Case Study: Model W Hand

16-848 January 31, 2022

Nancy Pollard

ROBOTIC MANIPULATION

Complex manipulation with a simple robotic hand through contact breaking and caging

Walter G. Bircher*, Andrew S. Morgan, Aaron M. Dollar

Humans use all surfaces of the hand for contact-rich manipulation. Robot hands, in contrast, typically use only the fingertips, which can limit dexterity. In this work, we leveraged a potential energy–based whole-hand manipulation model, which does not depend on contact wrench modeling like traditional approaches, to design a robotic manipulator. Inspired by robotic caging grasps and the high levels of dexterity observed in human manipulation, a metric was developed and used in conjunction with the manipulation model to design a two-fingered dexterous hand, the Model W. This was accomplished by simulating all planar finger topologies composed of open kinematic chains of up to three serial revolute and prismatic joints, forming symmetric two-fingered hands, and evaluating their performance according to the metric. We present the best design, an unconventional robot hand capable of performing continuous object reorientation, as well as repeatedly alternating between power and pinch grasps—two contact-rich skills that have often eluded robotic hands—and we experimentally characterize the hand's manipulation capability. This hand realizes manipulation motions reminiscent of thumb–index finger manipulative movement in humans, and its topology provides the foundation for a general-purpose dexterous robot hand.

INTRODUCTION

The dexterity of a robotic hand can be greatly increased when all of its surfaces are used for manipulation, rather than just the fingertips (*1*). Despite this, most manipulation research is rooted in the as-

that the system can be viewed in terms of total summed actuation effort and overall system energy, with corresponding variations in energy based on object location and configuration. Instead of the traditional method of calculating and controlling individual joints

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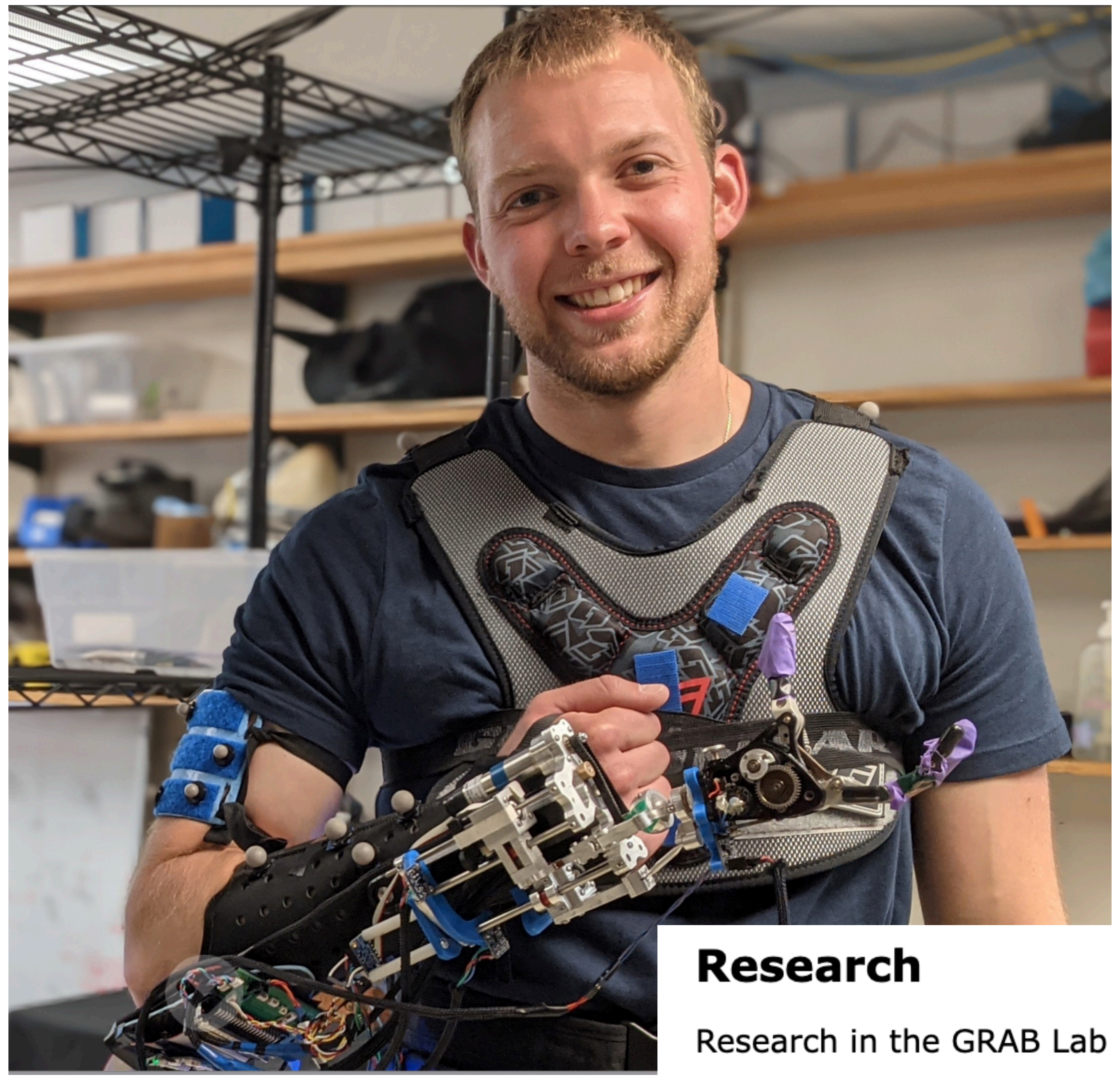
I'm a Hardware Dev Engineer at Amazon Robotics AI in Seattle. I completed my Ph.D. in Mechanical Engineering (2021) under the supervision of Aaron Dollar in the GRAB Lab at Yale University. My thesis focused on robotic manipulation, specifically how hand design can be leveraged to increase dexterity. I co-founded ReCore (2020), a medical device startup focused on frugal innovation for underserved markets. I have a Bachelor's degree in Mechanical Engineering from the University of Nebraska-Lincoln (B.S. 2014) and two Master's degrees from Yale (M.S. & M.Phil 2018). In the past, I worked at Tethon3D (2015), the NASA Jet Propulsion Lab (2014), and Honeybee Robotics (2013).

Andrew Morgan



Aaron Dollar

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the GRAB LAB

https://www.eng.yale.edu/grablab/research.html

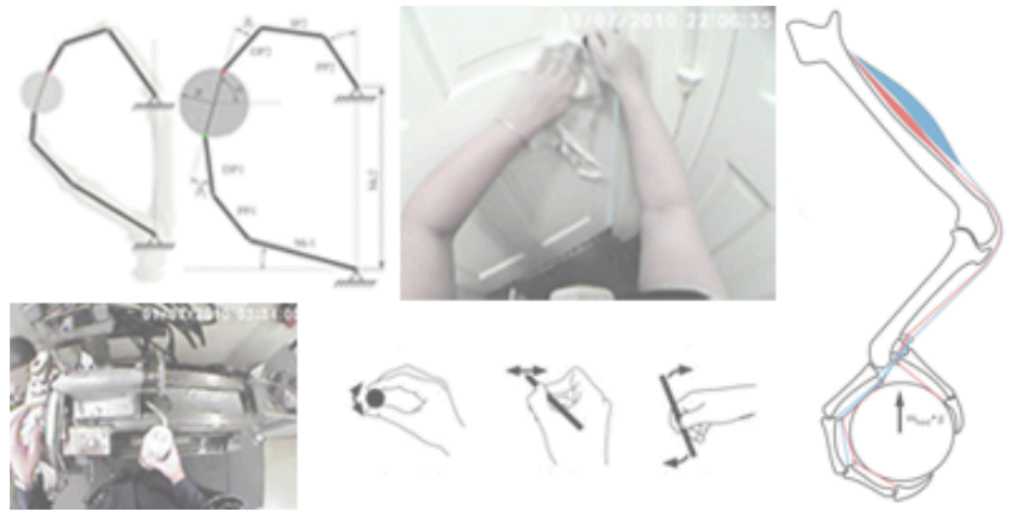
Research

Research in the GRAB Lab is focused on the following efforts:

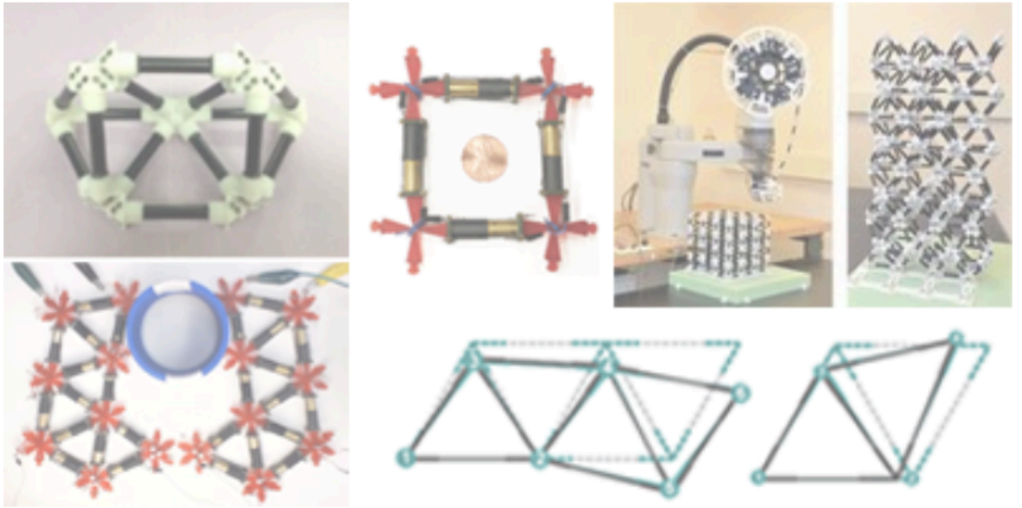
(* inactive projects as of 2018)

Robust Grasping and Manipulation

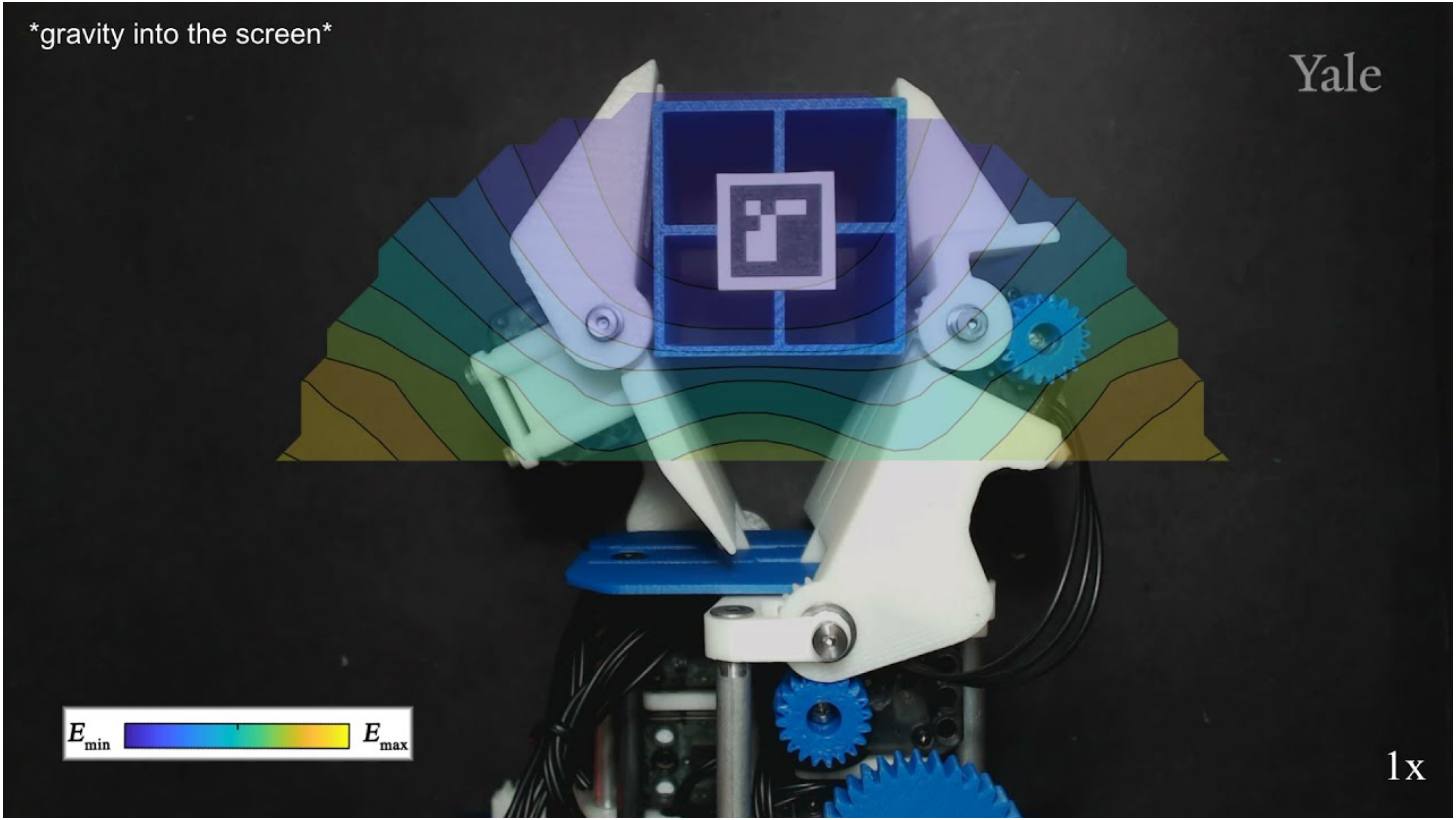
Upper Limb Prosthetics



Biological Grasping and Manipulation



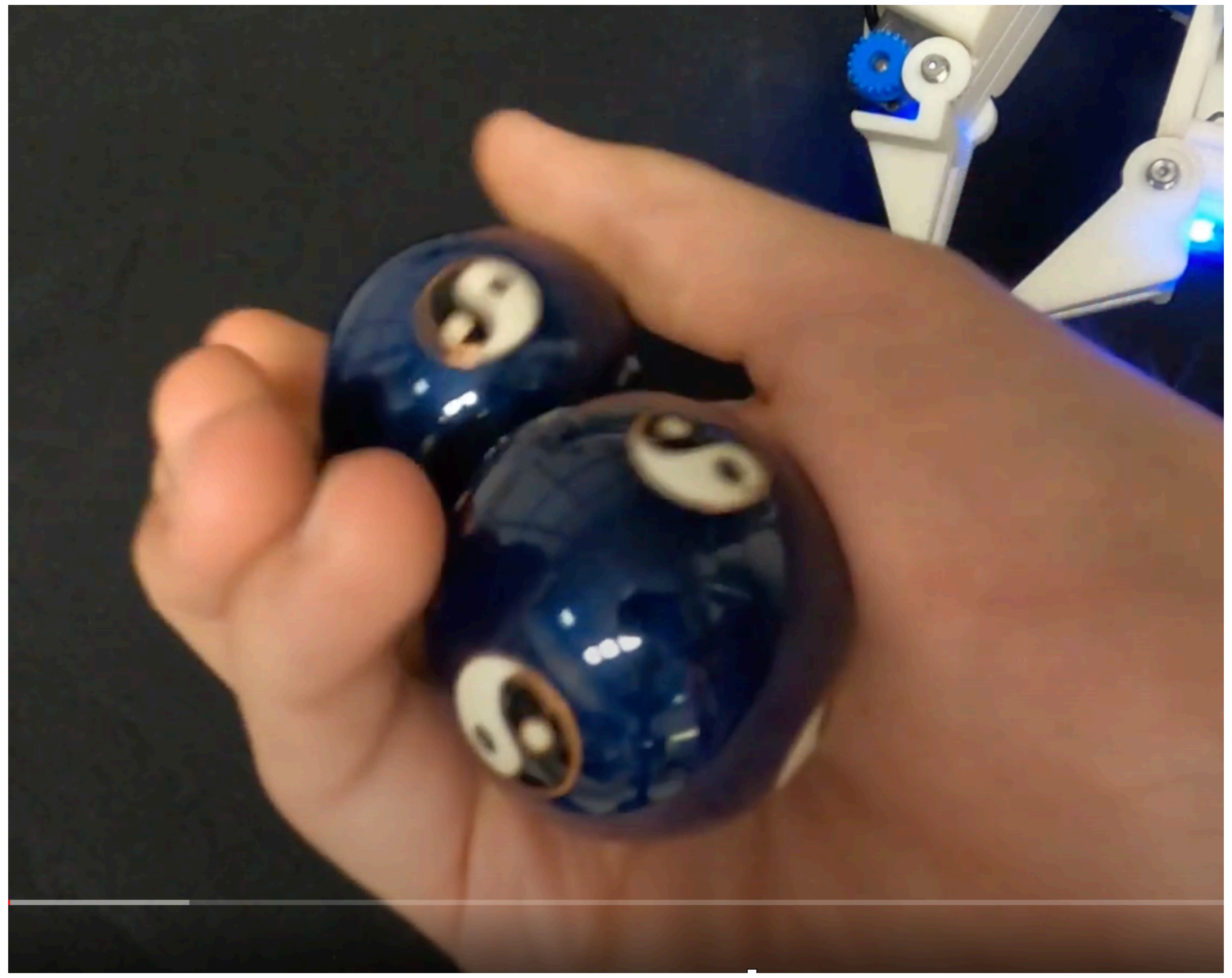
Soft and Cellular Robots



https://www.youtube.com/watch?v=-dUhGyaH4Vc

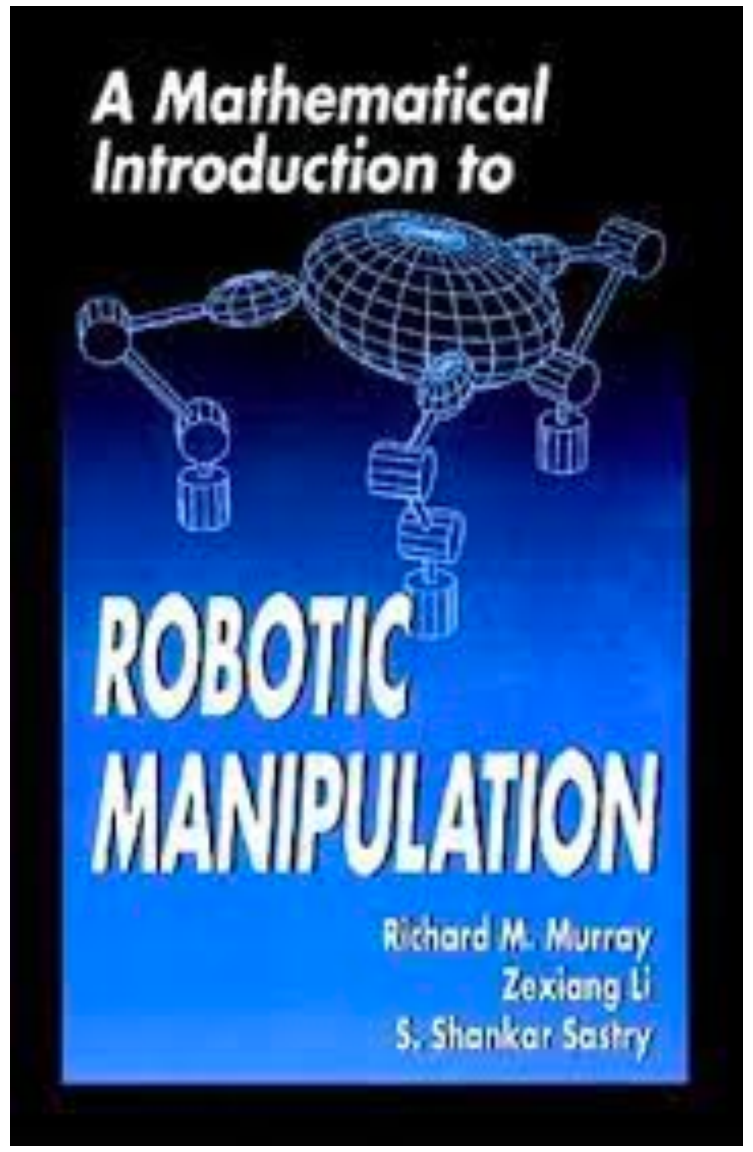
Motivation

- Many human manipulations involve complex, changing whole-hand contact



- These contacts are difficult to sense, track, and model

- We would like an approach that sidesteps this modeling



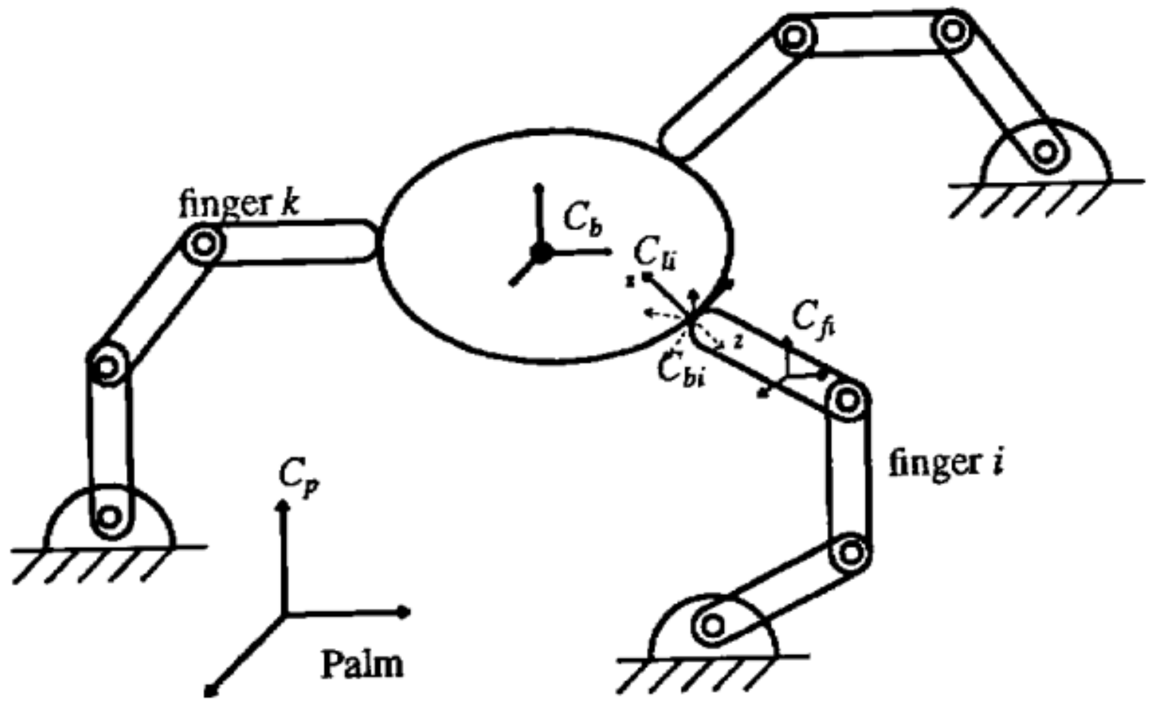


Figure 1 shows a manipulation system with a k-fingered robot hand. We assume that the number of joints of finger i, $i = 1, \ldots, k$, is m_i, and denote by θ_i, $\tau_i \in R^{m_i}$ the joint variable, and the joint torque vector, respectively, of finger i. To describe the contact constraints between the object and the fingers, we define a set of coordinate frames as follows: The reference frame, C_p, is fixed to the hand palm; the body coordinate frame, C_b, is fixed to the mass center of the object; at the ith point of contact with finger i, $i = 1, \ldots, k$, the local frame, C_{bi}, of the object is fixed relative to C and the origin is at the point of contact

Main ideas

- Let’s assume that manipulation is accomplished by going from one low-energy state to another
- While manipulating, try to maintain the object within a caging grasp to avoid ejecting it from the hand

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Caging Planar Bodies by One-Parameter Two-Fingered Gripping Systems

International Journal of Robotics Research 1999
https://journals.sagepub.com/doi/pdf/10.1177/02783649922066222

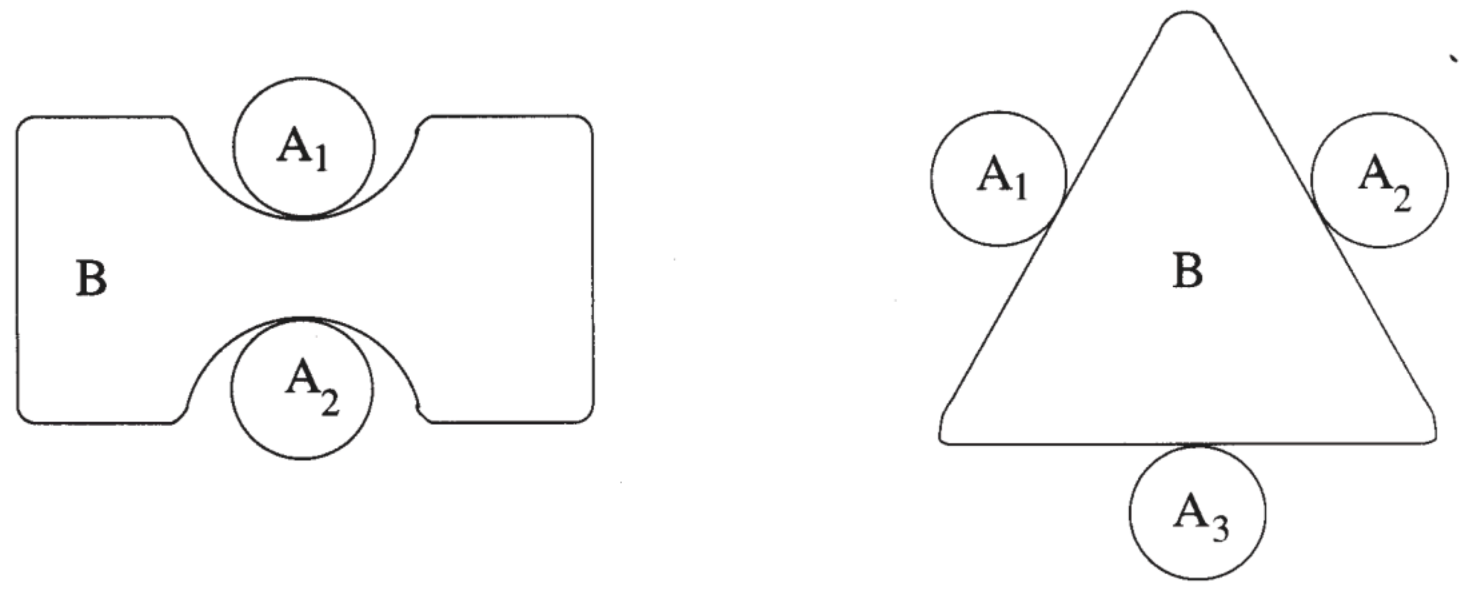


Fig. 1. Examples of two-fingered (left) and three-fingere (right) immobilizing grasps.

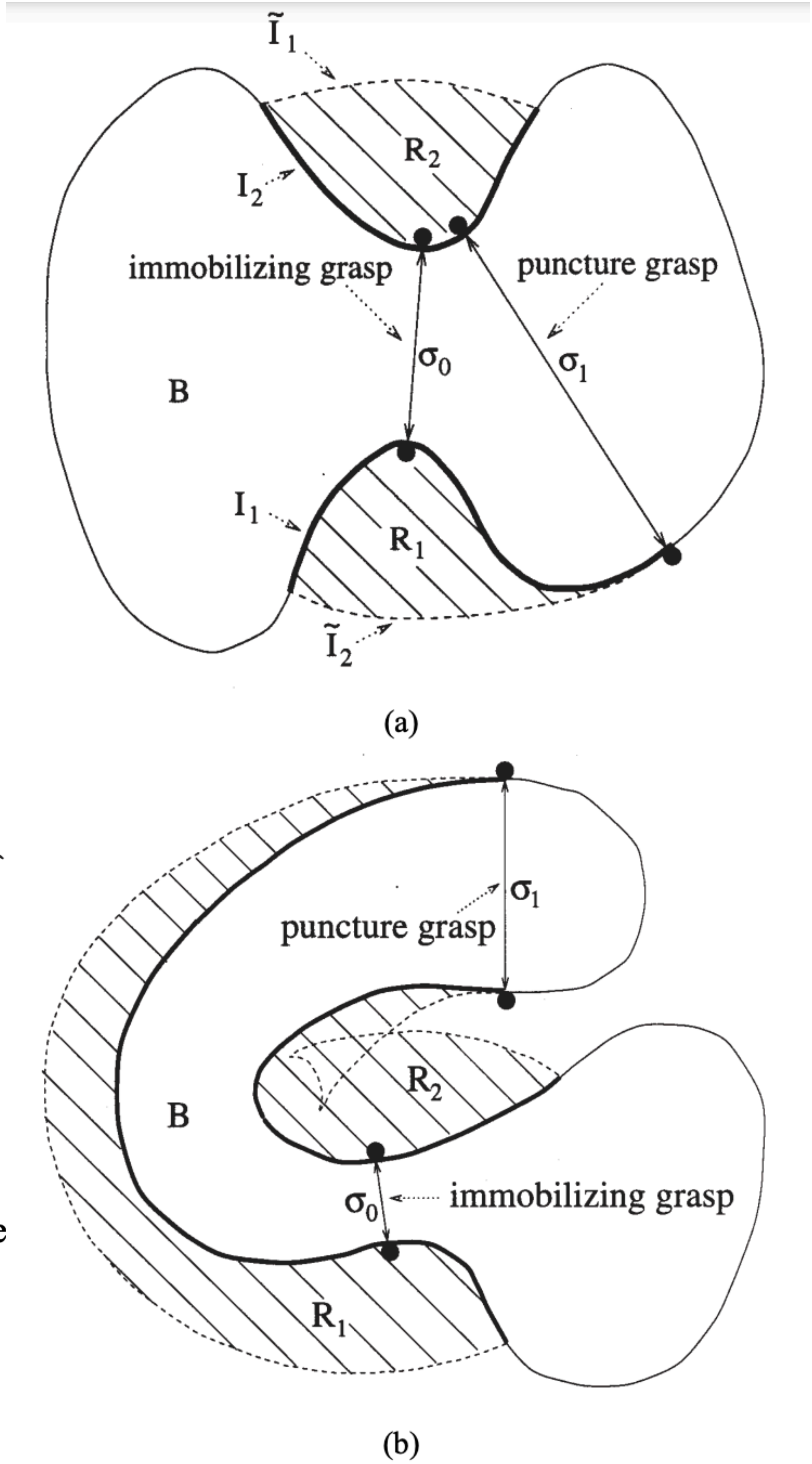


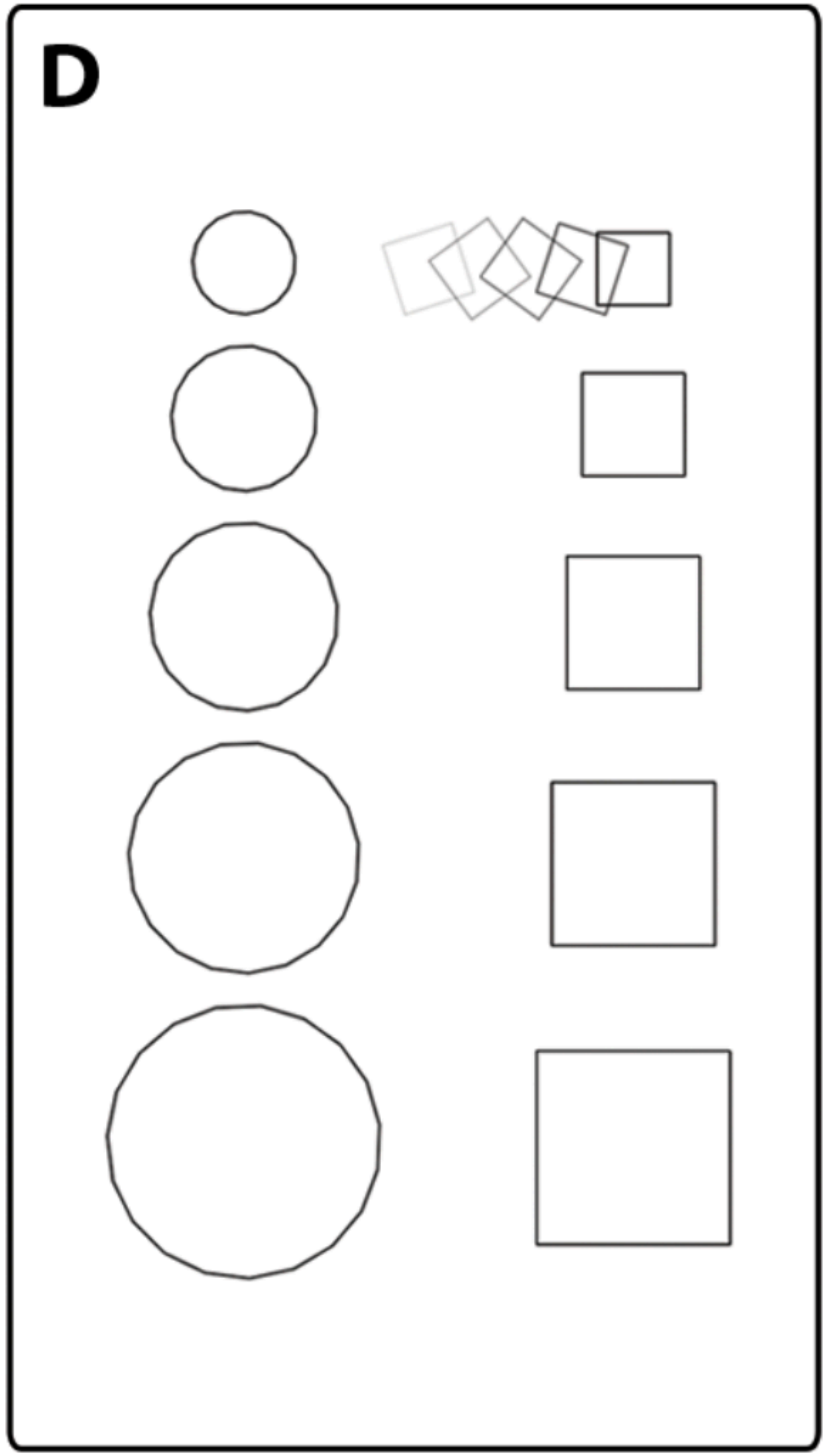
Fig. 9. Two objects and their capture regions. Every placement of the fingers in $\mathcal{R}_1$ and $\mathcal{R}_2$ with an opening $\sigma \leq \sigma_1$ forms a cage about $\mathcal{B}$.

What they did

Sample many designs, pick the optimal one

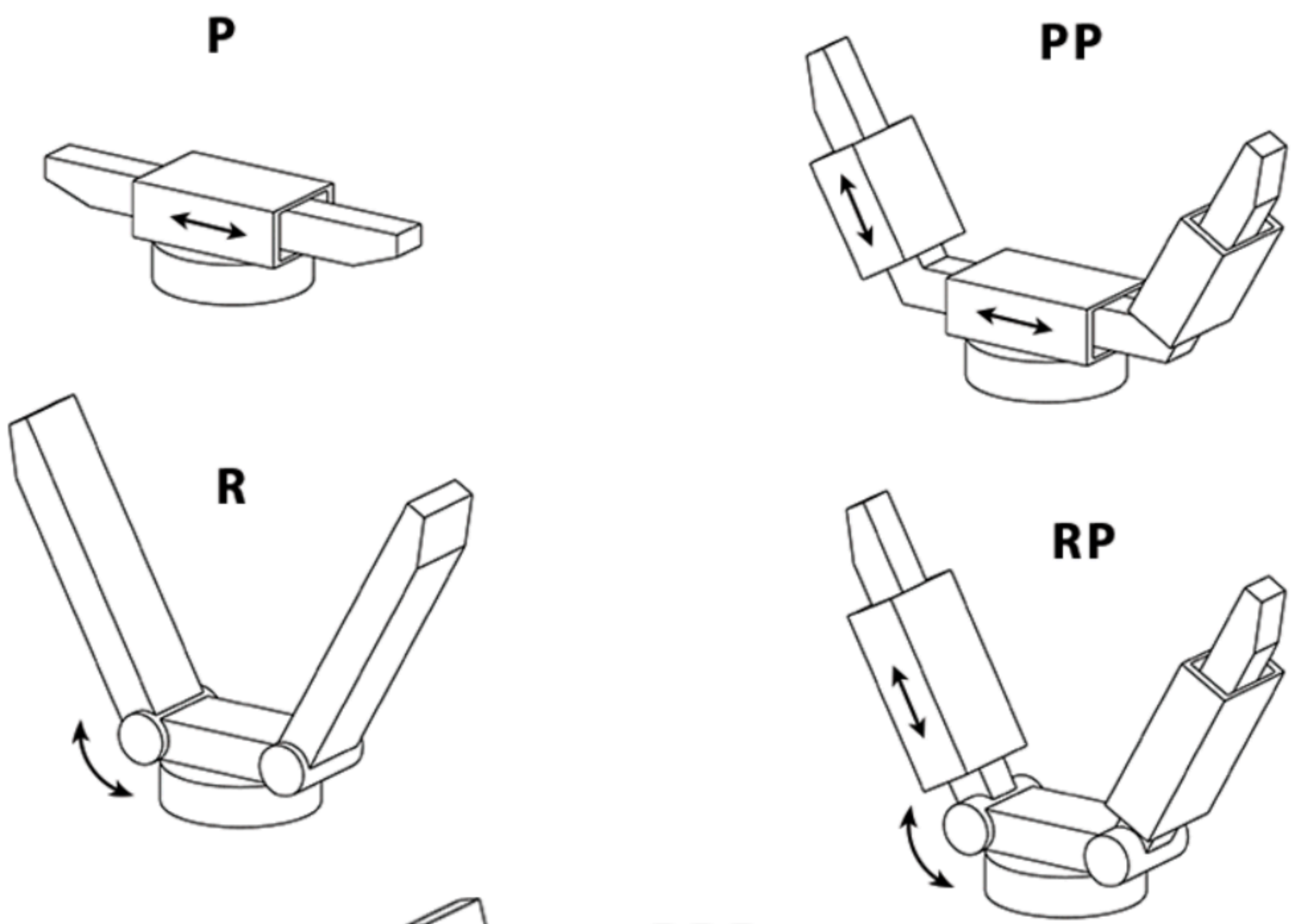
- 6250 unique hand designs
- 14 kinematic topologies
- 10 objects

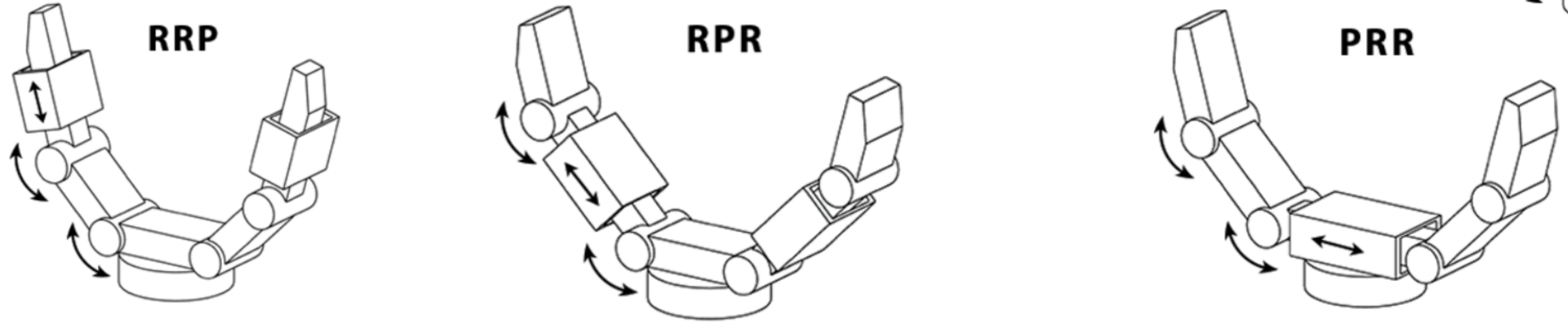
10 Sample Objects



14 Hand Topologies

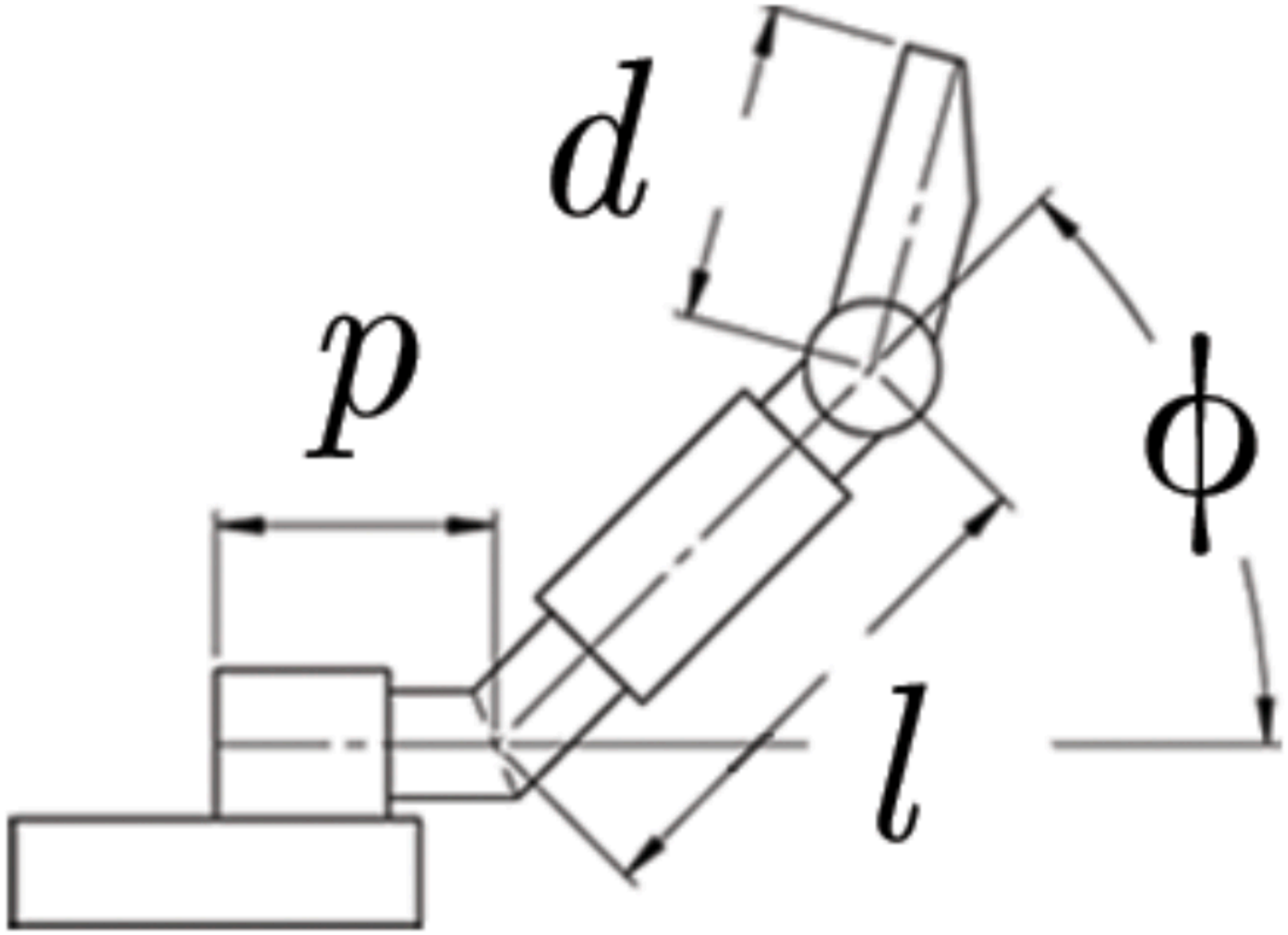
- R, P, RR, PP, RP, PR, RRR, PPP, RRP, PPR, RPR, PRP, RPP, and PRR
- R = revolute
- P = prismatic
- All hands are symmetrical
- 2 fingered hands
- No finger has more than 3 joints



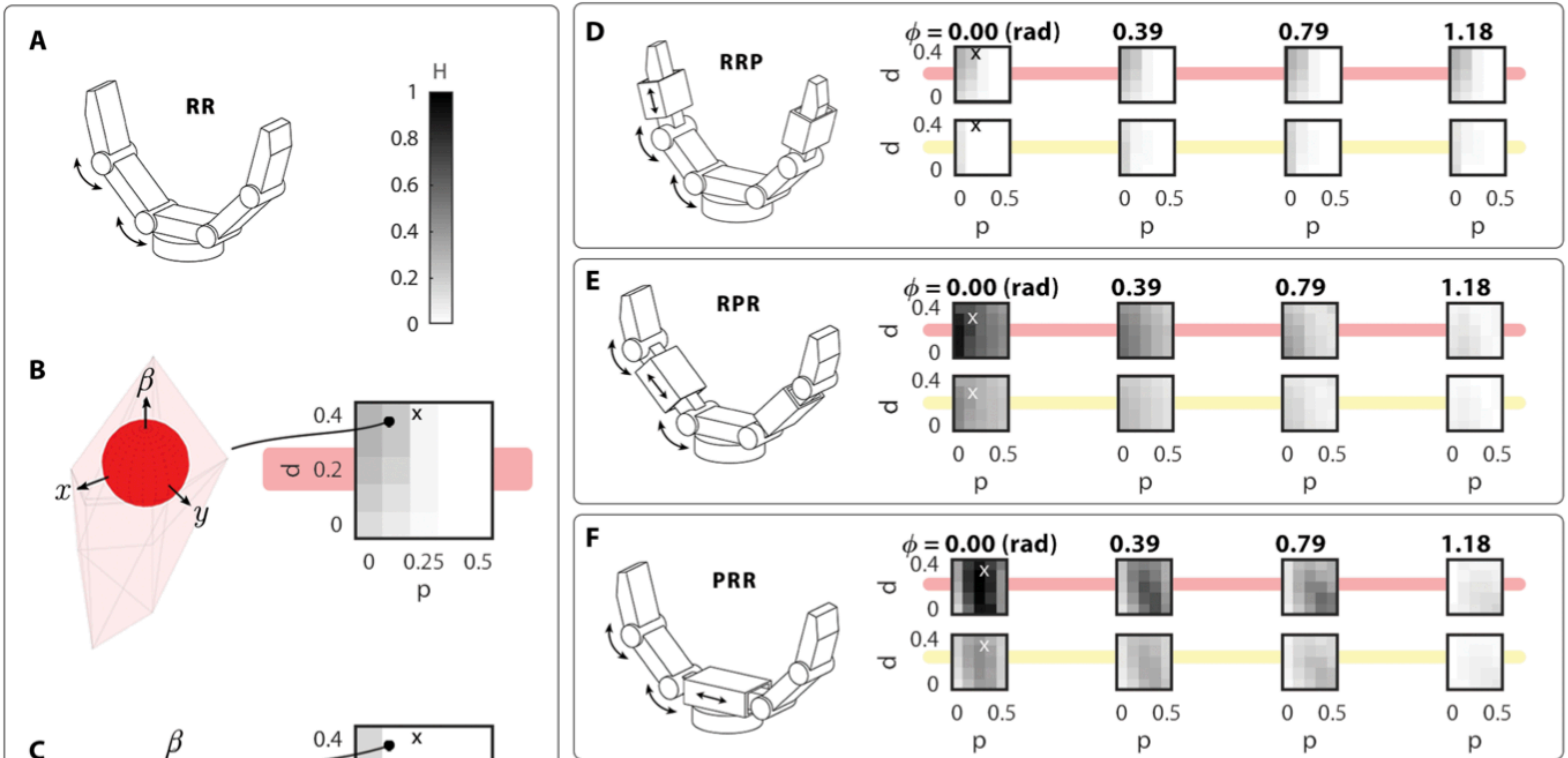


6250 Hand Designs?

- Sample p, d, and ϕ



Results of the design optimization



Ok… so how is each design evaluated?

Main objective function H

$$H_O = \frac{1}{U_{\max} Q} \sum_{q=1}^{Q} \mathbf{w}^*_{cq}$$

Max energy seen for this hand

Number of tests

- all object shapes
- all object poses

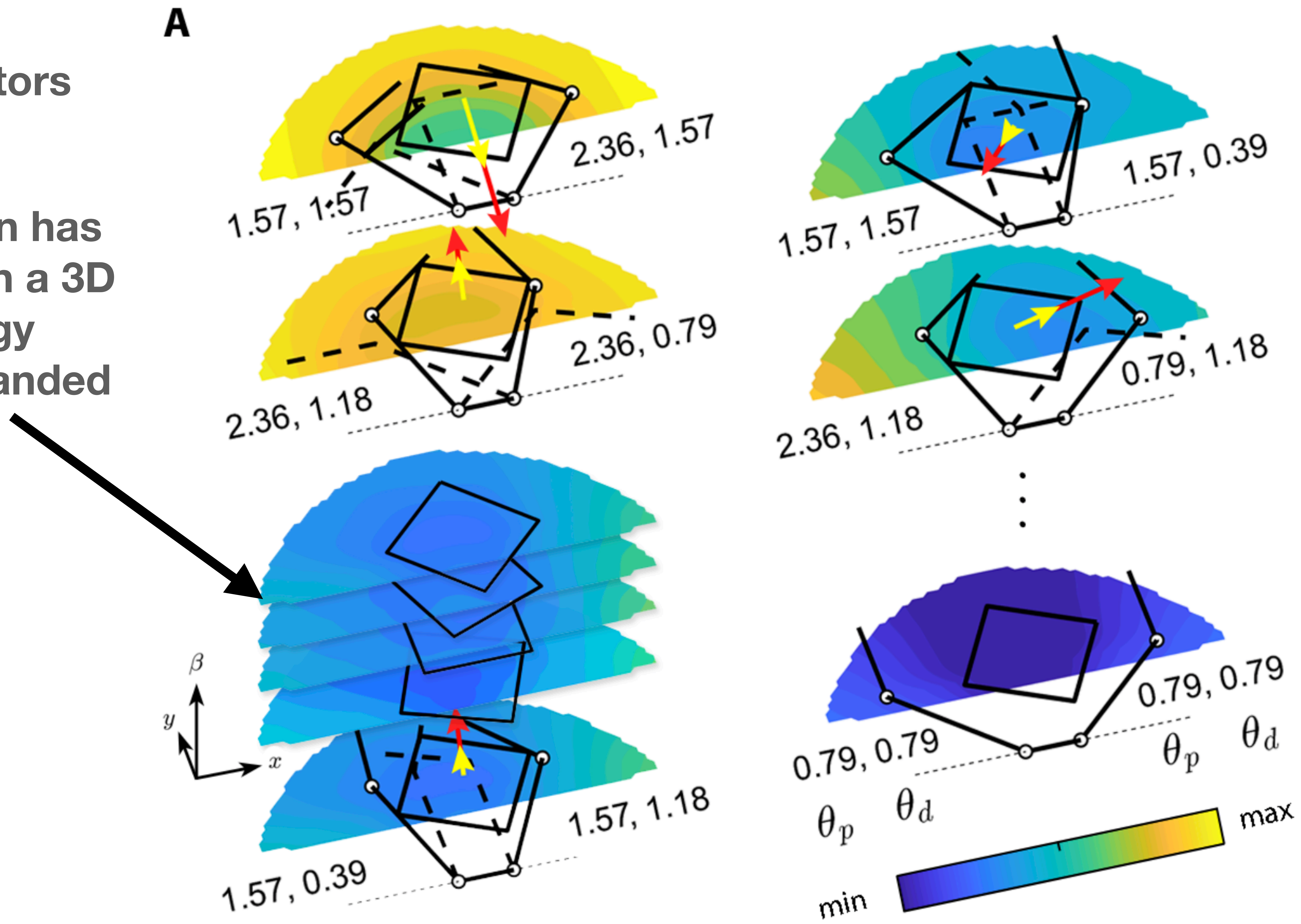
radius of the wrench space ball representing “manipulability” for a test object in a test configuration

(A wrench is just a vector that contains both forces and torques)

To figure out this wrench space ball, we first need to talk about energy fields (colors)

Commanding the hand to a pose when the object is “in the way” results in potential energy stored in the actuators (color coding blue to yellow).

Every object position and orientation has an energy / color coding, resulting in a 3D stack of energy values. These energy values are only good for one commanded hand pose.



To figure out this wrench space ball, we first need to talk about energy fields (colors) and their gradients (arrows)

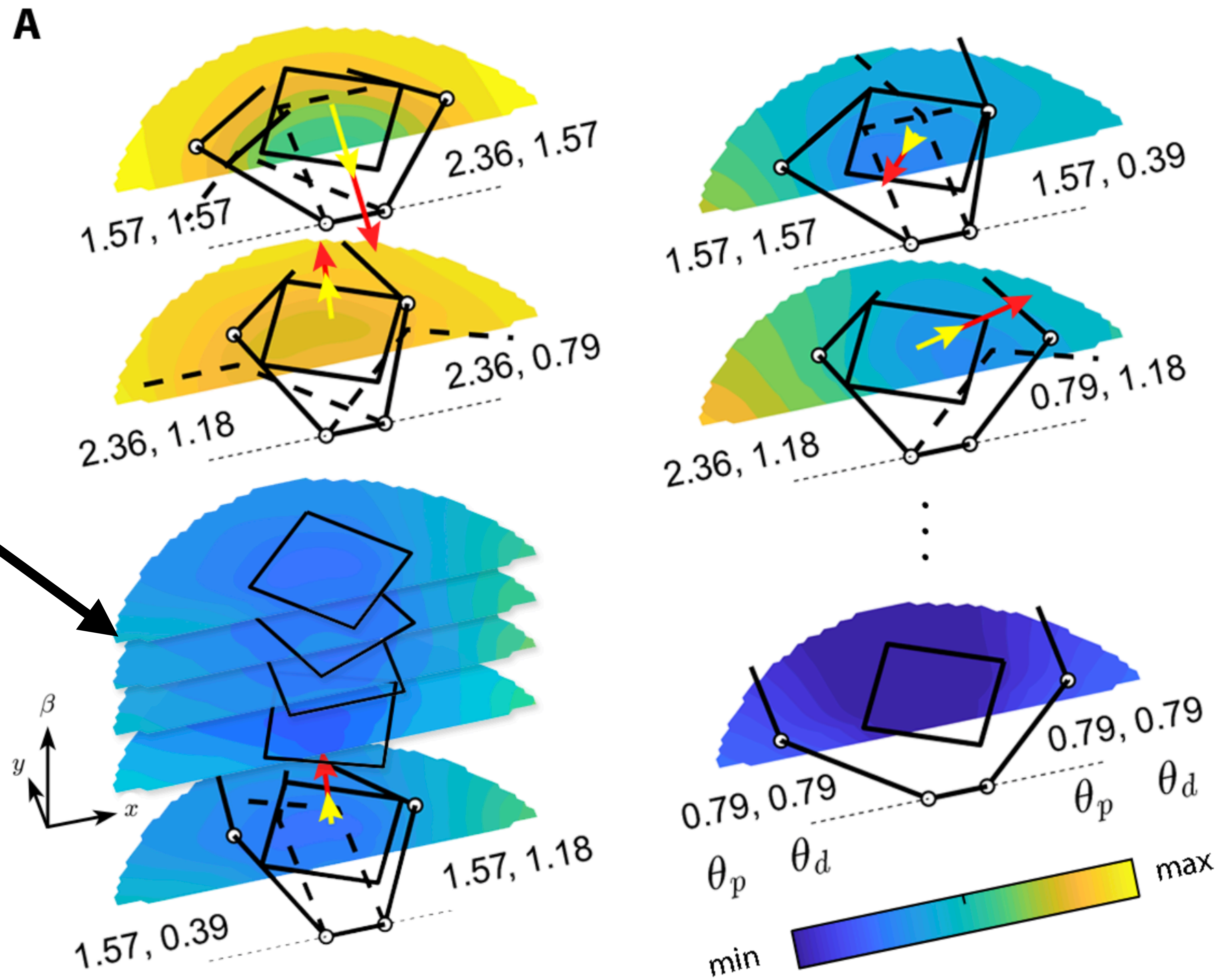
Commanding the hand to a pose when the object is “in the way” results in potential energy stored in the actuators (color coding blue to yellow).

Every object position and orientation has an energy / color coding, resulting in a 3D stack of energy values. These energy values are only good for one commanded hand pose.

We can take the gradient of this energy to obtain a vector field. The gradient at selected object configurations is shown as red arrows

These red arrows represent force that would be applied to the object

- in this configuration
- with this commanded pose



What to take from all this? Every new commanded hand pose has its own stack of energy fields with an associated red arrow (the gradient) at each point!

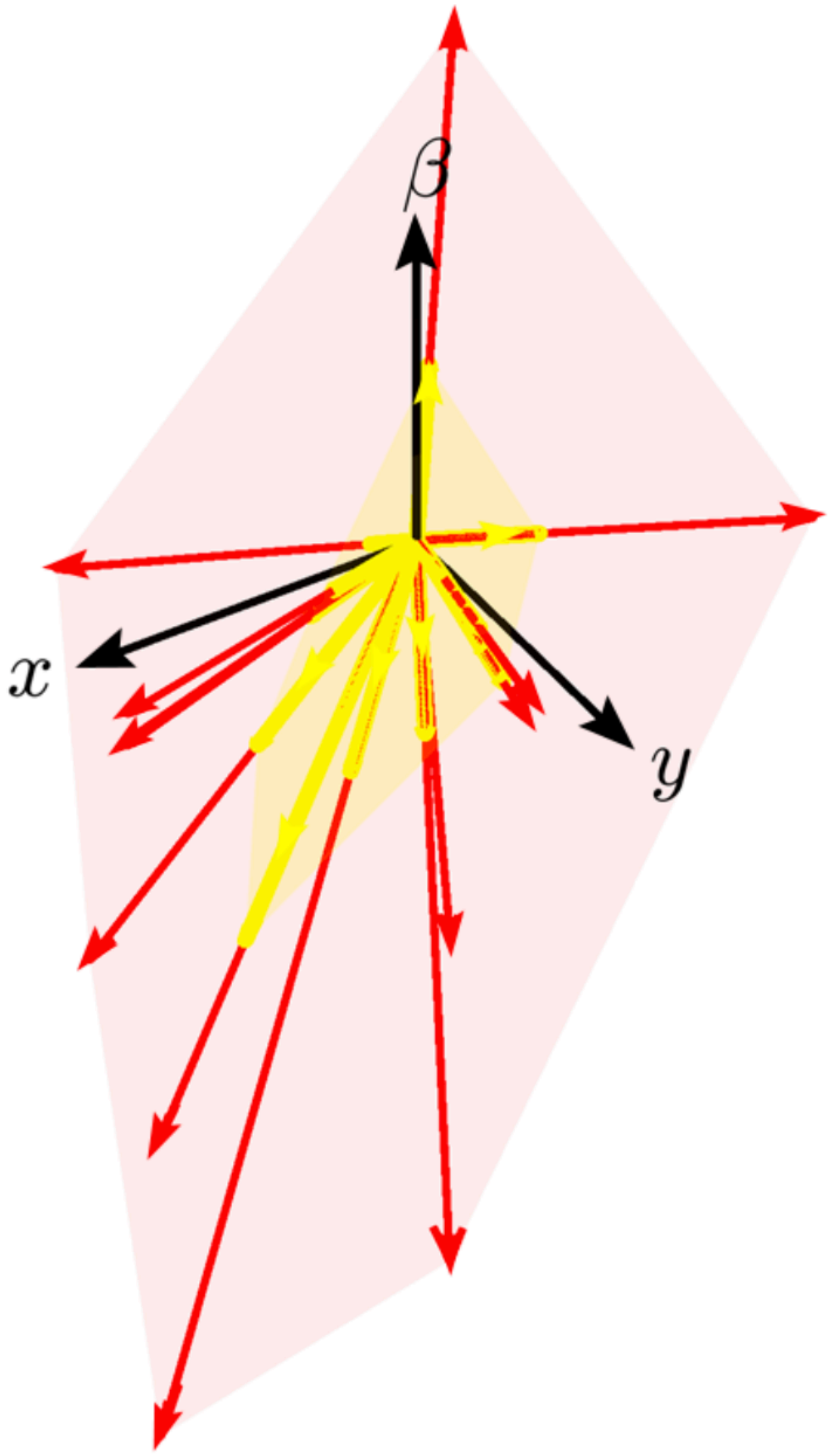
Wrench space ball from gradients

For a single
- object shape, and
- object pose

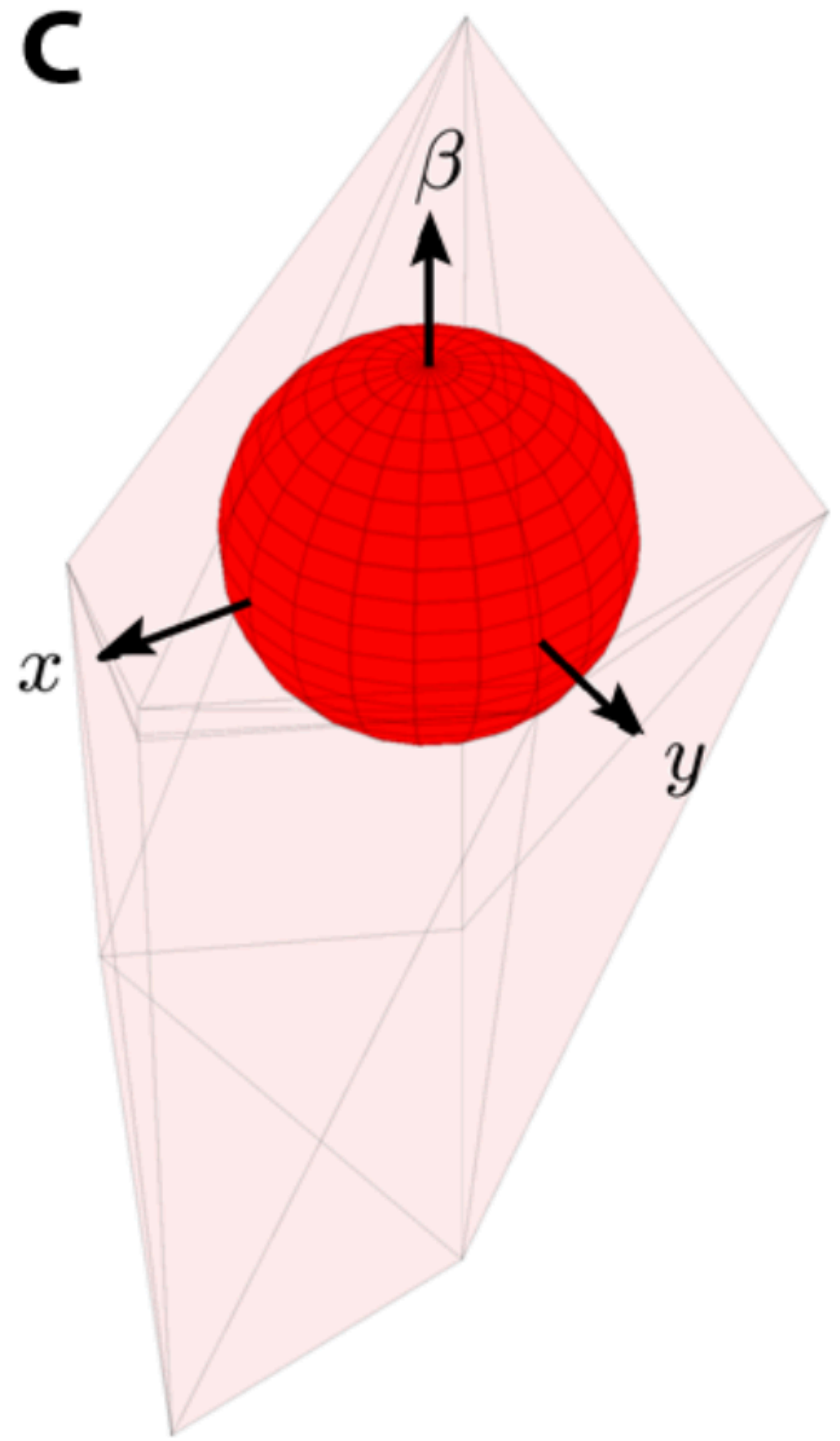
we can collect the red gradients that result from a sampling of the entire space of hand pose commands.

The convex hull of these vectors can be interpreted as the space of forces and torques that can possibly be applied to this object while it is in this configuration.

The larger this volume is the better!   We measure that by fitting the largest size ball centered at the origin, which weights equally forces and torques in all directions.

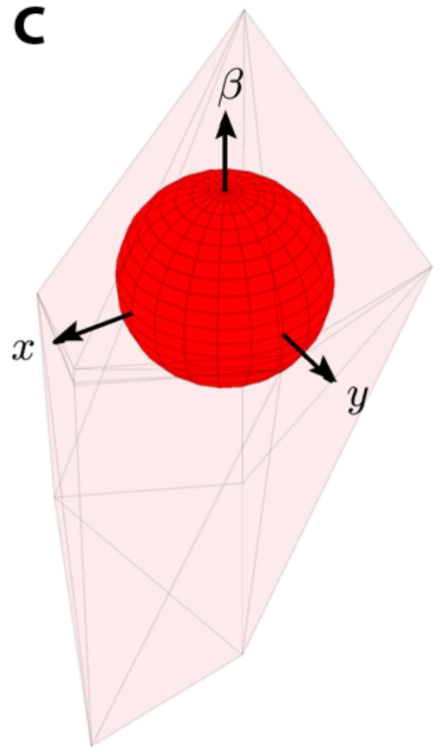


Collected red gradients and their convex hull.



The radius of the largest wrench space ball that fits into the volume = $\mathbf{w}_{cq}^{*}$

So .. to evaluate, we just average those radii over all the test cases



$$H_O = \frac{1}{U_{\max} Q} \sum_{q=1}^{Q} \mathbf{w}^{*}_{cq}$$

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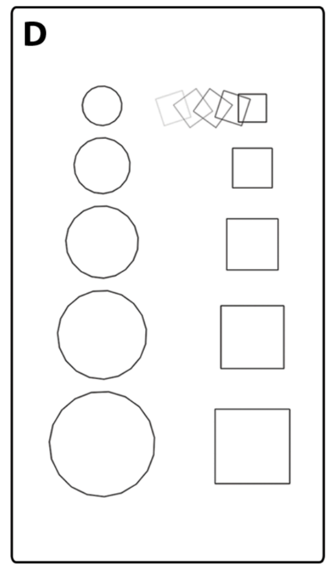

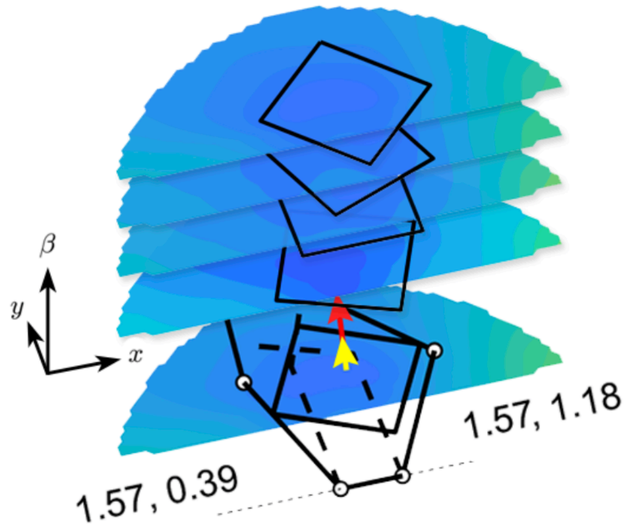

One last thing — What is Energy and how is it measured?

The paper assumes that energy is linearly related to the "error" between desired and actual pose

Number of motors/actuators

Actual (observed) angle for this joint

Setpoint (desired angle) for this joint

$$U = \sum_{i=1}^{n} \tau_i K_i (\theta_{\mathrm{d}_i} - \theta_{\mathrm{sp}_i})$$

Transmission ratio (maps angles in the world to angles about the motor shaft)

Torque generated by the motor (assumes it is a constant source of torque)

Repeatability tests

Fig. 4. The Model W experimentally manipulates objects to low-energy regions of the workspace as predicted by simulated energy maps. (**A**) A histogram showing the distribution of object trajectory endpoint energy percentages of all 360 trials. The distribution shows that objects move to low-energy (<10%) regions of the workspace as predicted by simulated energy maps and that energy maps are actionable. The small peaks near 20 and 30% energy correspond to "pinch grasp" trials in which the object became stuck in the unsimulated physical geometry of the distal joints. (**B** and **C**) Left: Photograph of the "right" grasp trials with object T3 with grid of starting locations (green markers). Right: Corresponding energy map, object trajectories (yellow lines), and object ending locations (red markers). (**D** and **E**) The same images for the "power" grasp trials with object T1.