathbf{Q}, \mathbf{P}}{\operatorname{argmin}} \sum_k \sum_i w_i * L_i(k)$$

for  $k \in \{1, 2, \dots, N_{keyframes}\}$

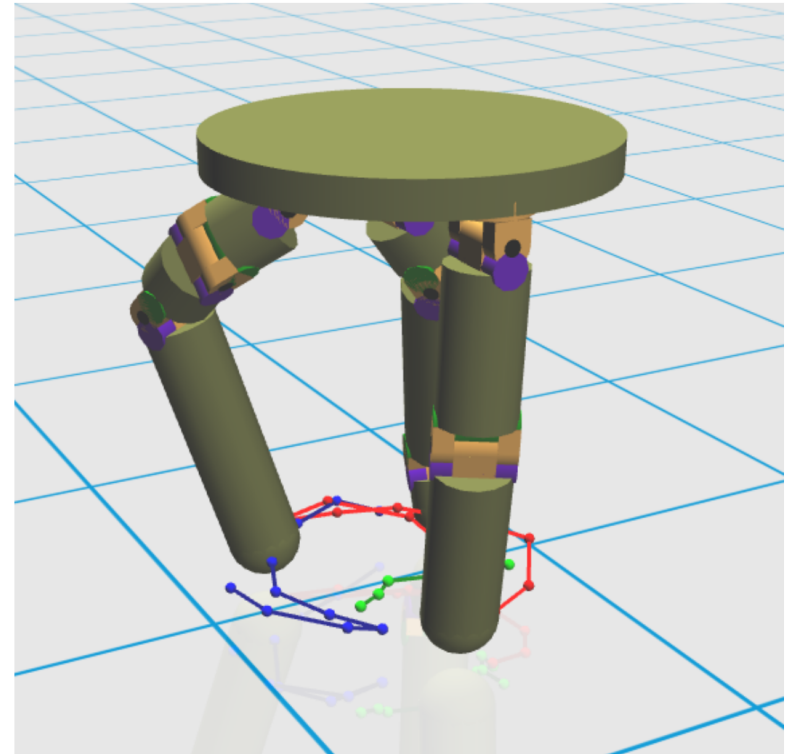
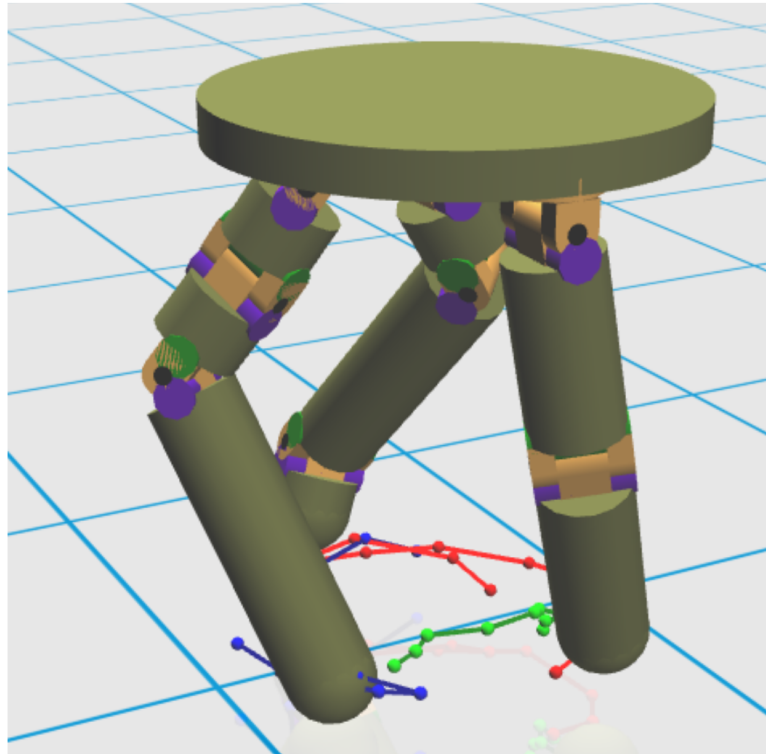
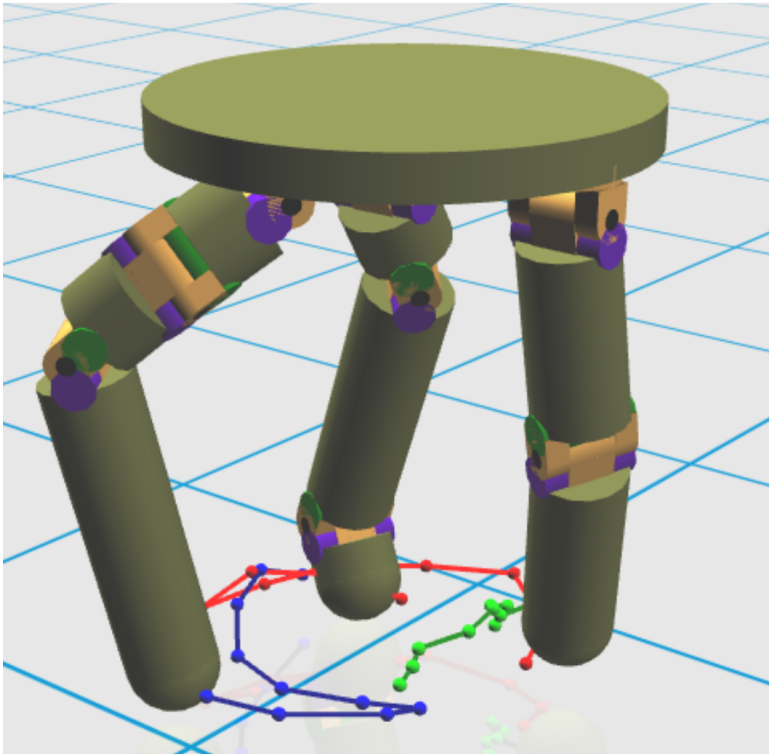
- Morphological parameters  $\mathbf{M}$ :
  - finger lengths
  - joint axes
  - locations of fingers on the base
- Joint positions  $\mathbf{Q}$  (hand poses at each keyframe)
- Contact points  $\mathbf{P}$  (on fingertips)

# Synthesis Objective Terms

Contact Point Costs

$$L_{eeTarget}(k) = \sum_i c_i * ||p_i - p_{target}||^2$$

$$L_{fingerContactDistSurface}(k) = \sum_i ||p_{proj} - p_i||^2$$



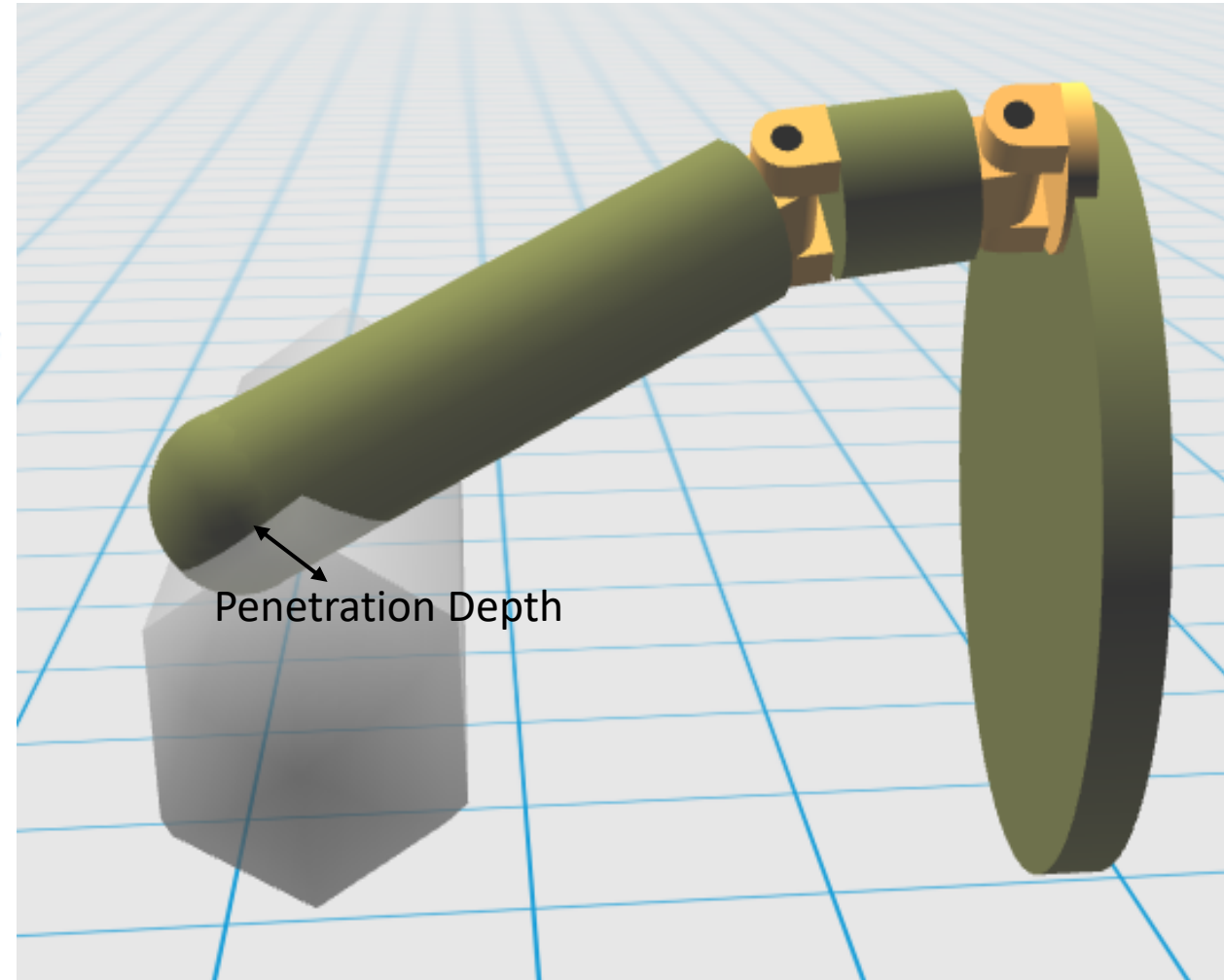


# Synthesis Objective Terms

## Collision Penalties

$$g(x) = \begin{cases} 0 & x \leq -\epsilon \\ \frac{x^3}{6\epsilon} + \frac{x^2}{2} + \frac{\epsilon x}{2} + \frac{\epsilon^2}{6} & -\epsilon \leq x \leq \epsilon \\ x^2 + \frac{\epsilon^2}{3} & \epsilon \leq x \end{cases}$$

$$L_{collision}(k) = \sum_{i,j \in bodies} g(\text{penetration}(\text{body}_i, \text{body}_j))$$

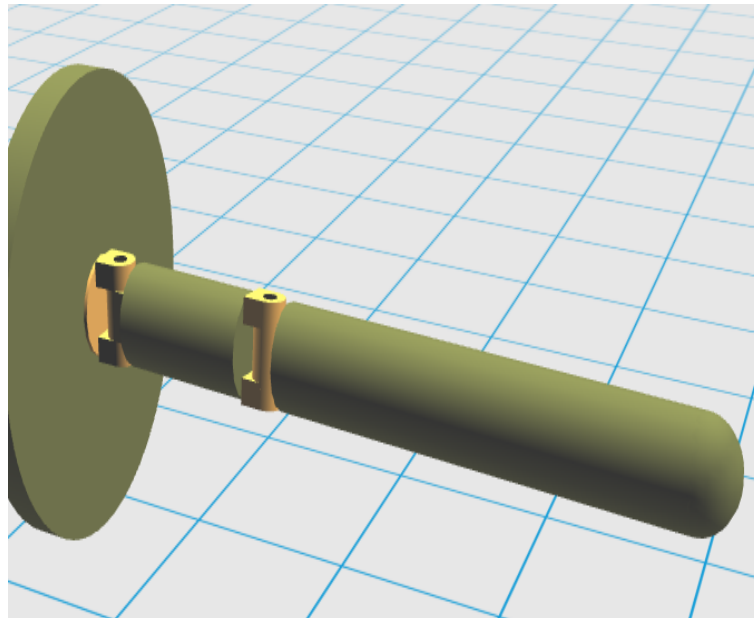
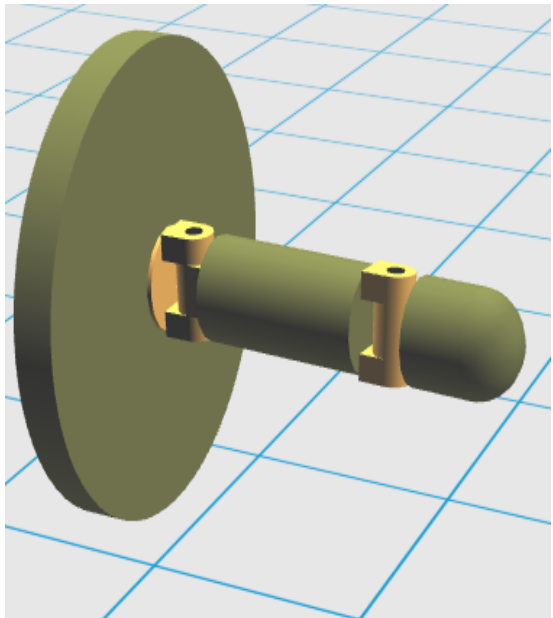


# Additional Costs

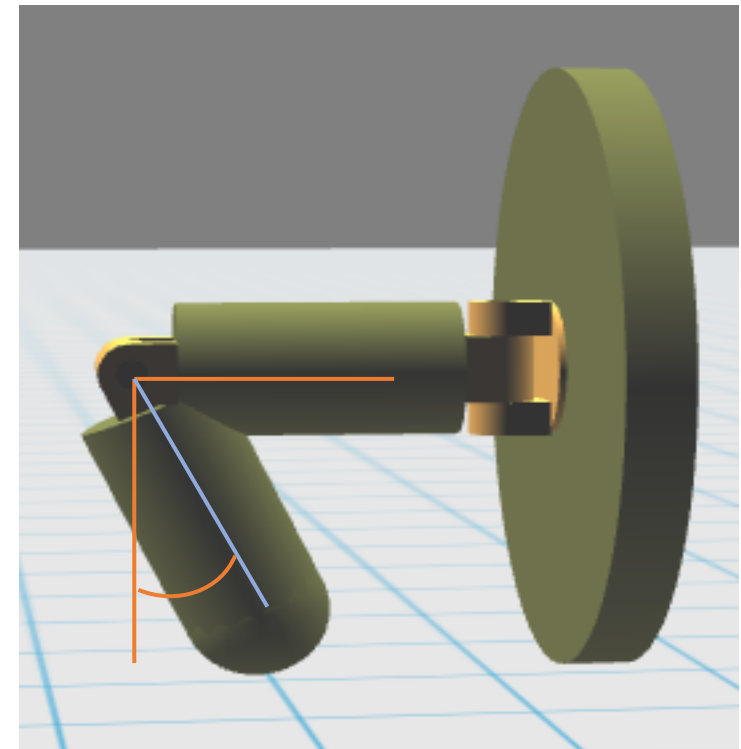
$$L_{fingerLengthRegularization} = \sum_i (l_i)^2$$

$$L_{jointLimits}(k) = \sum_{i \in keyframes} \sum_{a \in joints} g(a(i) - a_{max}) + g(a_{min} - a(i))$$

$$L_{fingerMinLengthCost} = \sum_i g(l_{min} - l_i)$$



Distal link: min length and a large length

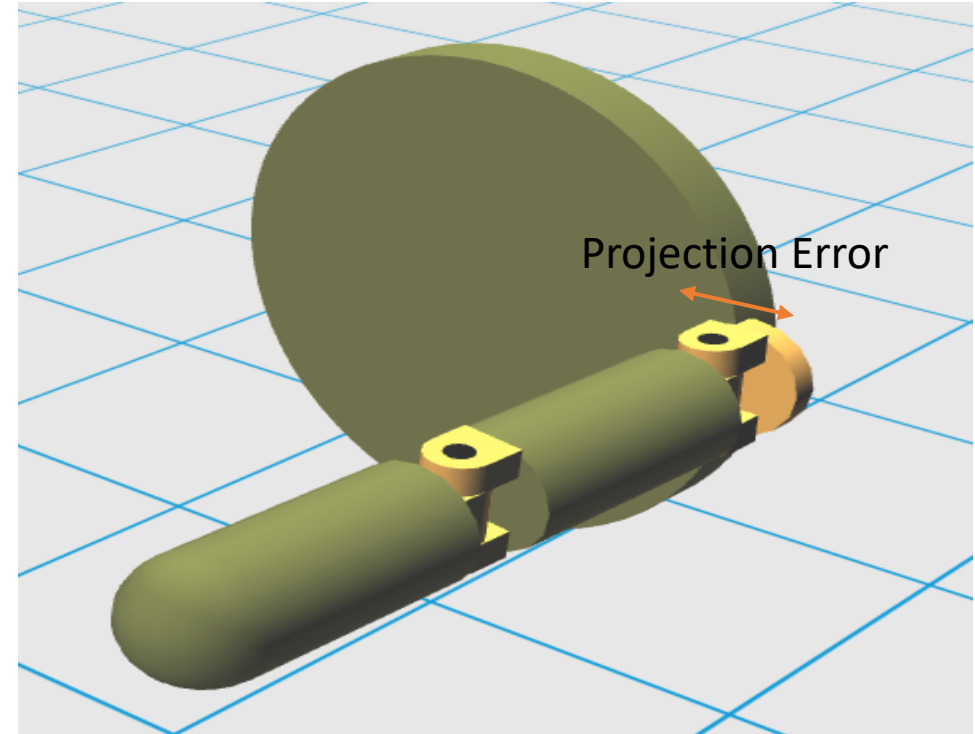
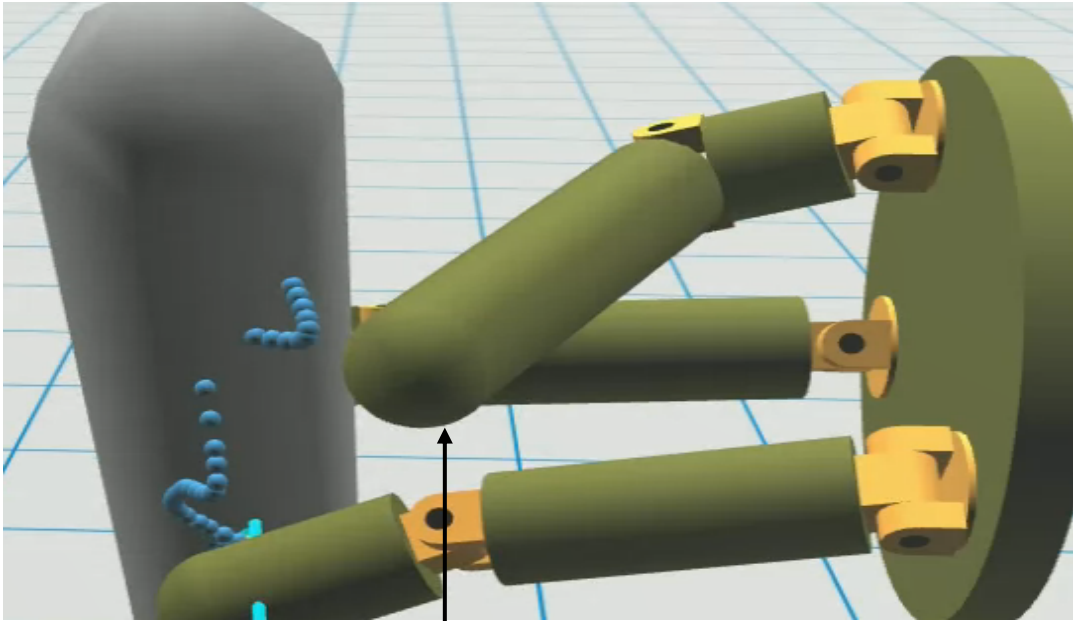


Joint Limit Violation

# Additional Costs

$$L_{fingerAcceleration}(k) = \sum_i (1 - c_i) * \ddot{x}_i^2$$

$$L_{fingerPositions} = \sum_i ||proj_{base}(b_i) - b_i||^2$$



Lifted finger transitions smoothly from one side to the other

# Controllability Constraints

## Jacobian Null Space:

Let  $E = \{e_0, \dots, e_k\}$  be an orthonormal basis of the Jacobian null space:

$$L_{jacNull} = \sum_i c_i * \sqrt{\sum_k (f \cdot e_k)^2}$$

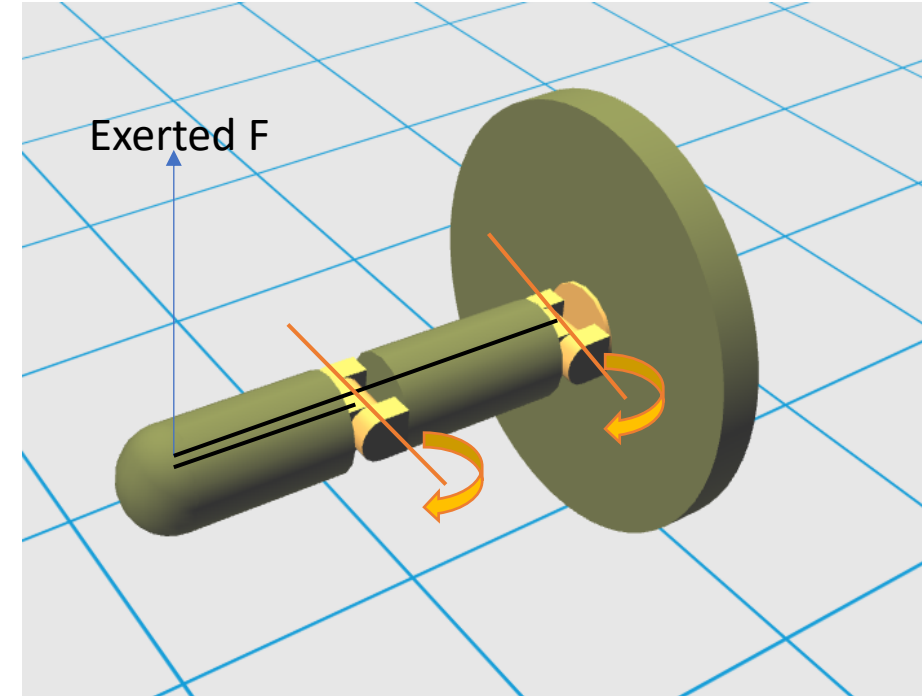
## Torque Regularization:

$$F = T \times r_{perp} / \|r_{perp}\|^2 + k * r_{perp}$$

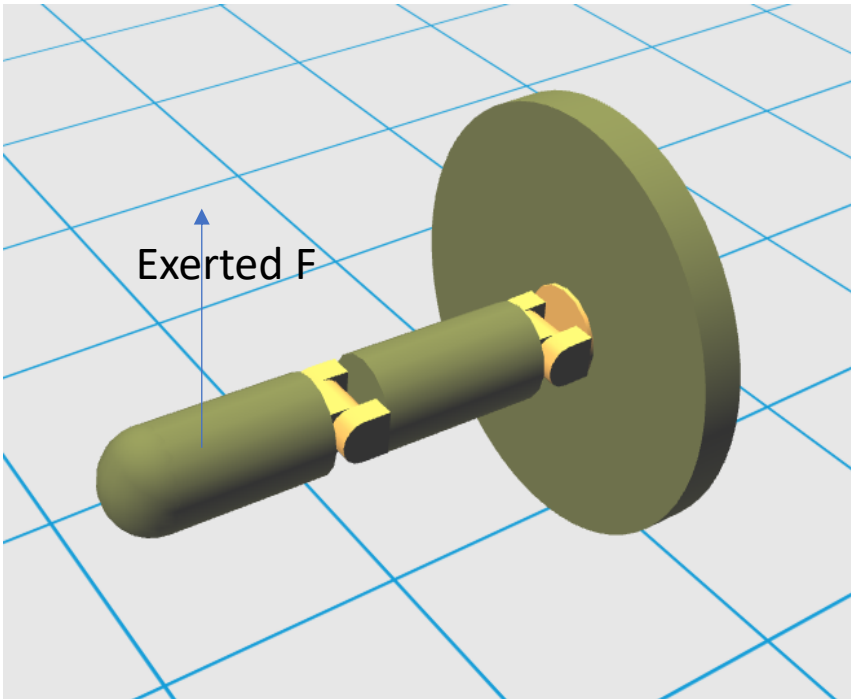
$$F = X * \alpha \longrightarrow \vec{\alpha} = (X^T X + \lambda^2 I)^{-1} X_T^T F$$

where  $X$  is the matrix consisting of column vectors  $T \times r_{perp} / \|r_{perp}\|^2$

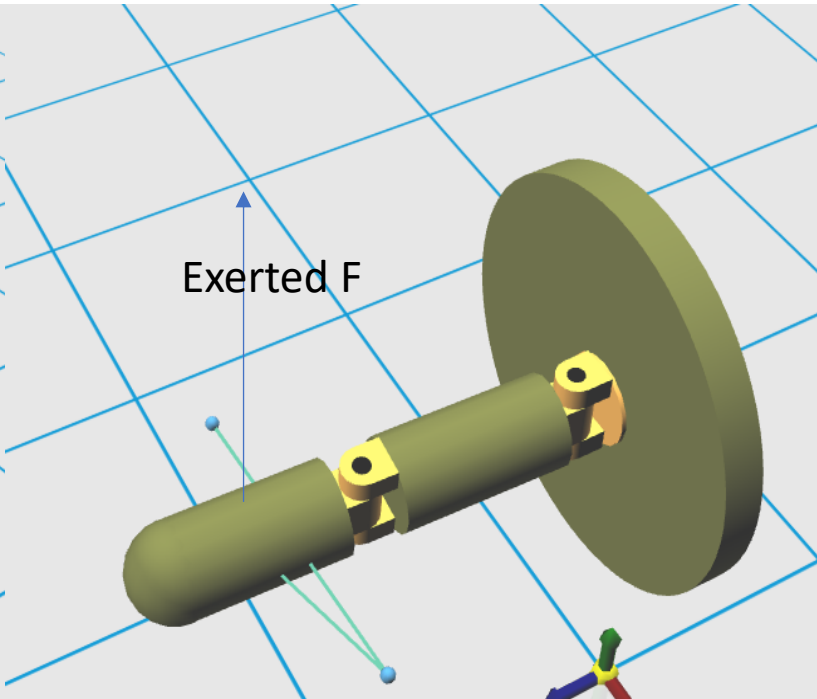
$$L_{torque} = \|\vec{\alpha}\|^2$$



# Controllability Constraints Demonstration



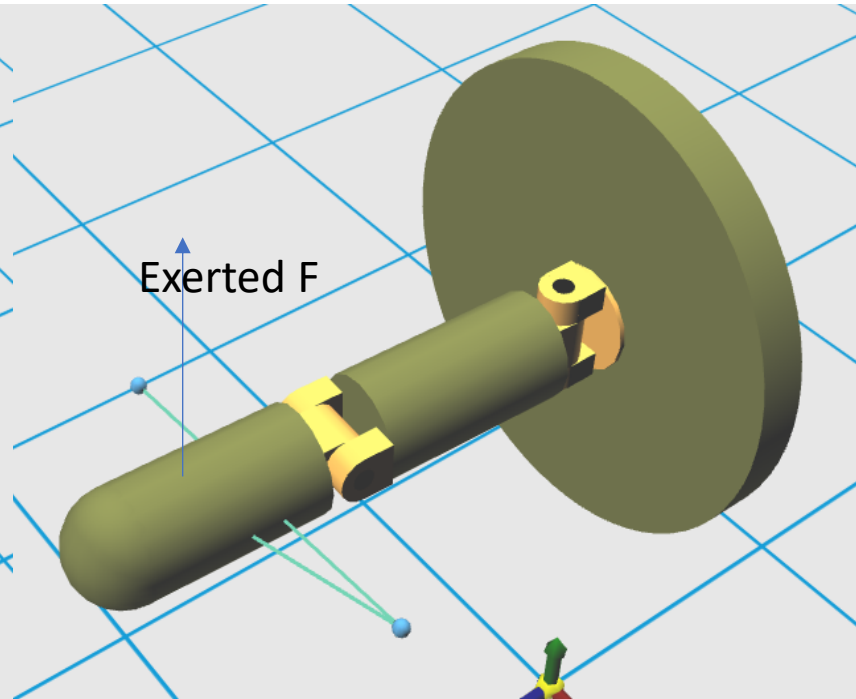
1. Finger held still: optimal joints



2. Finger rotates in plane  
Joints slightly off axis:

$$L_{\text{jacNull}} = 0$$

$L_{\text{torque}}$  very high



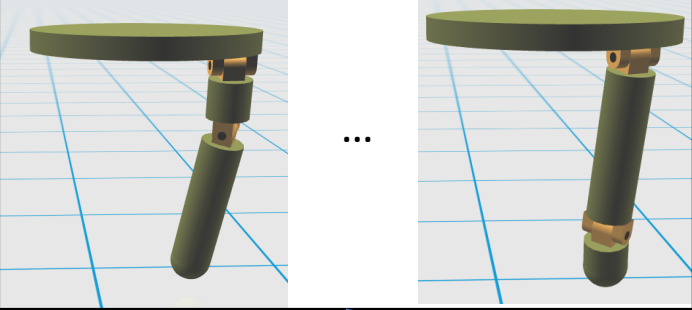
3. Finger rotates in plane:  
Optimal joint configuration



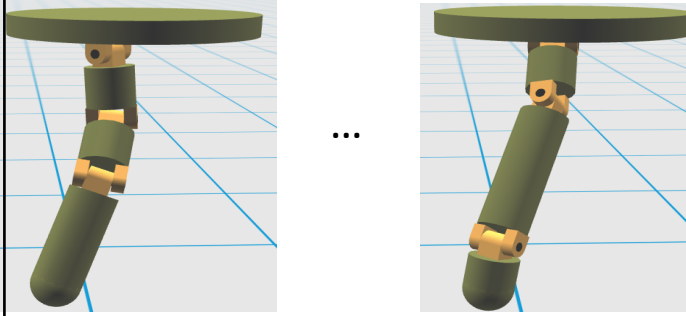
# Synthesis Design Loop

Individual Finger Designs: Optimized Independently with Random Seeds

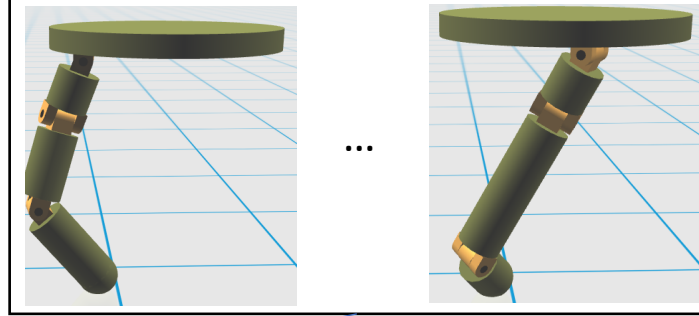
Finger 1



Finger 2

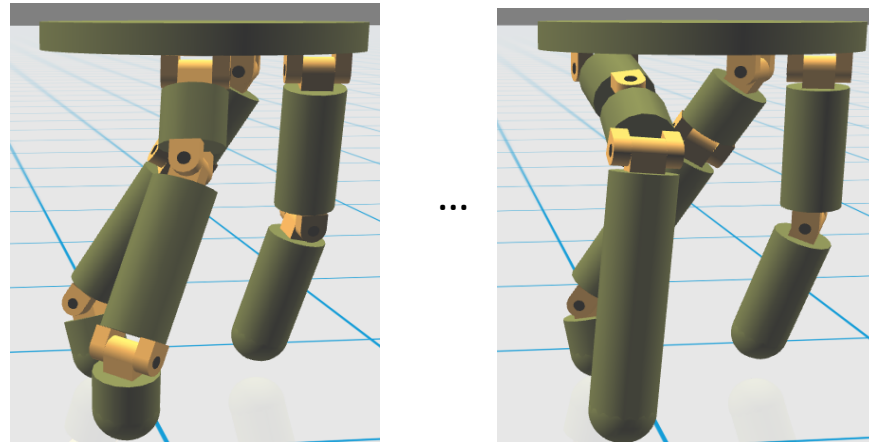


Finger 3



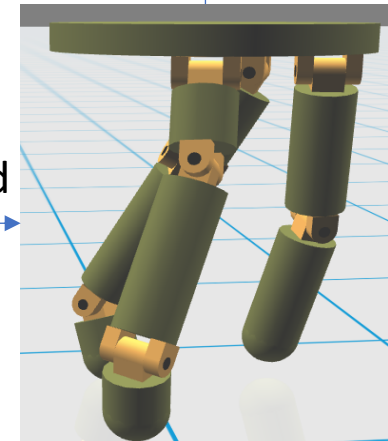
Re-optimize

Random Recombination + Re-Optimization



Add segments if  $L_{eeTarget} + L_{jacNull} > \text{threshold}$

Pick best hand



# Step 3: Whole Hand Optimization

# Whole Hand Optimization Problem

We wish to find a trajectory  $\mathbf{S} = \{\mathbf{S}_1, \mathbf{S}_2, \dots, \mathbf{S}_{N_{keyframes}}\}$  such that

$$\begin{aligned} \mathbf{S} &= \underset{\mathbf{S}}{\operatorname{argmin}} \sum_t \sum_i w_i * L_i(t) \\ \text{s.t. } c_j &\in [0, 1] \text{ for } 0 \leq t \leq T \end{aligned}$$

- Adjusts the motion so it fits to the designed hand
- Uses floating objectives + additional objectives
- Also optimize for robot poses  $\mathbf{q}$
- Morphology stays fixed

# Additional Optimization Terms

Additional terms (from floating) adapted for hand:

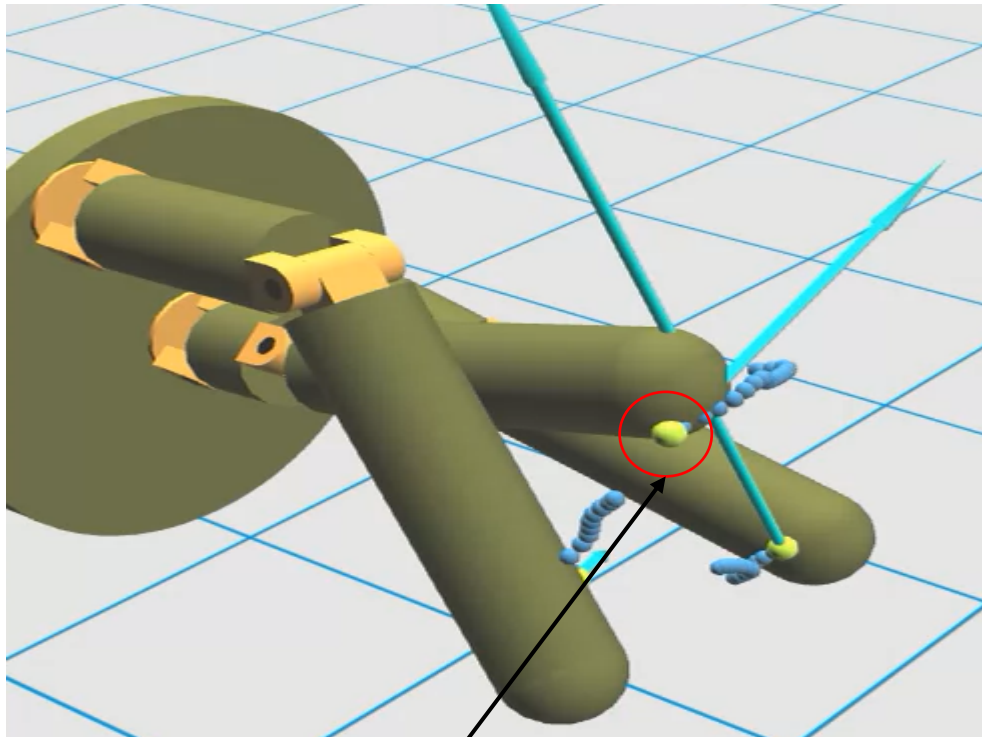
Contact projection onto fingertip surface

$$L_{ci\_finger}(t) = \sum_i c_i ||r_{proj} - r_i||^2$$

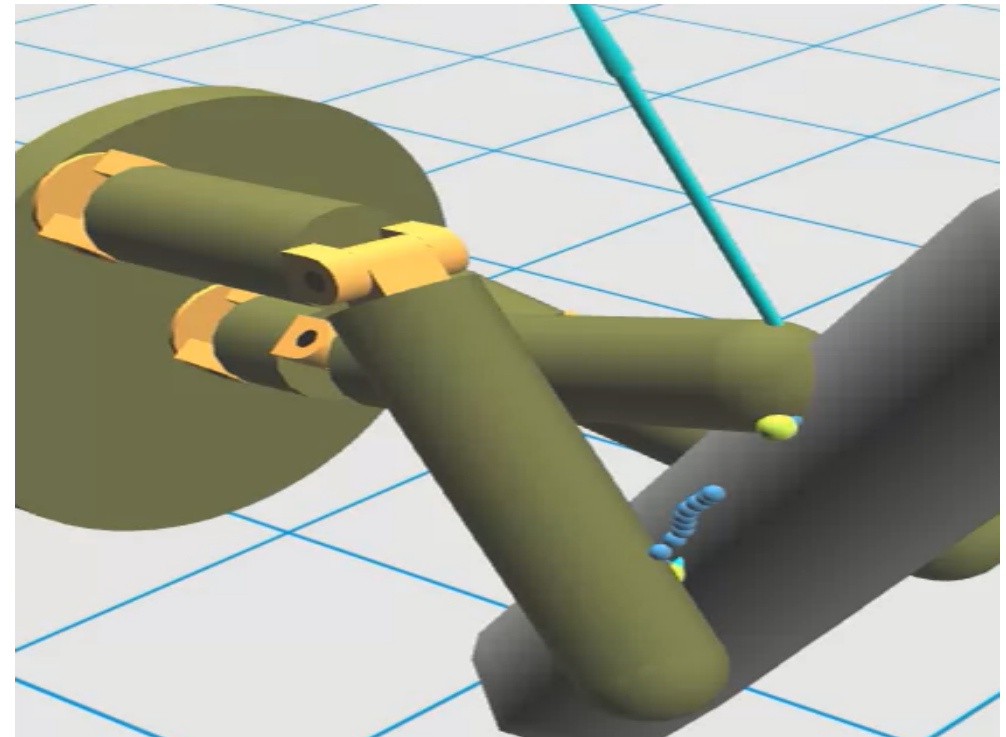
Friction Cone wrt fingertip surface

$$L_{frictionCone}(t) = \sum_i c_i * \exp(\alpha(||f_{i,local} - n * (f_i \cdot n_i)|| - \mu f_i \cdot n_i))$$

Hand Friction Cone Demonstration (without term)



Contact way outside friction cone w.r.t. finger



Caused by (small) errant collision with object

# Additional Optimization Terms

Terms copied over from the synthesis step:

Controllability constraints

$$L_{jacNull} = \sum_i c_i * \sqrt{\sum_k (f \cdot e_k)^2}$$

$$L_{torque} = \|\vec{\alpha}\|^2$$

Collision (includes ground, hand, object, external objects)

$$L_{collision}(k) = \sum_{i,j \in bodies} g(\text{penetration}(\text{body}_i, \text{body}_j))$$

Other:

$$L_{fingerAcceleration}(k) = \sum_i (1 - c_i) * \ddot{x}_i^2$$

$$L_{jointLimits}(k) = \sum_{i \in keyframes} \sum_{a \in joints} g(a(i) - a_{max}) + g(a_{min} - a(i))$$



# Slippage Terms

Slippage w.r.t. object

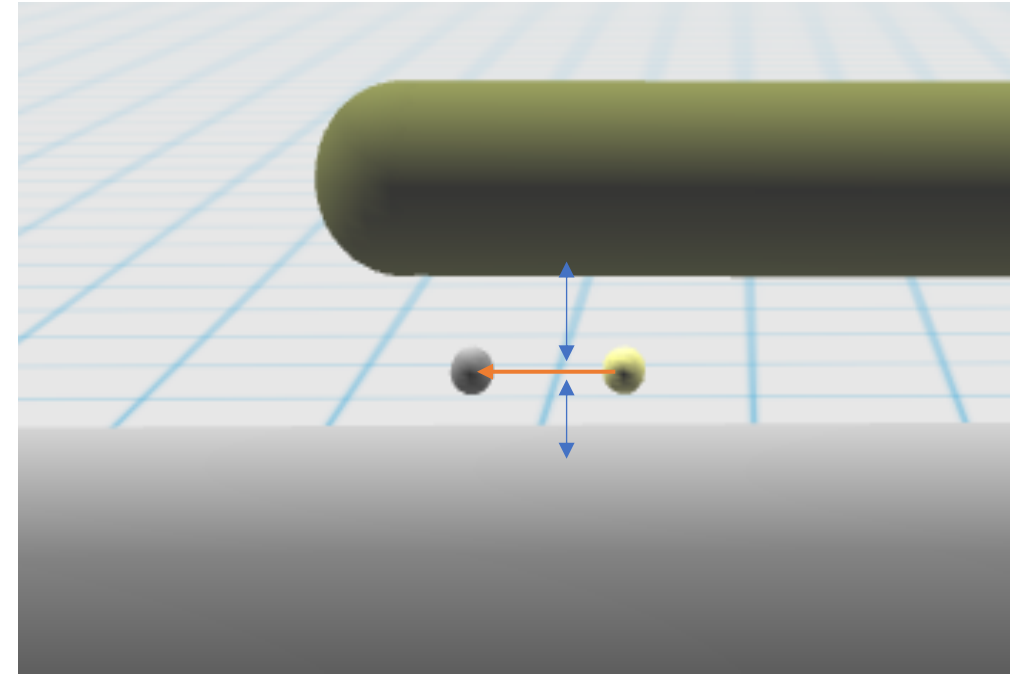
$$e_{object}(i, t) = r_{i,proj\_object}(t) - r_i(t)$$

$$L_{ci\_object\_slippage}(t) = \sum_i ||c_i f_i||^2 * ||(\dot{e}_{object}(i, t))||^2$$

Slippage w.r.t. finger

$$e_{finger}(i, t) = r_{i,proj\_finger}(t) - r_i(t)$$

$$L_{ci\_finger\_slippage}(t) = \sum_i ||c_i f_i||^2 * ||(\dot{e}_{finger}(i, t))||^2$$



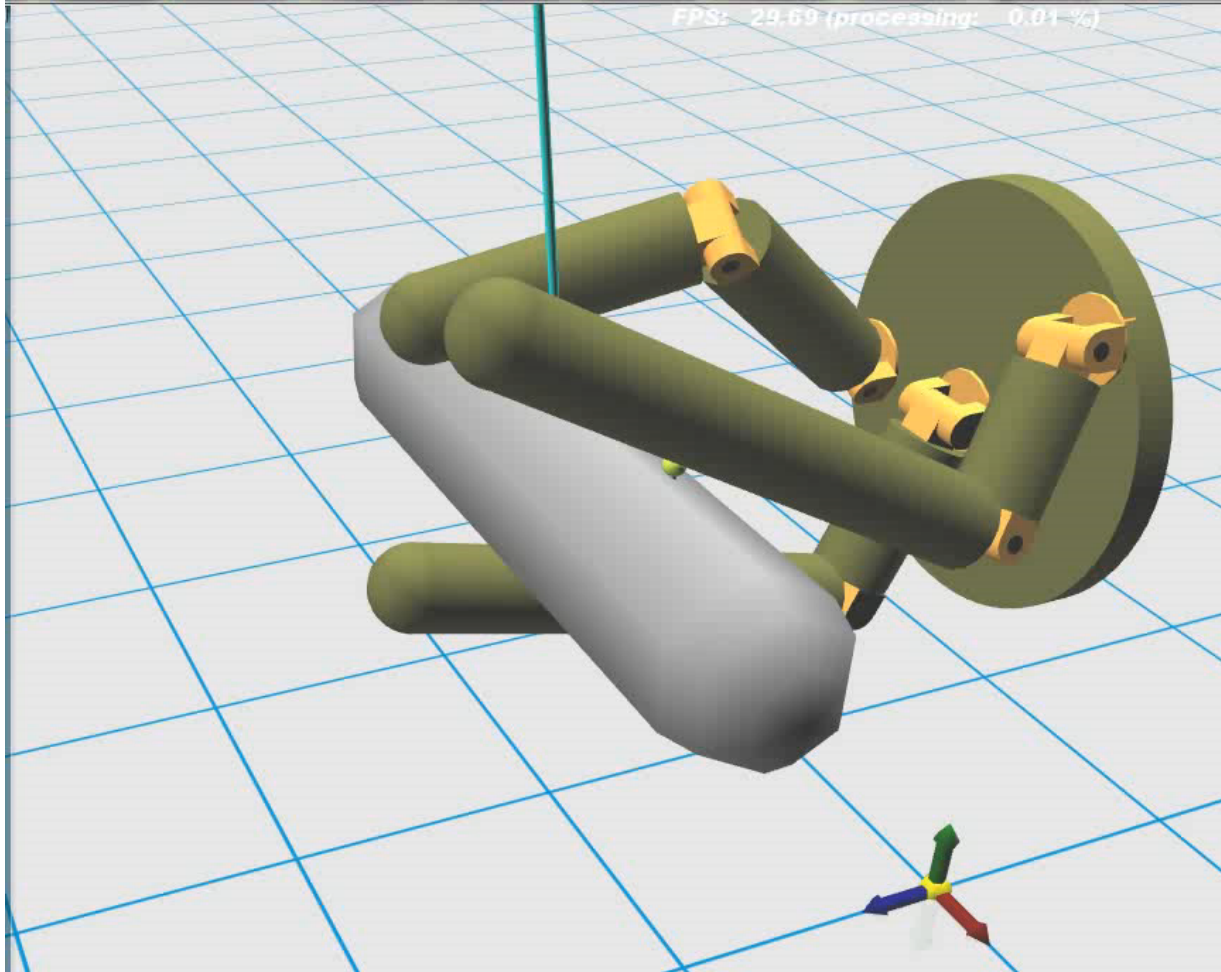
Zero slip penalty

Bottom Line: distance slipped on object = distance slipped on fingertip (w.r.t. world frame)

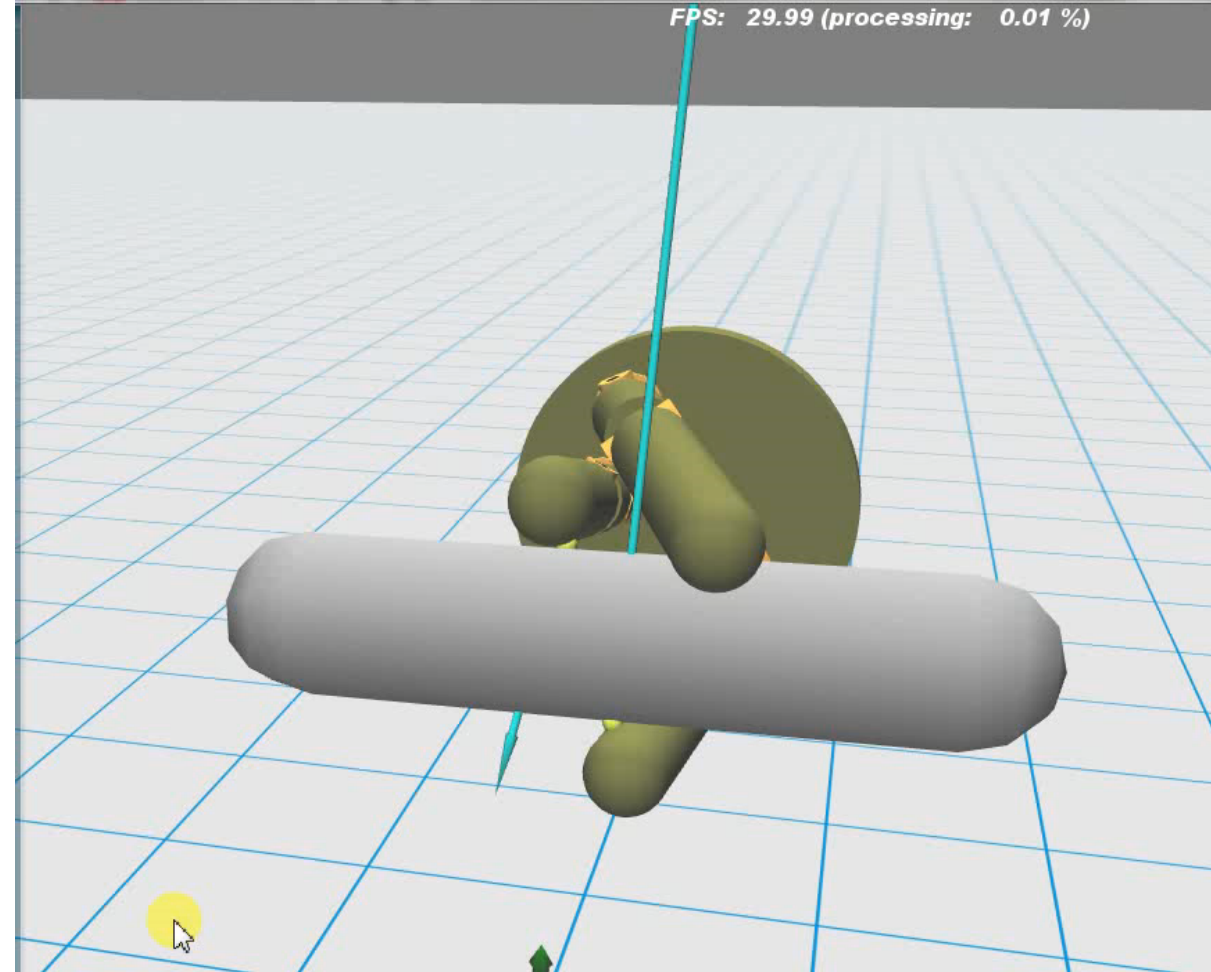
Slip directions w.r.t world frame line up

Not a complete model, but helpful

# Simple Manipulations

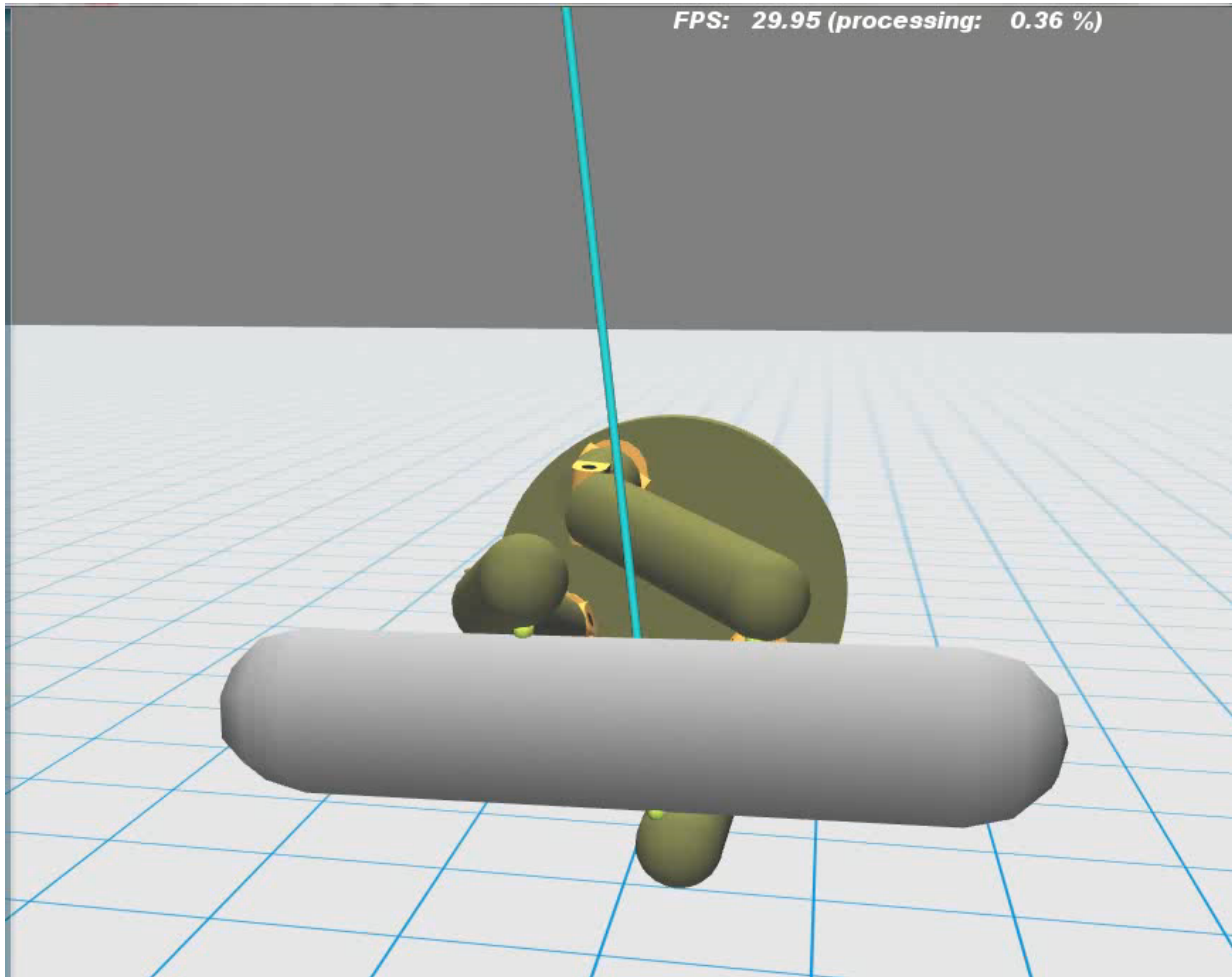


Translate

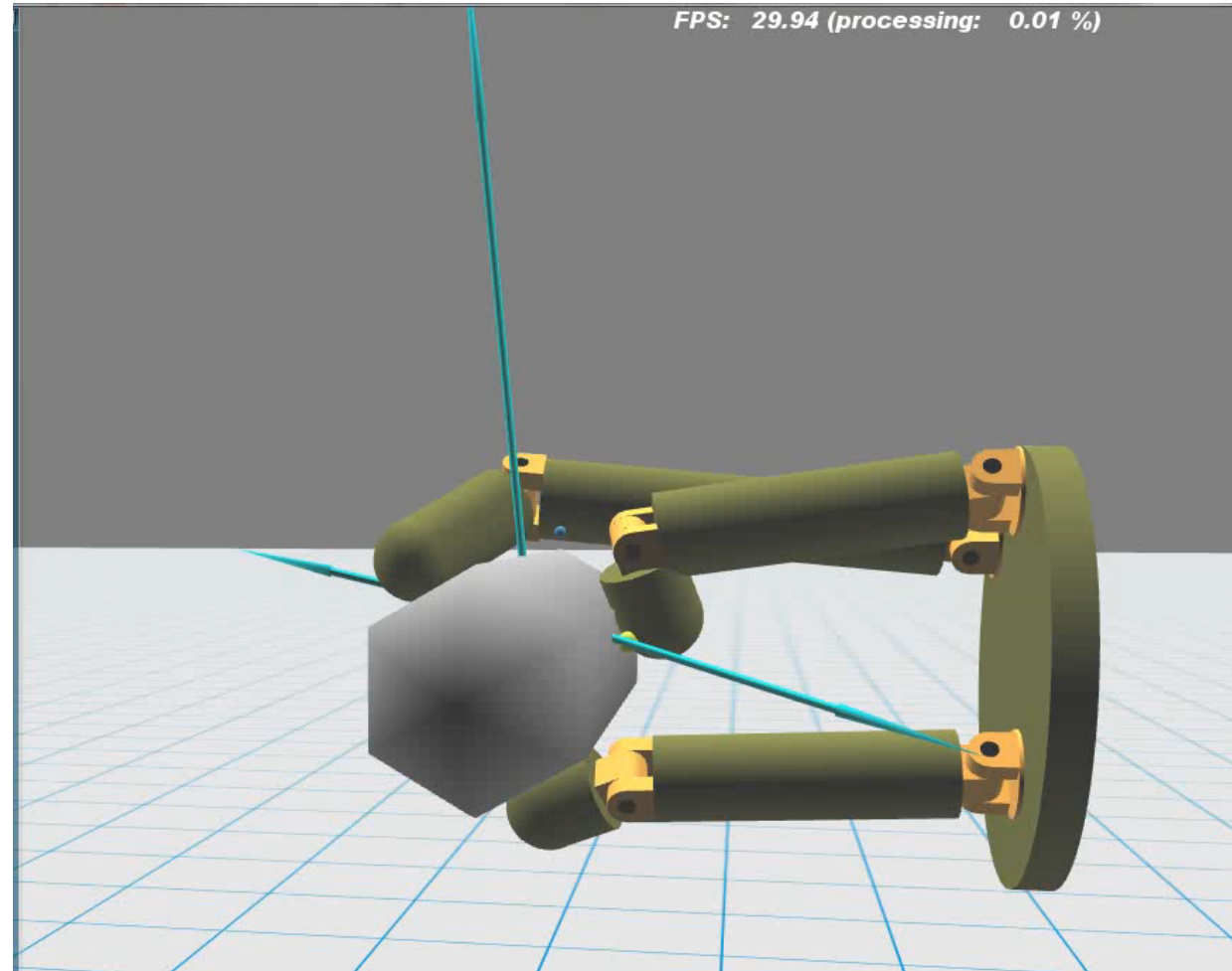


Vertical Rotate

# Examples

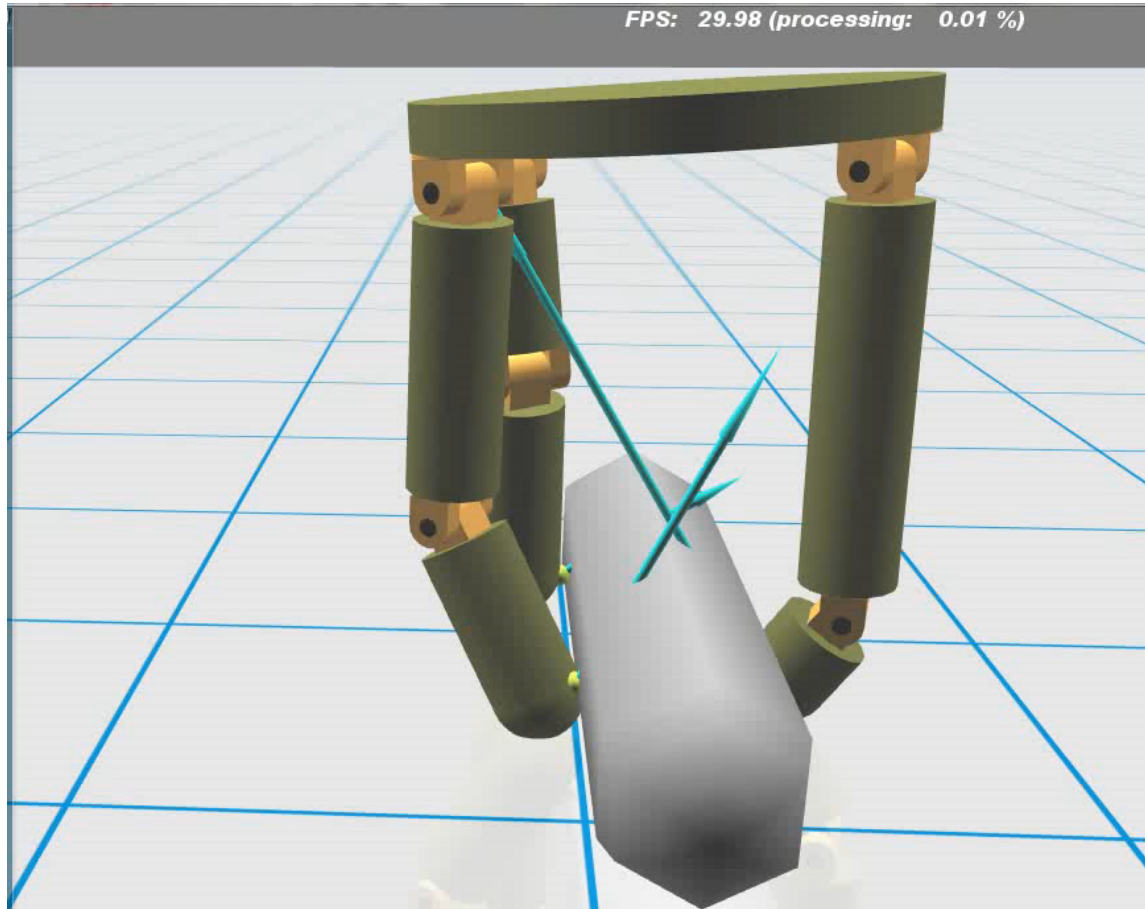


180 Rotation

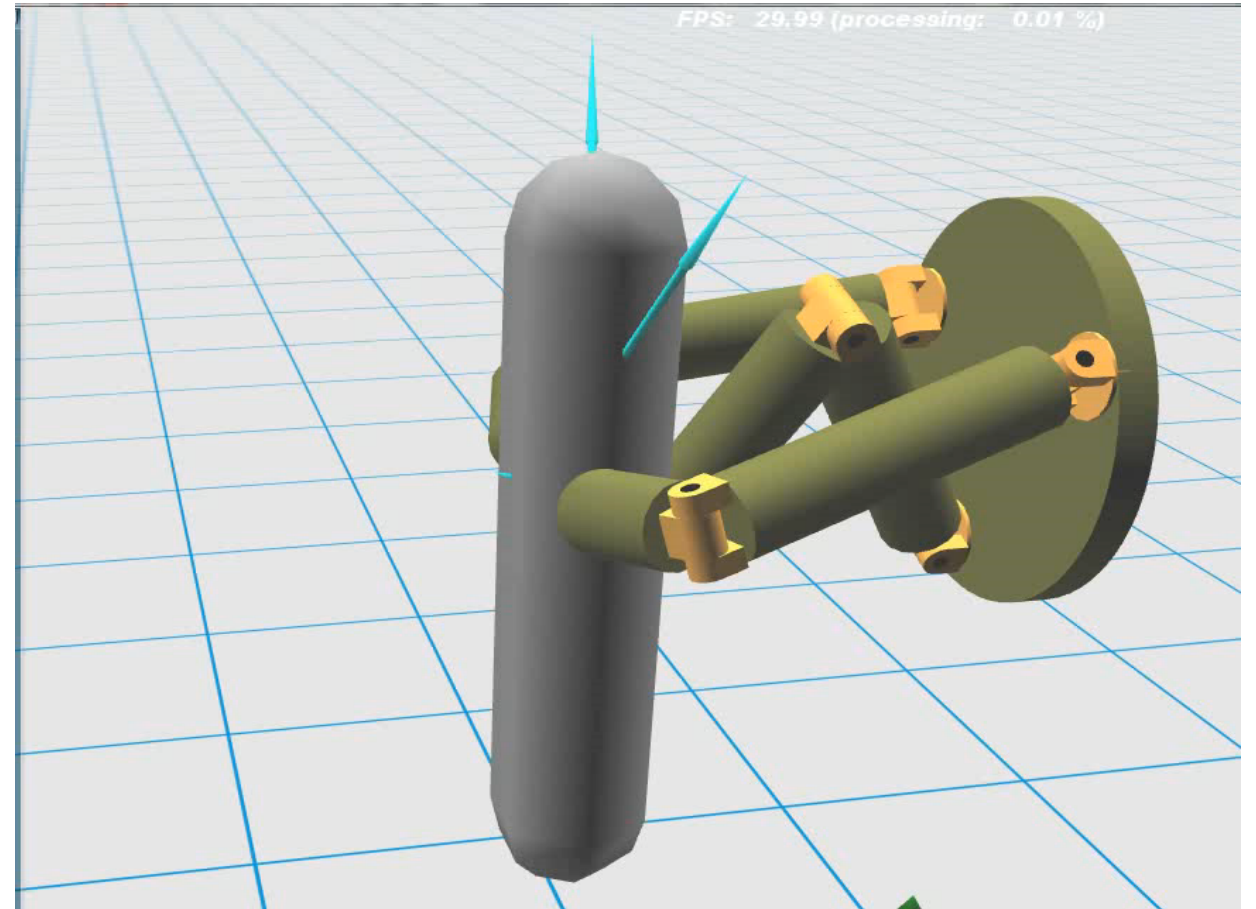


Rotate and Bow Out

# More Examples



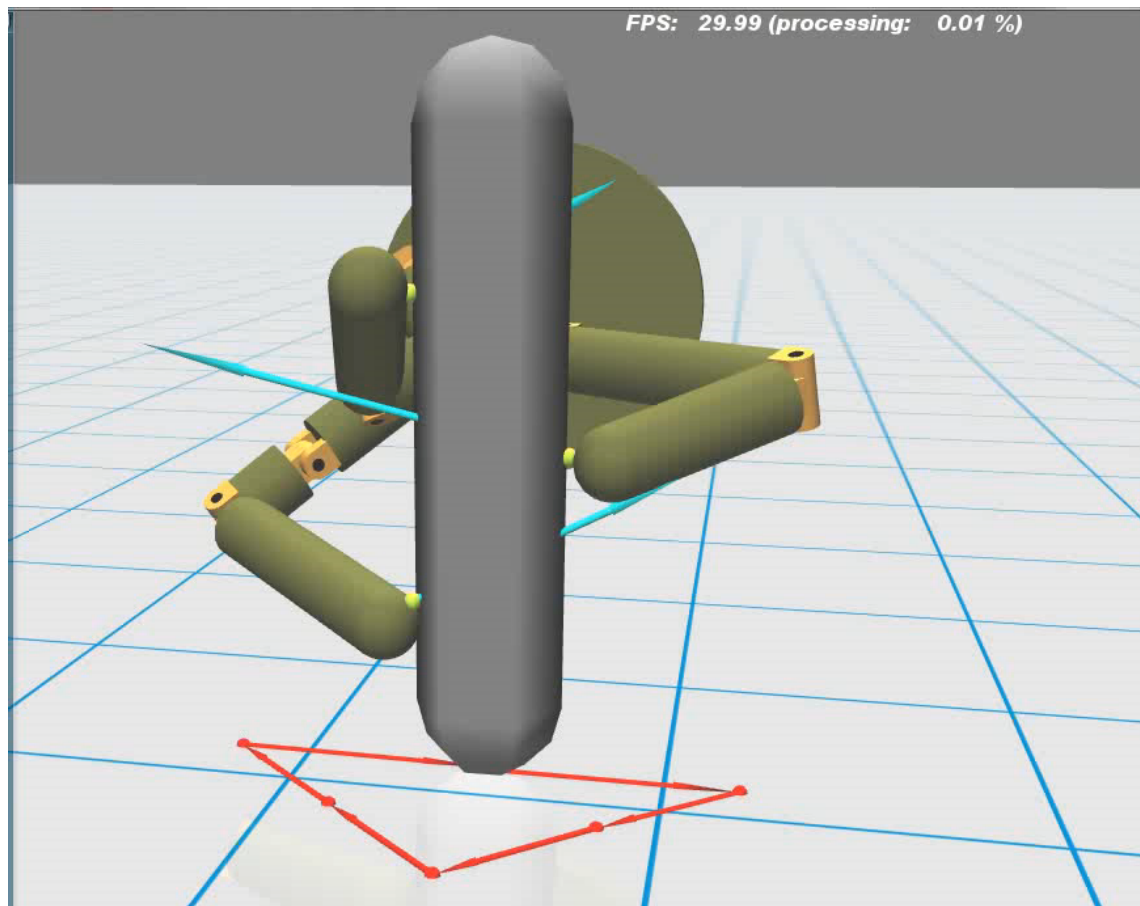
Pick up and rotate



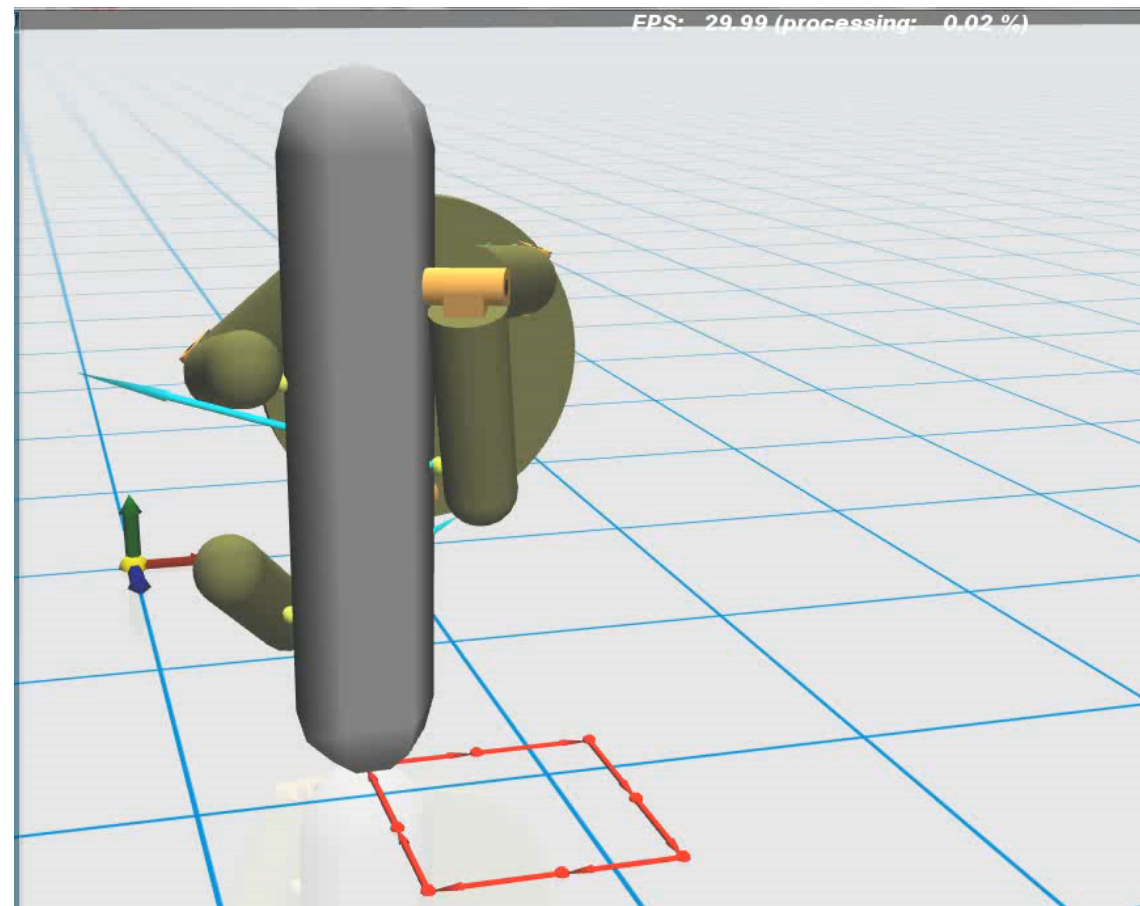
Vertical flip



# Alternative Objective: Drawing



Draw triangle



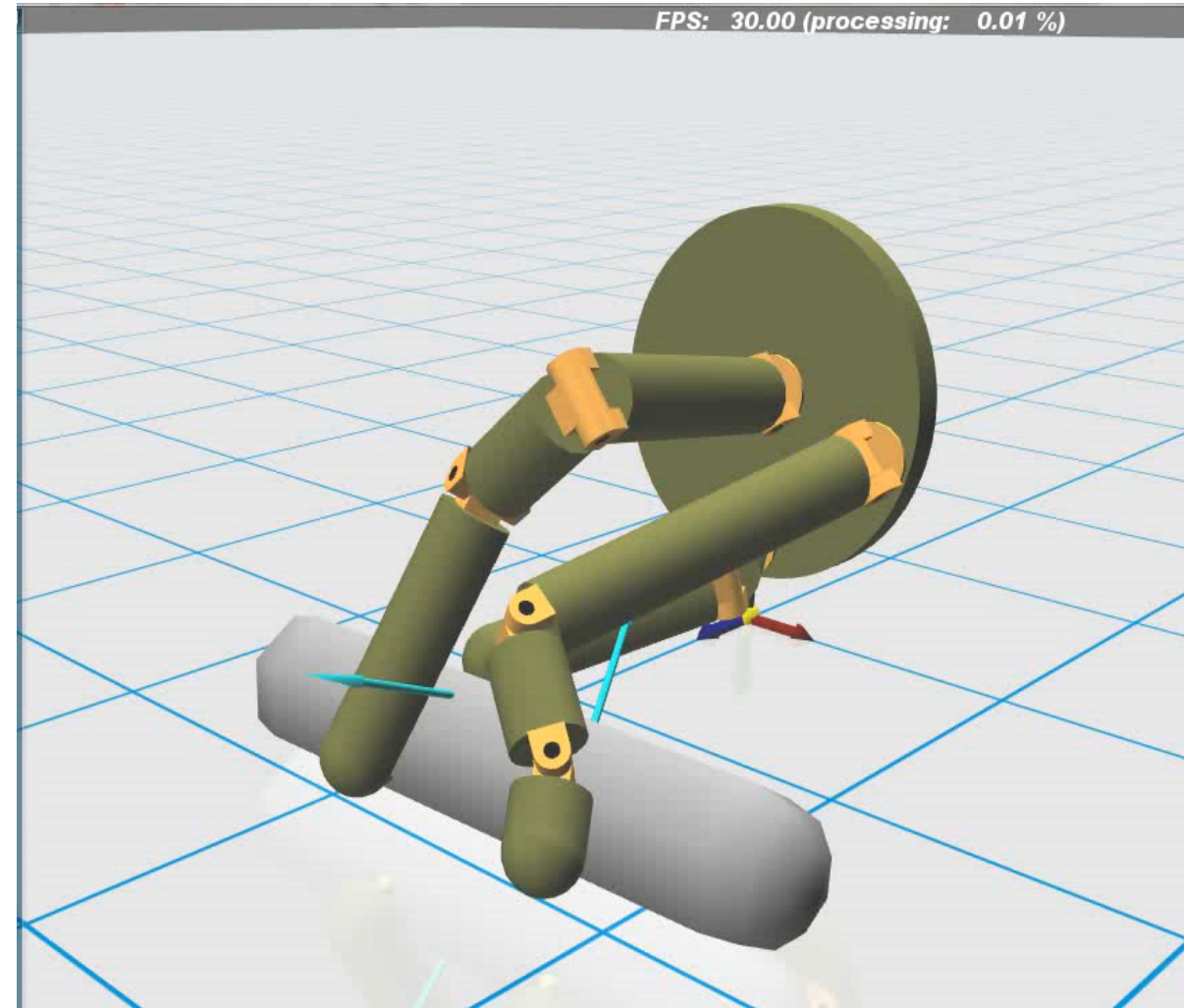
Draw box



# Tabletop Rotation: Two versions

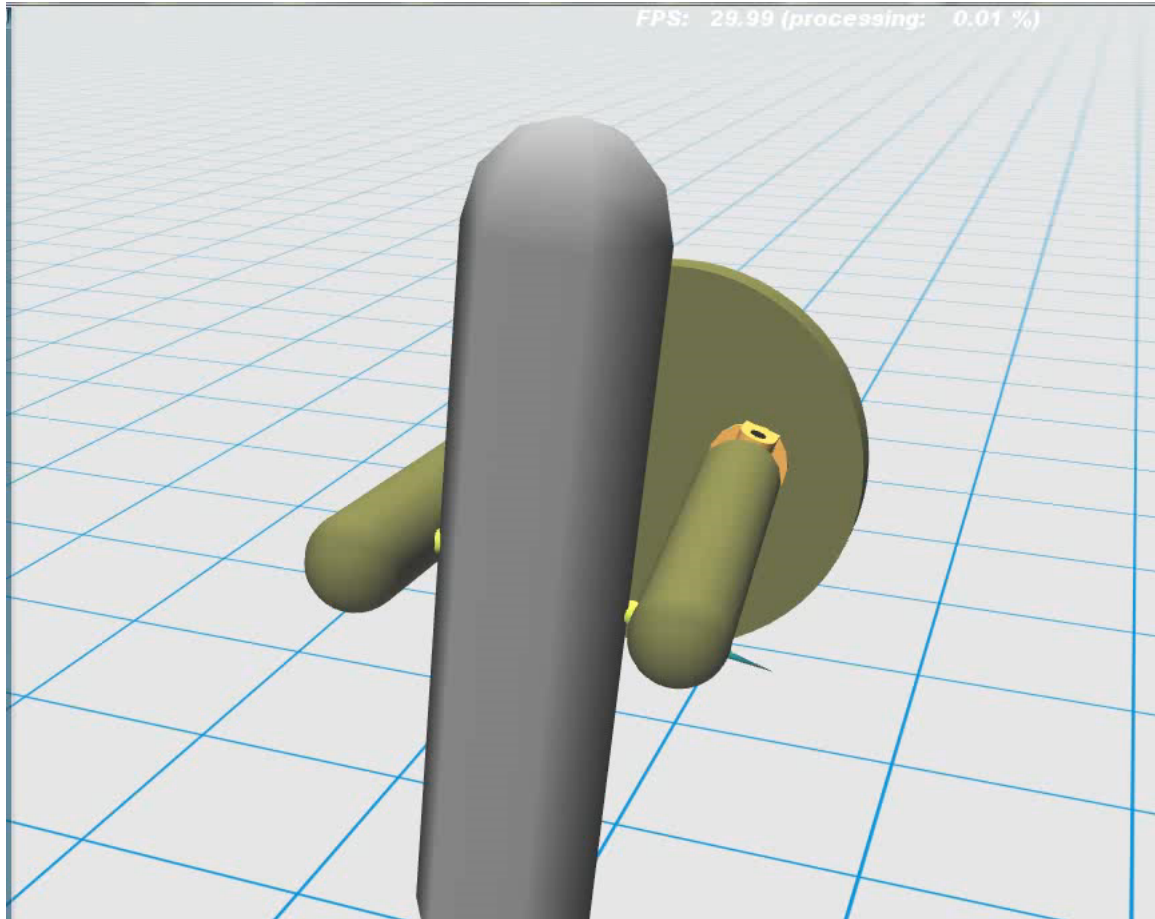


Tabletop overtop

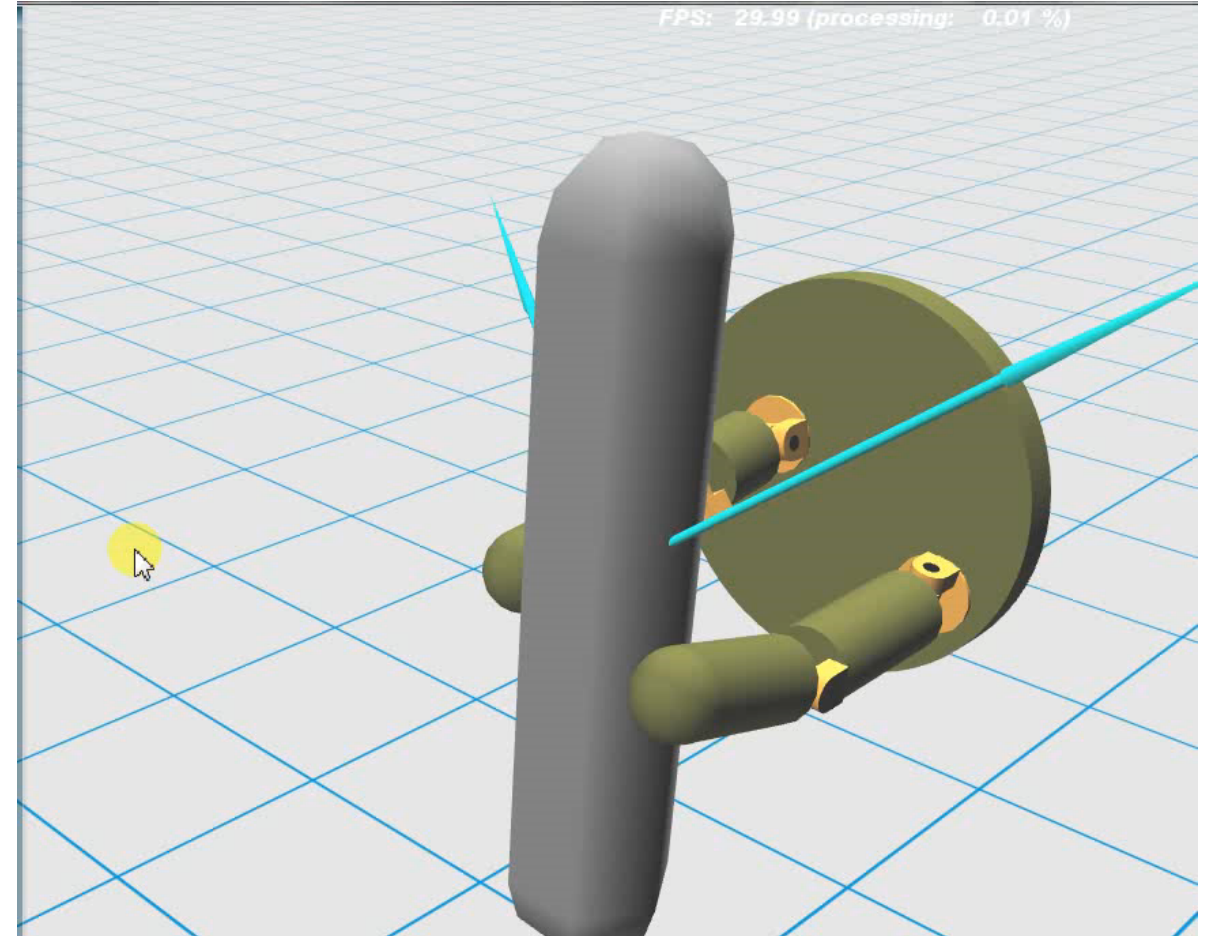


Tabletop from the side

# Building Up a Motion From Primitives

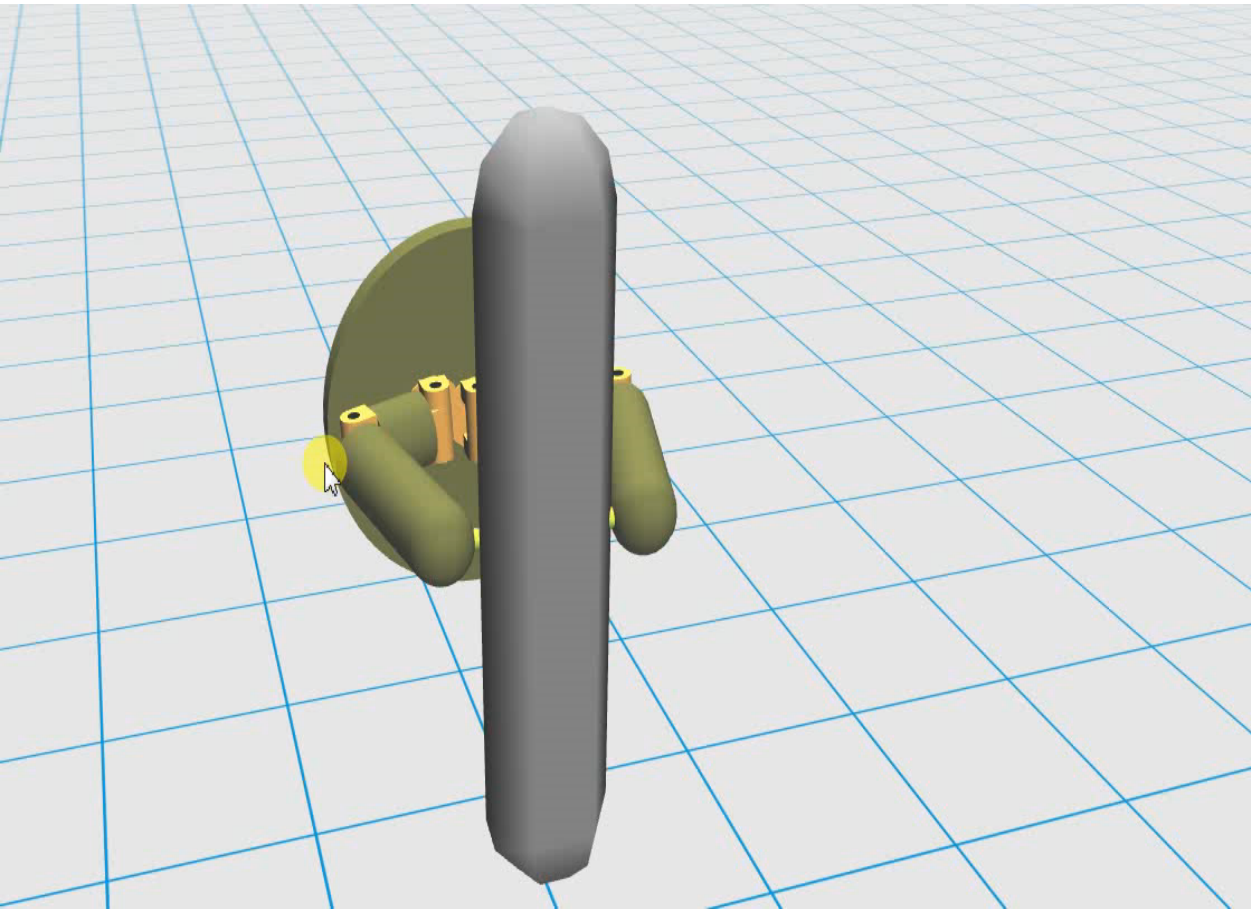


Horizontal (no gravity)

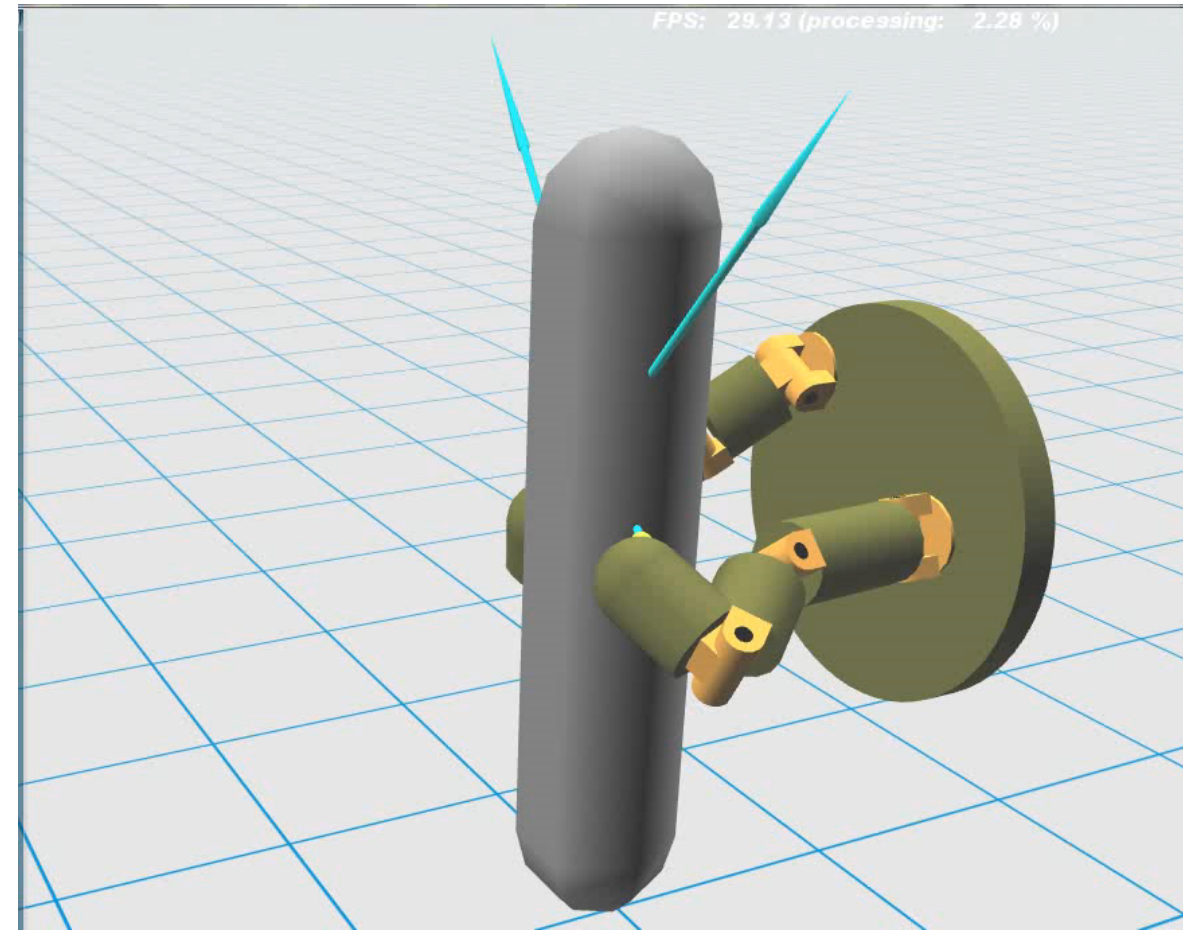


Horizontal (with gravity)

# Building Up a Motion From Primitives



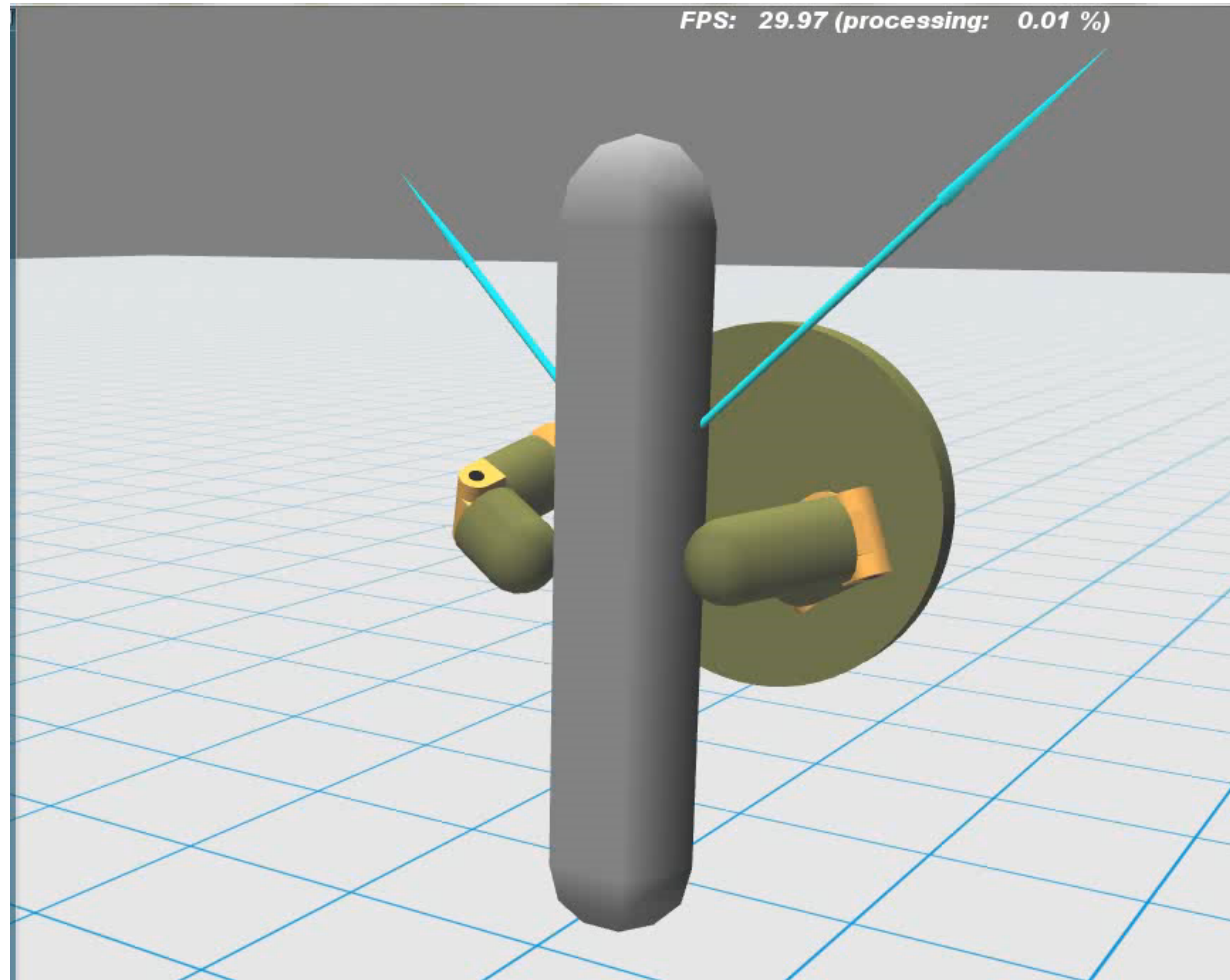
Circle in plane (no gravity)



Circle in plane (with gravity)

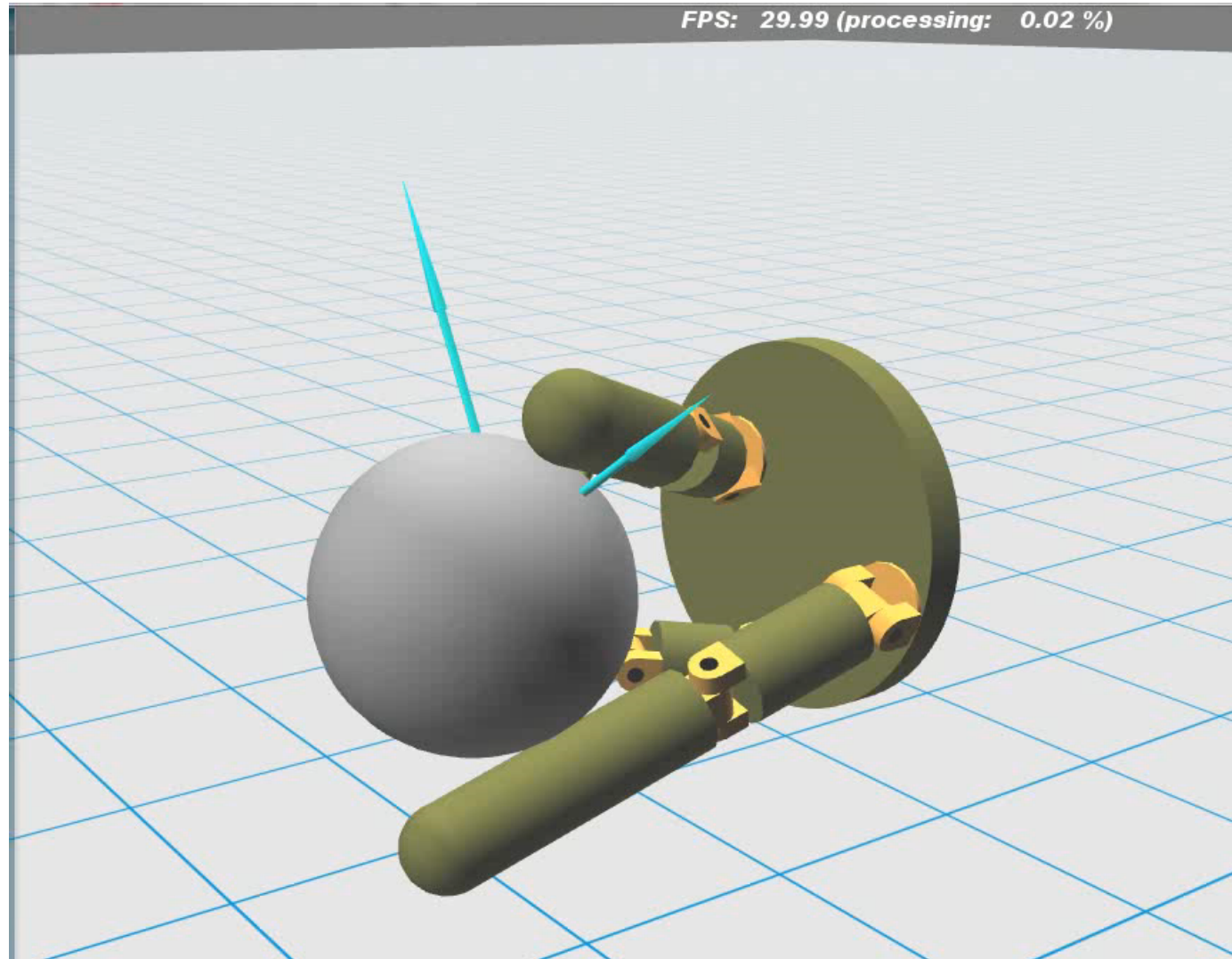


# Building Up a Motion From Primitives



Hemisphere (with gravity)

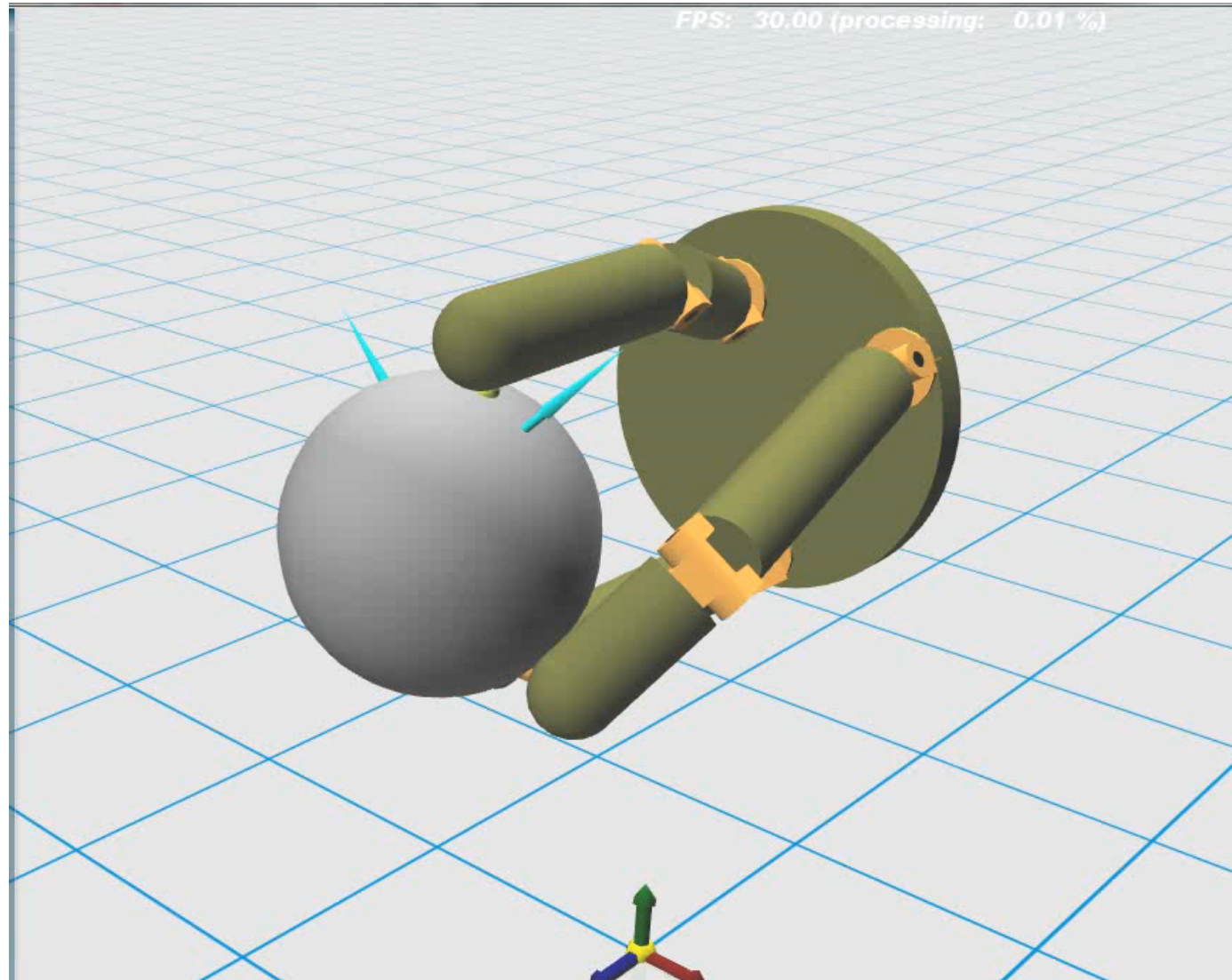
# “Multi-objective” Chaining Example



Sphere Rotation

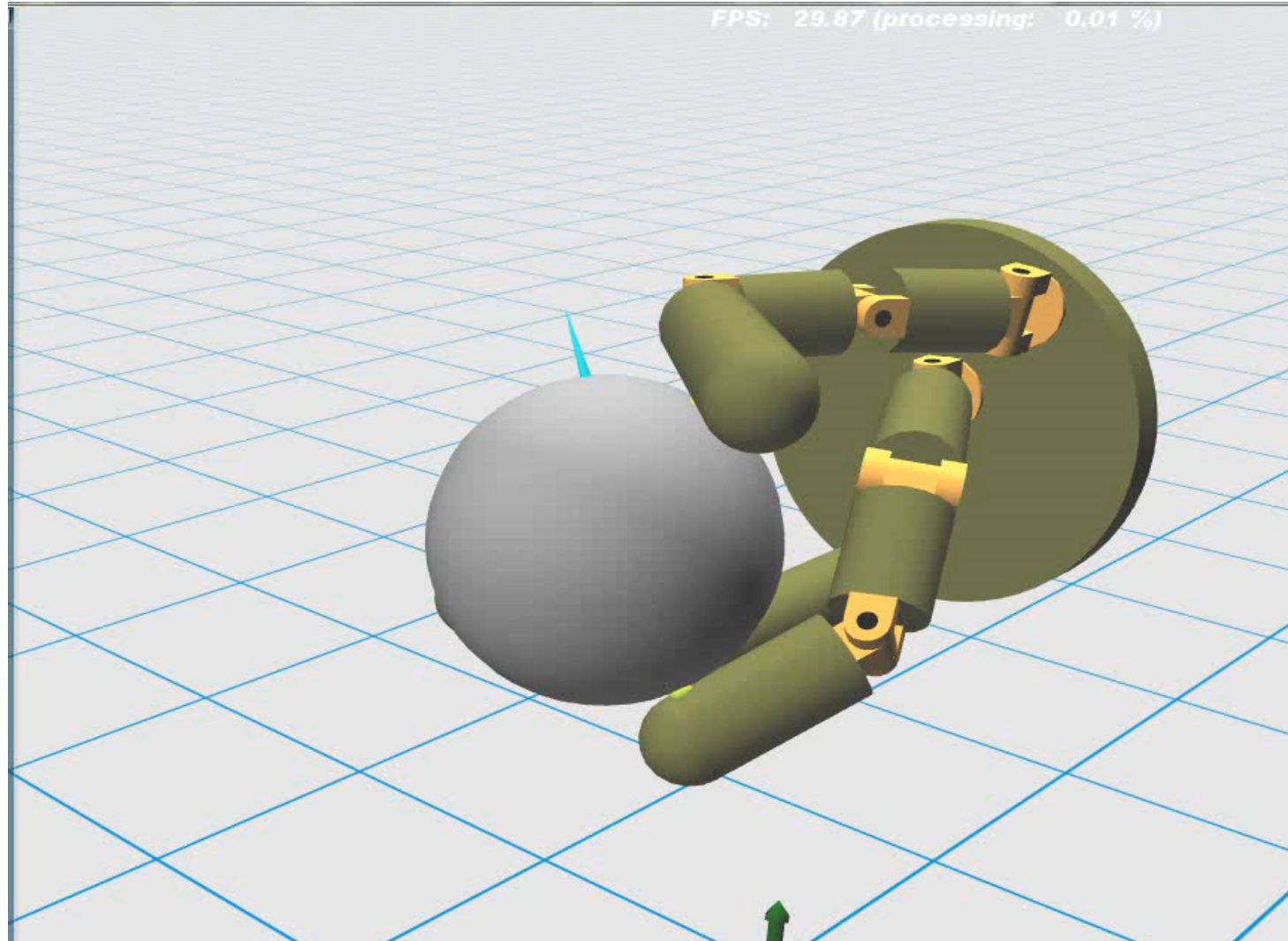


# “Multi-objective” Chaining Example



Sphere Rotation + translation

# “Multi-objective” Chaining Example



Sphere Rotation + xy translation

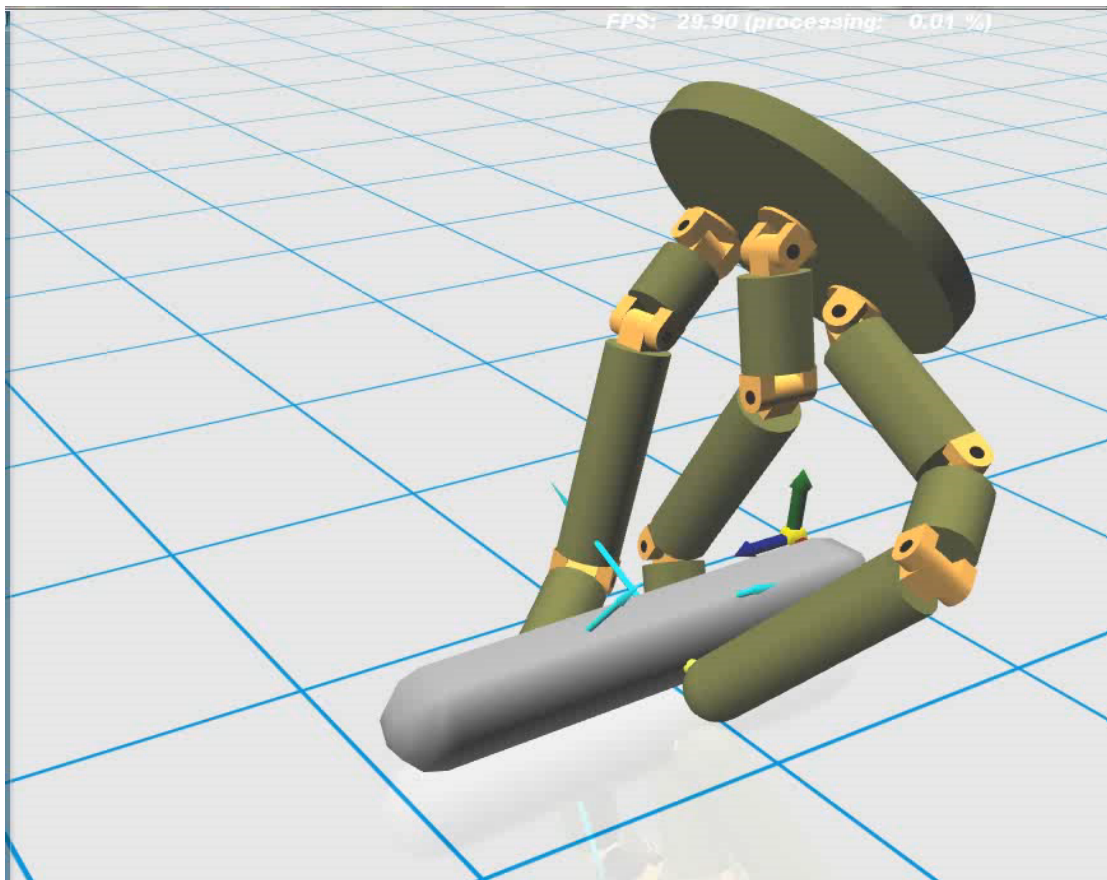
# Common Patterns

- The mechanisms for each task look totally different!
- Non-obvious/non-trivial designs
- Different numbers of links for each hand: scales with complexity
- Trajectory complexity tends to correspond to importance of fingers
- Hands become more aesthetically pleasing as we add more complexity to motion

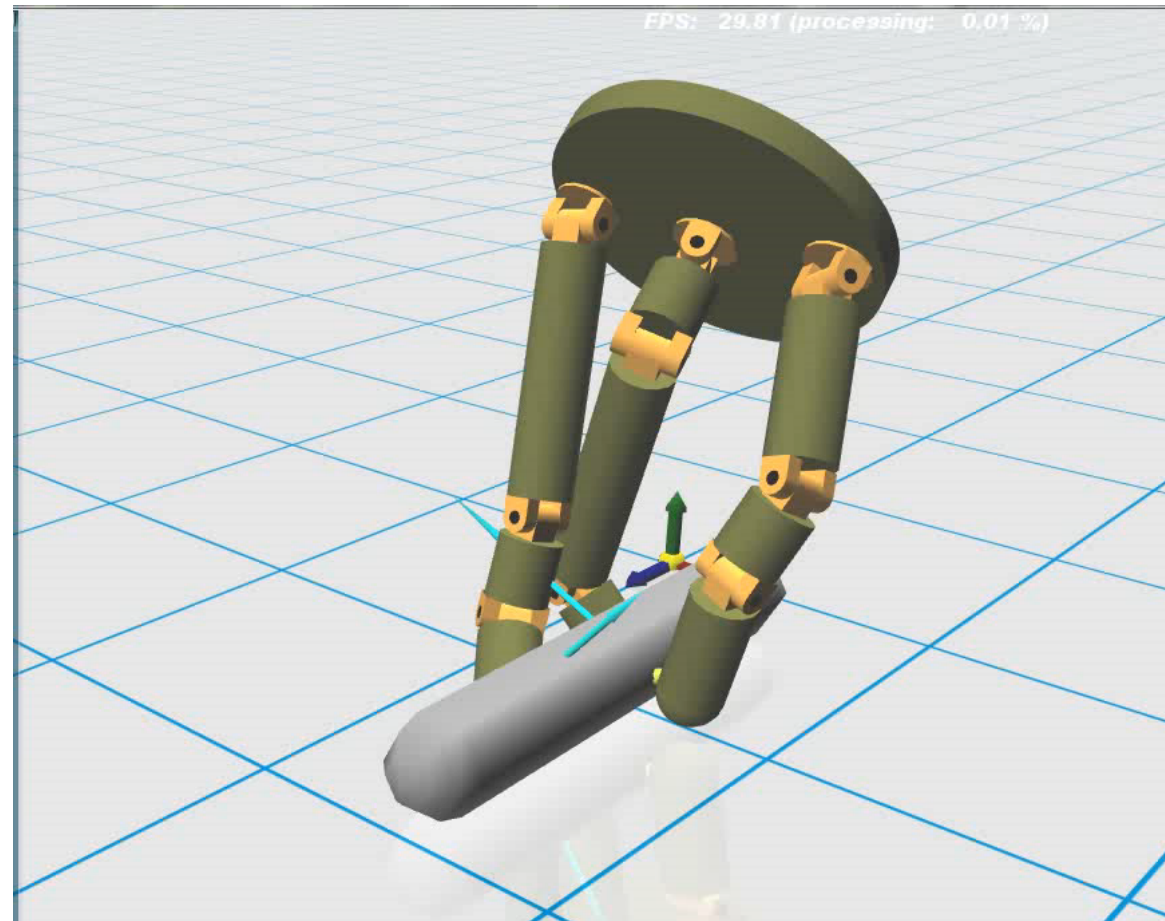
# Limitations

- Slippage dynamics not exact
  - discouraged, not prohibited
  - usually not problematic except at high curvature
- User must provide a good base position and reasonable initial contacts
  - contacts selected with concept of fingers in mind
- Random contact initialization:
  - can work but unreliable
  - disconnect between optimization steps

# Pencil Pickup Slip Demonstration



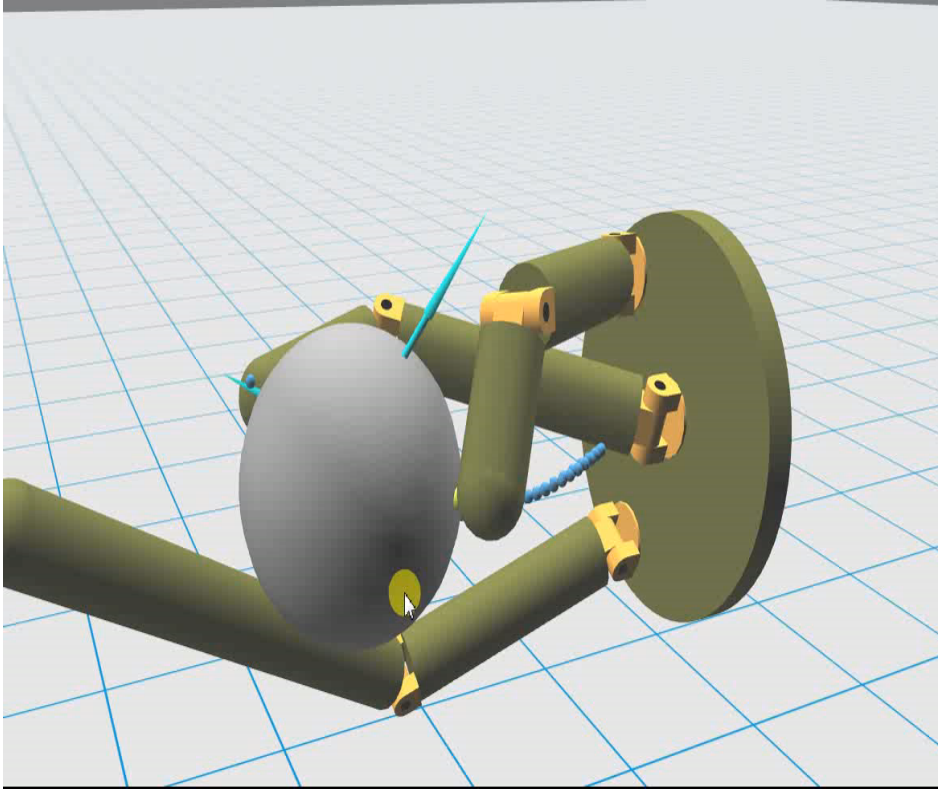
Acceptable Slippage



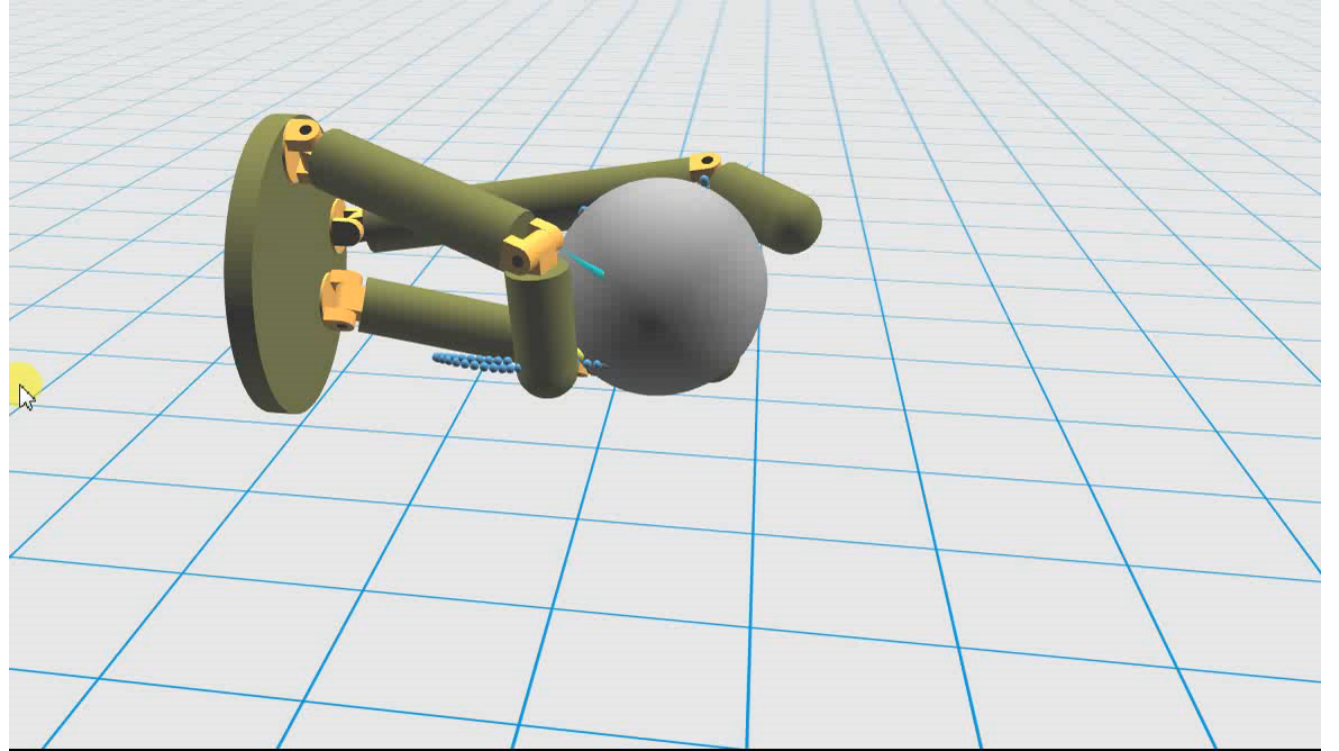
Uncomfortable Slippage



# Automatic Contact Brittleness Demo



Sphere translate: Ok mechanism



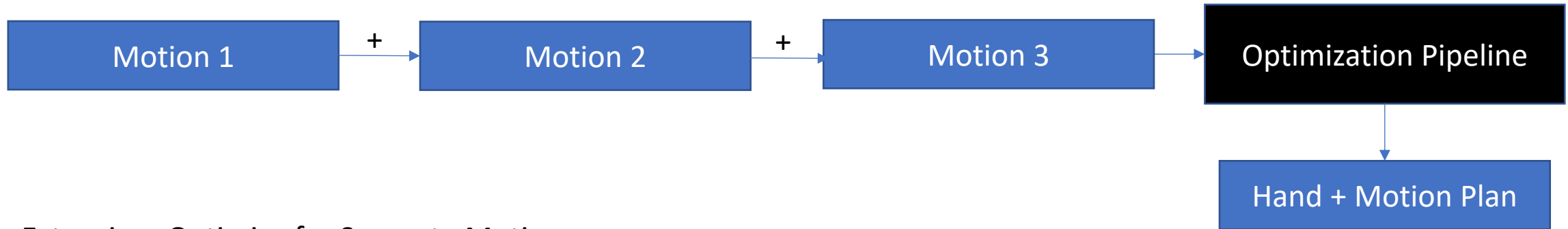
Sphere translate: Brittle mechanism

# Additional Topics For The Future

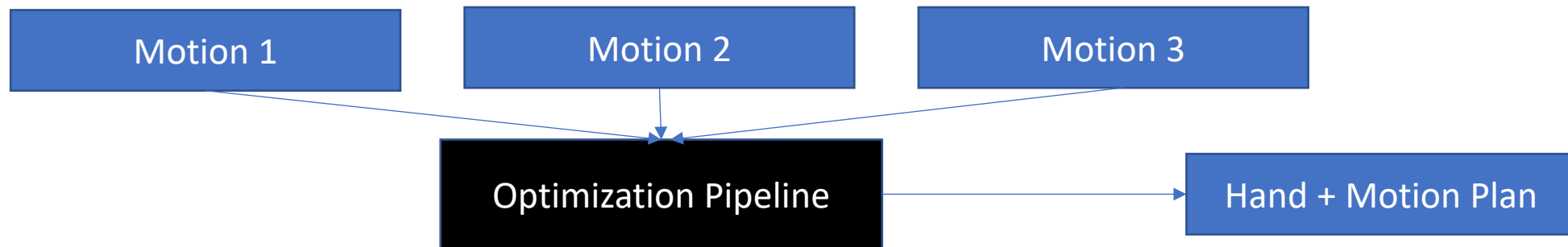
- Multi-objective optimization
- Initial Contact Planning
- Robustness through Physical Simulation
- Incorporating Dimensionality Reduction (Linkages/Synergies)

# Multi-Objective Optimization

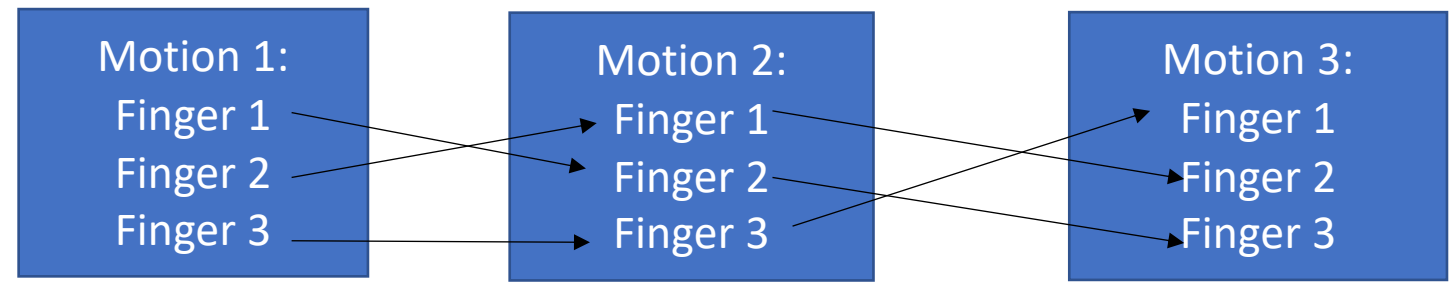
Current Capability: Motion Chaining



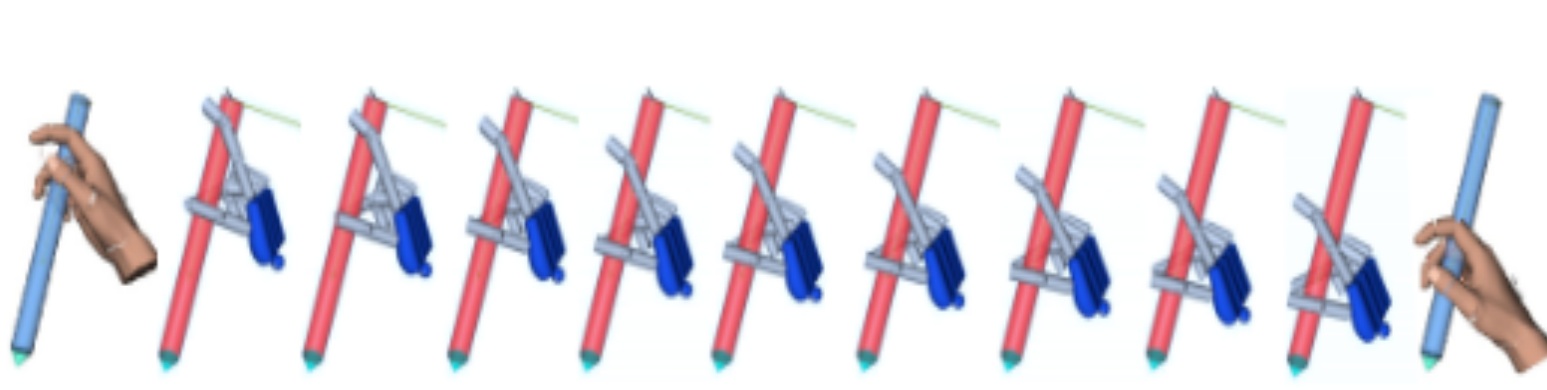
Extension: Optimize for Separate Motions



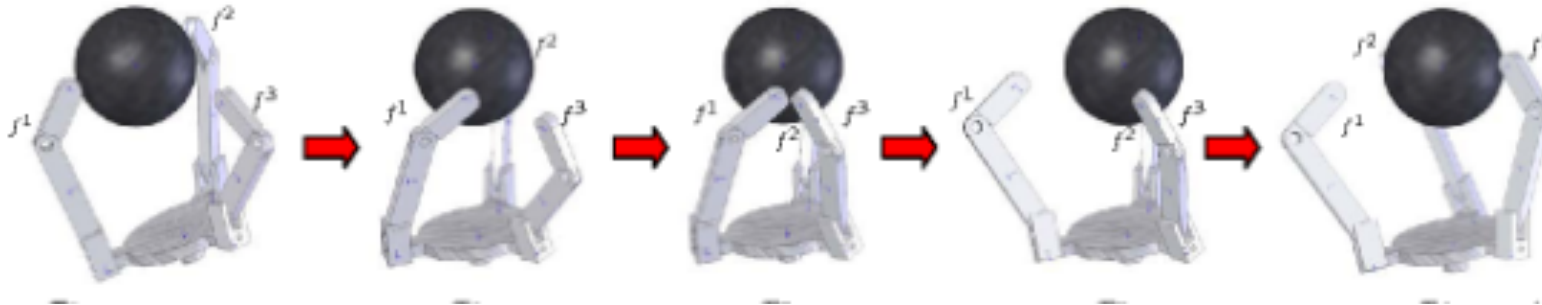
Problem: how do floating contacts match up?  
----  $(n!)^{k-1}$  combos for n fingers, k motions



# Initial Contact Planning/Additional Floating Heuristics



Vinayavekhin 2011: re-grasp on a cylinder



Xu 2007: finger gaiting for sphere rotation

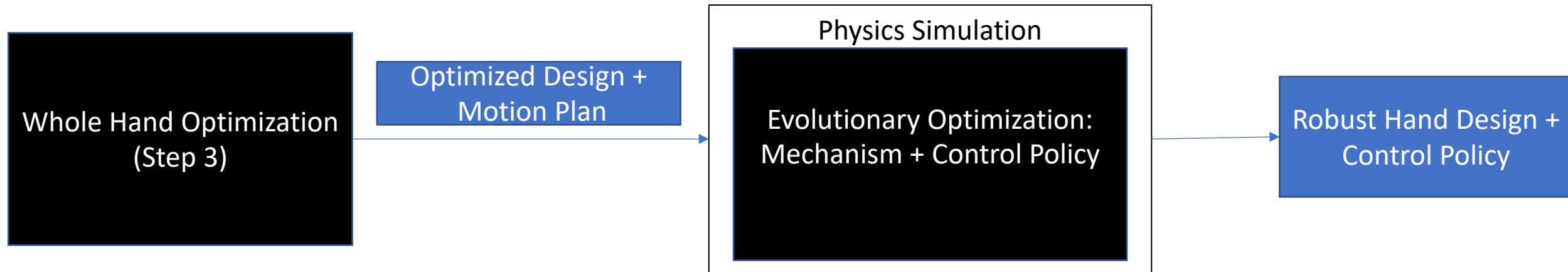


Twirling a pencil

[1] Finger gaits planning for multifingered manipulation Xu 2007

[2] Towards an automatic robot regrasping movement ... Vinayavekhin 2011

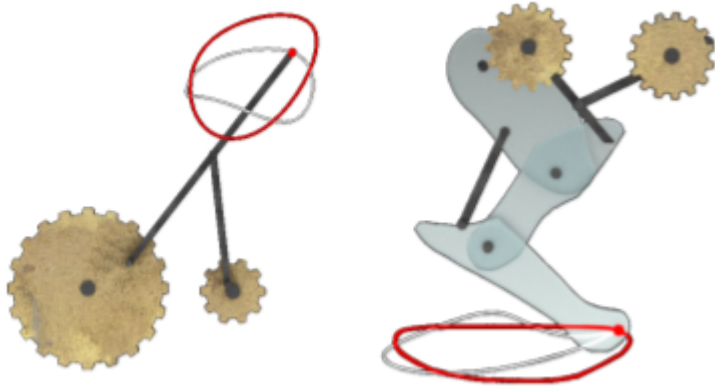
# Robustness Through Physical Simulation



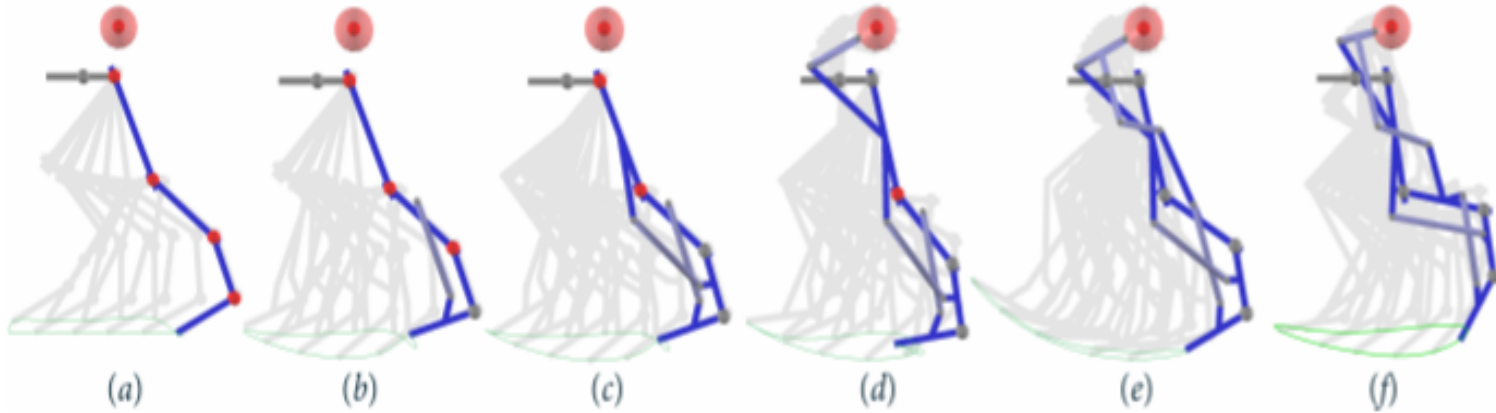
- Use synthesized mechanism as seed
- Control policy (torque): force feedback or open loop
- Gradient free optimization (e.g. Covariance Matrix Adaptation)
- Final step before fabrication



# Dimensionality Reduction



Coros 2013: linkage tracks target curve (red)



Thomaszewski 2014: motor replacement steps



Coros 2013: design and fabrication example

[1] "Computational design of mechanical characters" Coros 2013

[2] "Computational design of linkage-based characters" Thomaszewski 2014