Robot Hands: Mechanics, Contact Constraints, and Design for Open-loop Performance

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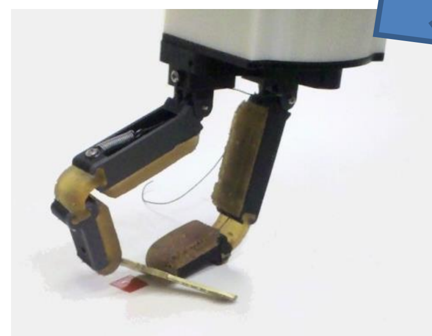
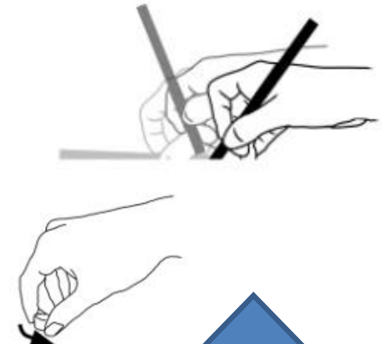
Yale GRAB Lab

Aerial Robotics

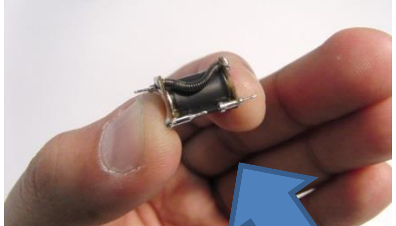
Robotic Grasping and Manipulation



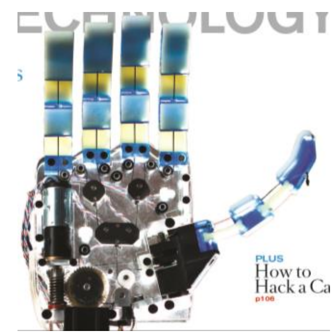
Human Manipulation



Active Cells

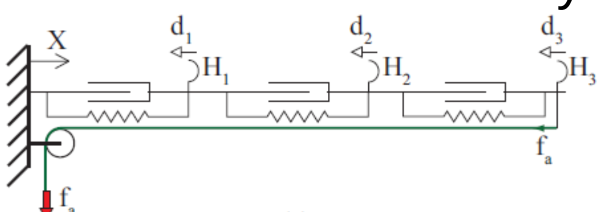


Upper-limb Prosthetics



Rehabilitation Robotics

Mechanisms and Theory



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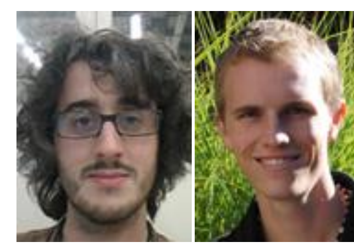

Rehabilitation Robotics

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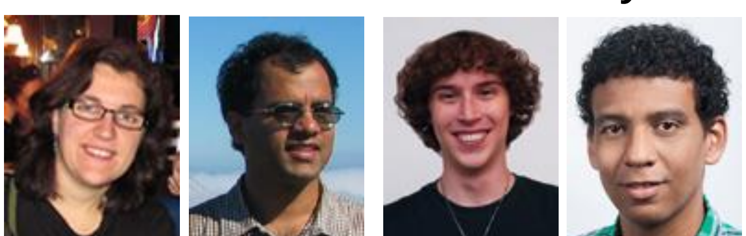

the GRAB LAB

Our Approach

- Develop hands optimized for open-loop operation, in the presence of uncertainty

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- Incorporate mechanical features for passive adaptability to object shape, size, position
  – Compliance and Differentials

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➡ "Mechanical Intelligence"

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- Why design for open-loop performance?
  - Lays the foundation for best performance
  - Prevents relying on “crutches”
  - Prioritizes simplicity, robustness

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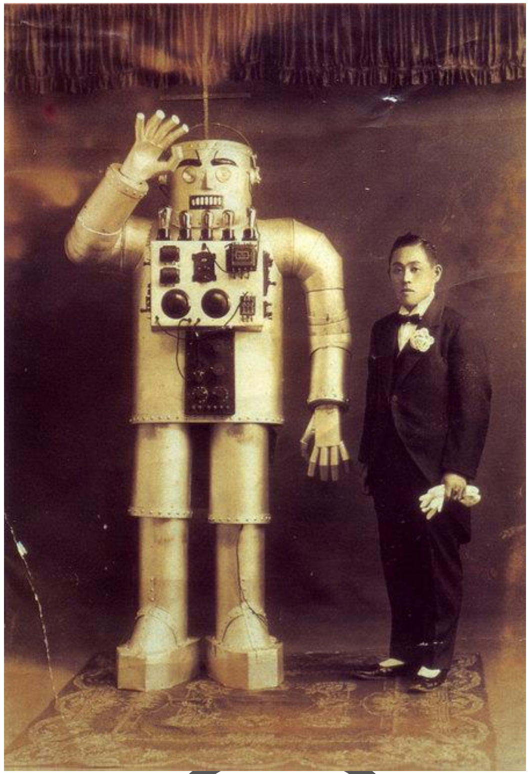
→ Addition of sensing can then be used to make performance even better

Some Practical Challenges for Grasping and Manipulation

- Variability in objects/properties is enormous
- Sensing is generally poor, expensive, fragile
- There is ALWAYS going to be some amount of uncertainty
- Controlled contact/forces in the presence of sensing errors is difficult

Rigid on Rigid → Bad Idea*

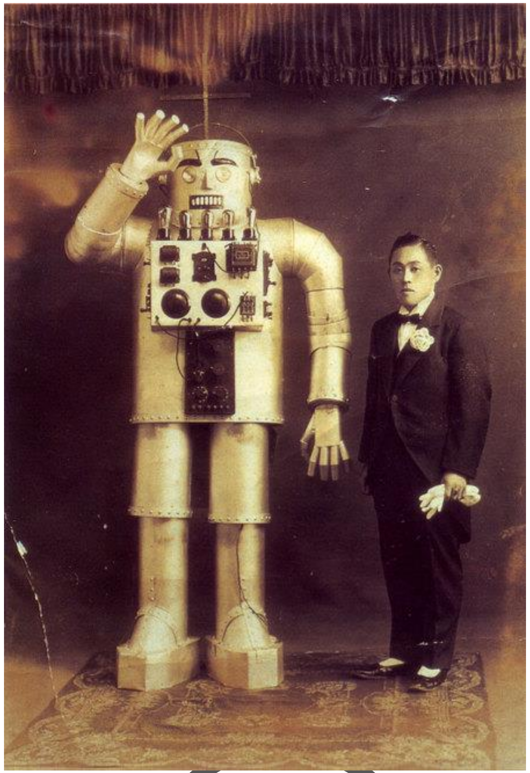
- Controlled contact between stiff structures is very difficult
  - →Vibrations/oscillations
  - →Poor control of force
- Primary reason: Overconstraint
  - – Contact creates closed chain
  - – No free or underconstrained DOFs
  - – Something has to "break"



* Unless absolutely required by strength/precision needs

Rigid on Rigid → Bad Idea*

- Engineered world is mostly stiff
- Facilitate contact via:
  - Compliance ("soft" constraint"
  - Passive DOFs
  - Underactuated mechanisms



* Unless absolutely required by strength/precision needs

Compliance for Stability

- Reduce contact instabilities due to position errors/vibration
  – Help ensure and distribute contact
  – Small motions minimally affect contact/force
- Roboticists have long proposed/been using compliant coverings on fingers
  – Salisbury Hand
  – Shimoga and Goldenberg 1992

--> Only good for small errors (~1mm)

Compliance for Stability

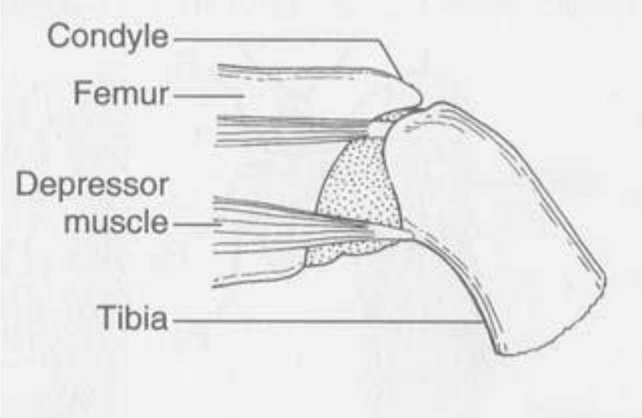
- Contact is a zero (mechanical) power task
  - Energy from velocities/accelerations has to go somewhere!
  - Must generally be absorbed by the structure
- Facilitates implementation of damping
  - Vibration isolation



Compliance for Adaptability

- Allows passive conforming to contact
  - No sensing and control required
  - Lower precision required
- Passive "disturbance" rejection
  - On the order of ~3cm

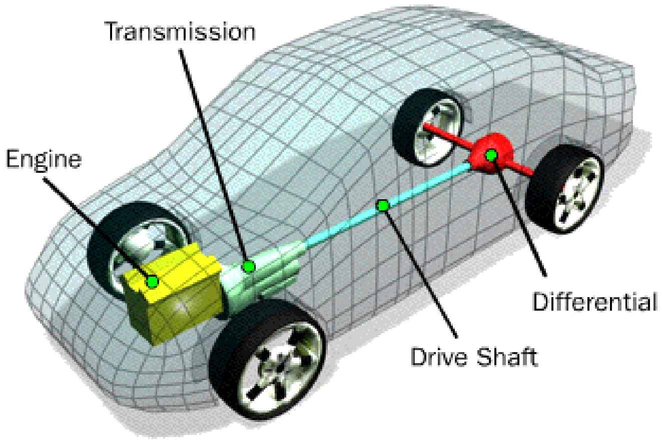
RHex

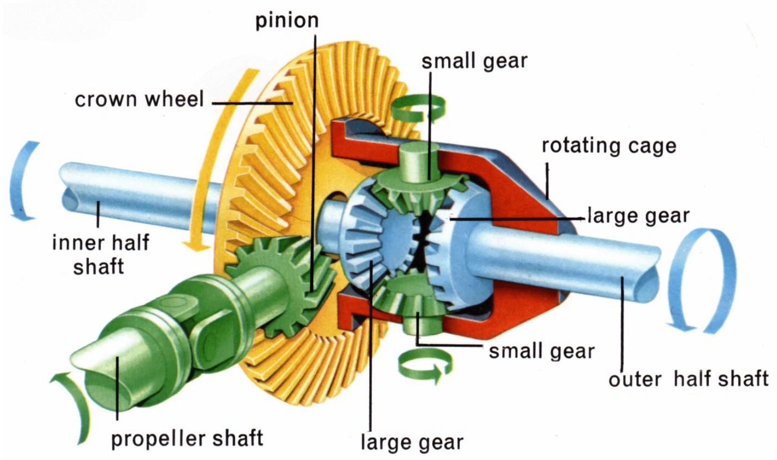


[Bob Full, Berkeley]

Adaptability++ → Differential Transmissions

- E.g. Automotive Differential
  - Allows your wheels to spin at different rates
  - Passively "specified" by curvature of turning
- Differentials = Underactuated Mechanisms



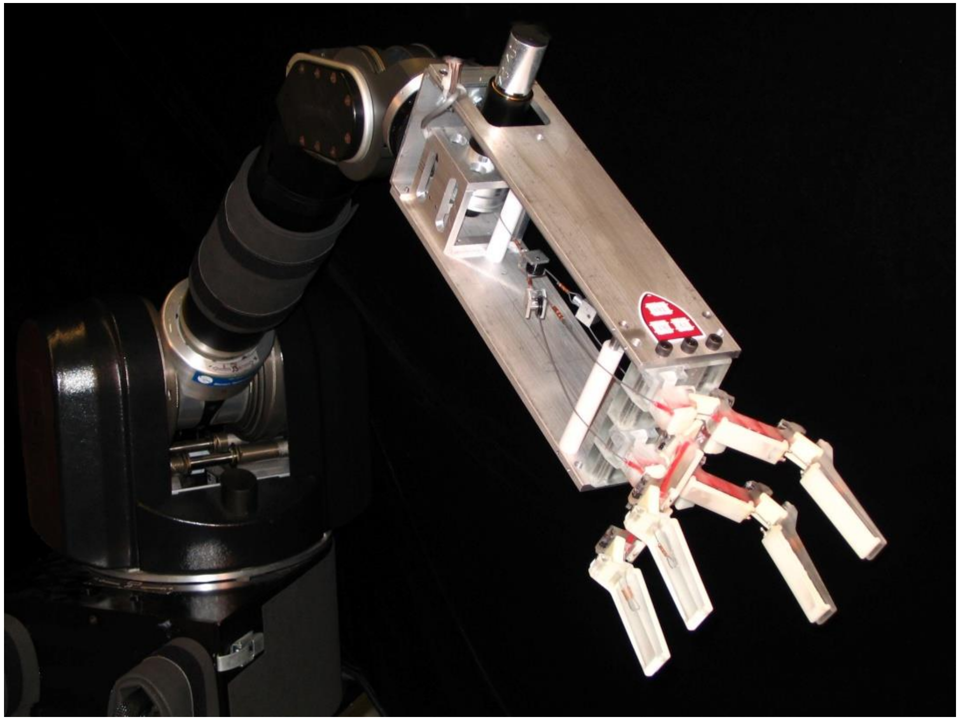


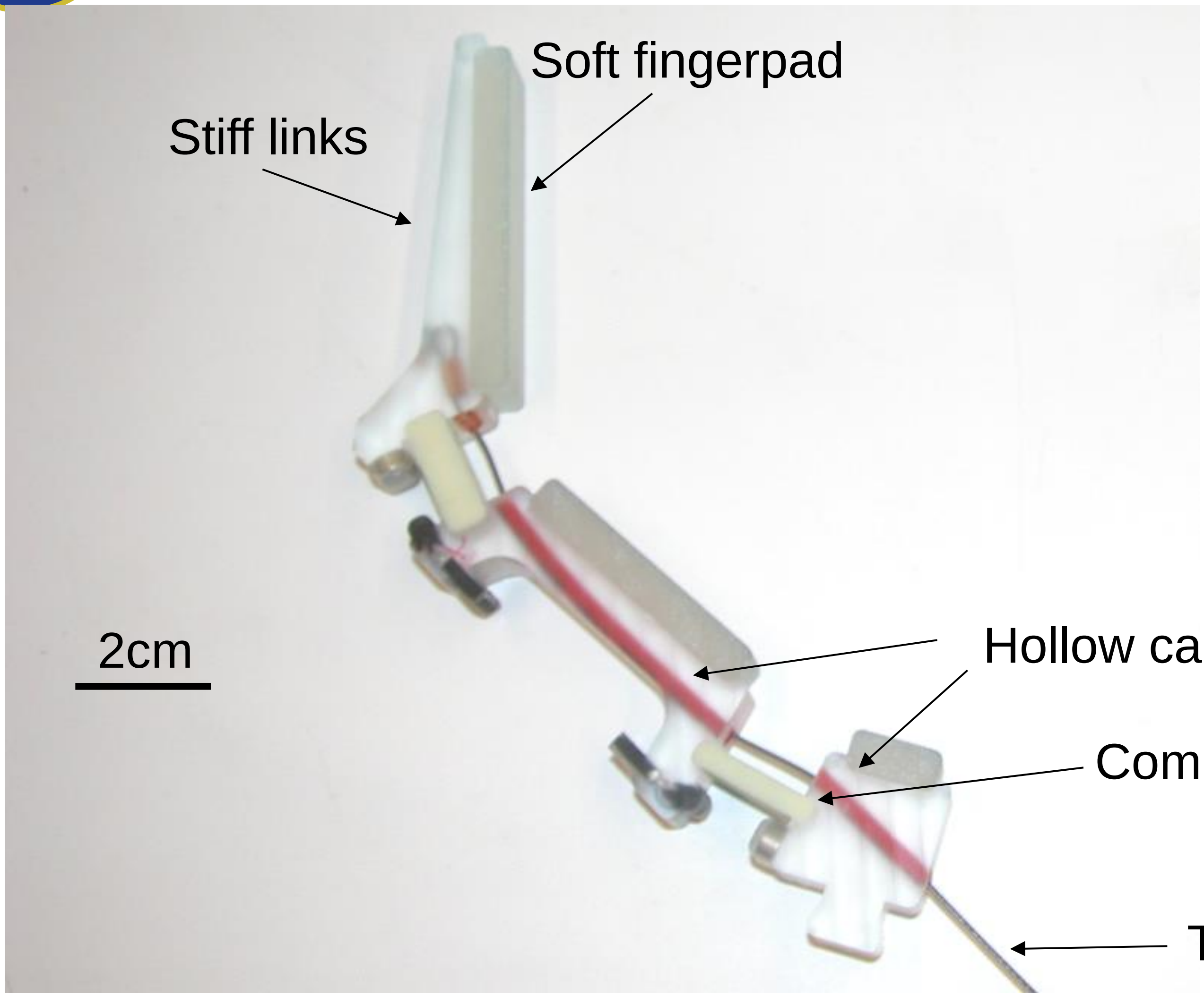
Adaptability++ → Differential Transmissions

- Both compliance and differential transmissions add DOFs
  - Compliant DOFs are “constrained” by F=kx
  - Differentials can be completely unconstrained
- N.B.: Biology uses both
  - Compliance in mechanical structure, coverings
  - Tendons often cross multiple joints
    - Differential transmissions
    - Whole structure is not generally “underactuated”

SDM Hand (PhD work)

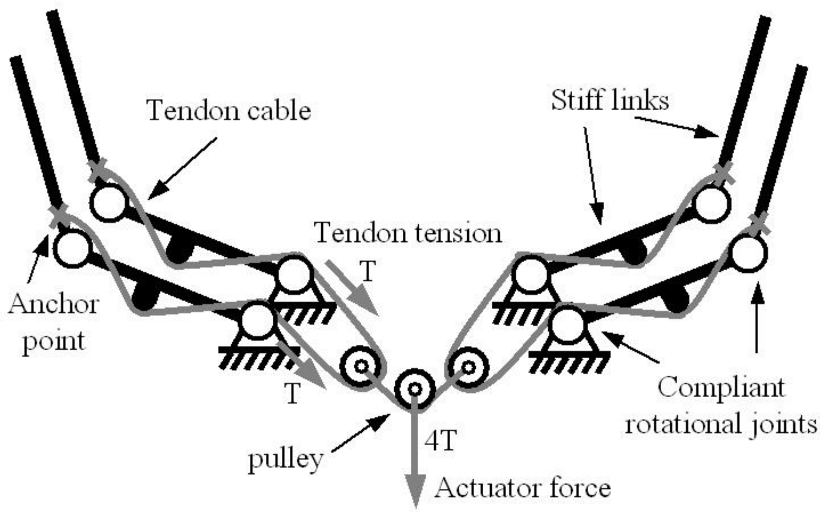
- 4 fingers
- 8 joints
- 1 actuator
- Open-loop control

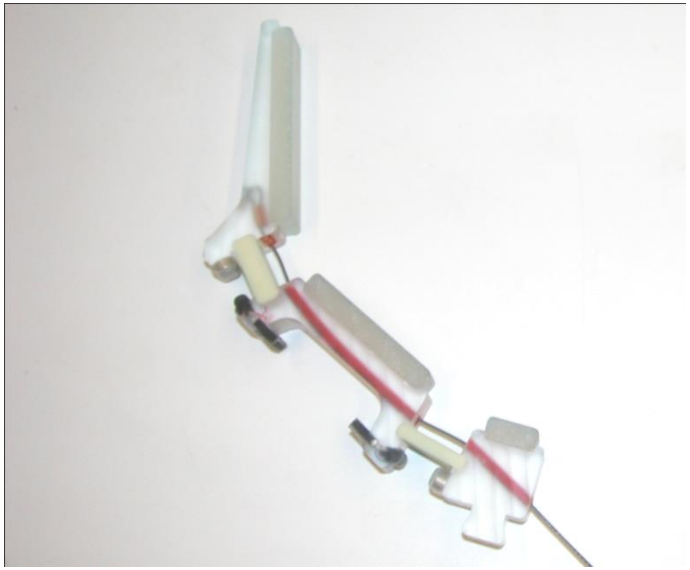



Soft fingerpad
Stiff links
2cm
Hollow cable raceway
Compliant joint
Tendon cable

Tendon Actuation Scheme

- Equal tension on all fingers
  - Regardless of position, contact
- Highly Adaptive!





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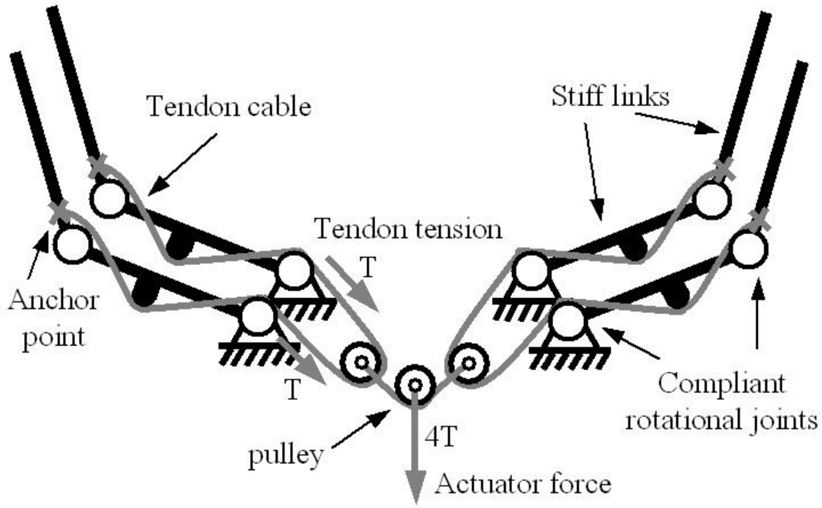
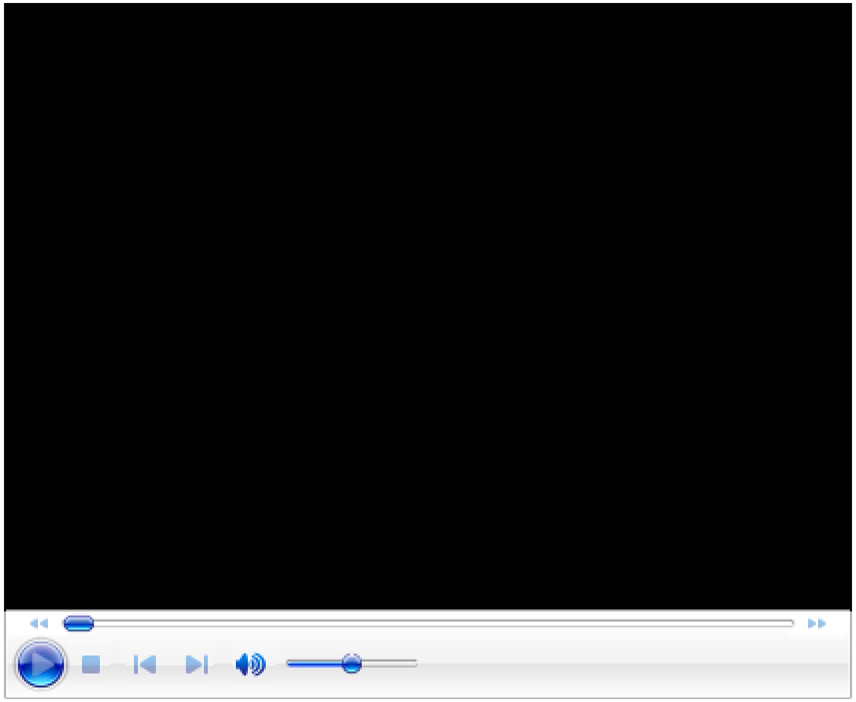
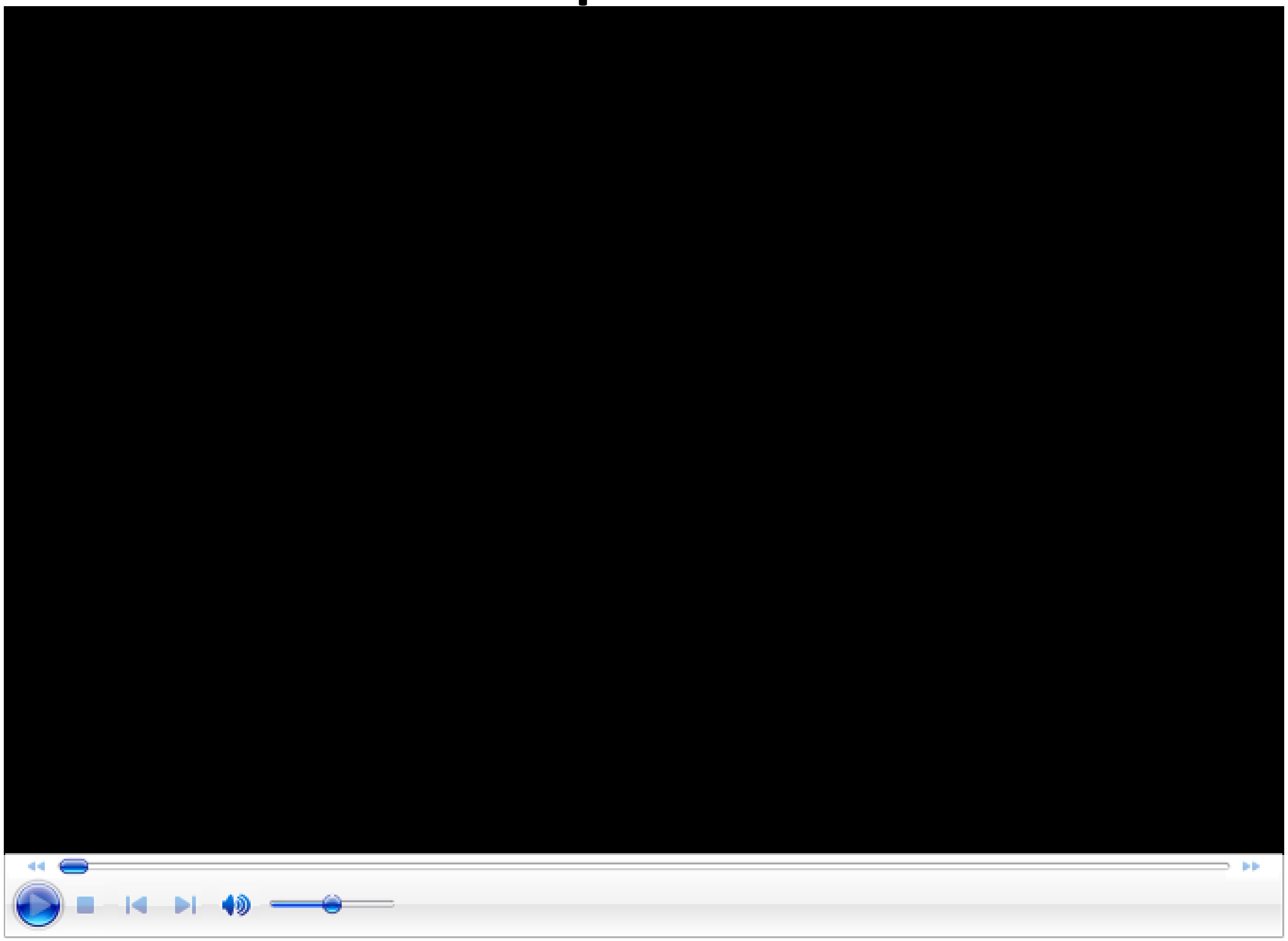




Teleoperation



Moving Past Power Grasps

- Grasping ≈ assembling object to arm
  - Power Grasping → "wrap" grasp
    - Used for large objects/high forces
  - Precision Grasping → fingertip grasp
    - Used for small objects/precise positioning
- Within-hand manipulation → moving object w.r.t. hand base
  - Via finger "individualization"

Moving Past Power Grasps

- Add dexterity to SDM-type hands without sacrificing grasping performance
- Keep it simple
  - Small number of actuators, optimize open-loop performance

Underactuated Mechanisms: Challenges/Opportunities

- Key property: Un/Underconstrained DOFs
- Must "constrain" them for system (static) stability
  - Constrained via contacts
  - "Soft" contraints via springs
    - System moves towards elastic average/equilibrium

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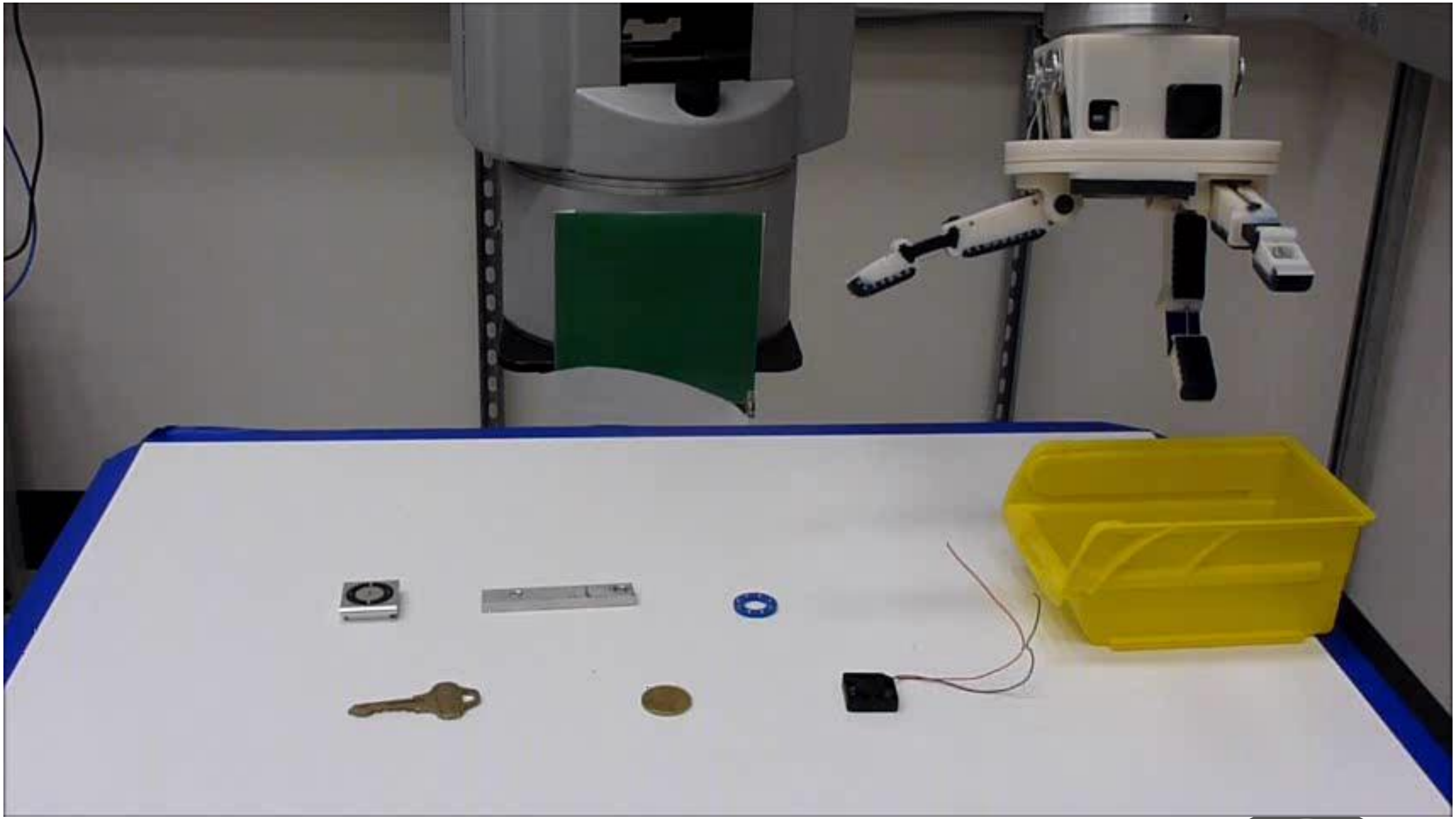
Underactuated Precision Grasping

- Main idea: Use environmental contacts at fingertips to exactly constrain system
  - Surfaces used as “affordances” to guide motion
  - Object may move to elastic equilibrium after those constraints are removed
- Performance bonus: Adaptability to hard surface constraints

Using environmental constraints

This primitive is object-agnostic!



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Within-Hand (Dexterous) Manipulation

- Main idea: Contacts and actuation from other fingers provides constraints
  - Either exactly constrained or underconstrained
- Challenge: Not OVER constraining the system when manipulating the object

Parallel Platforms

- All "practical" parallel platforms are exactly constrained
  - Neither under- nor over-constrained

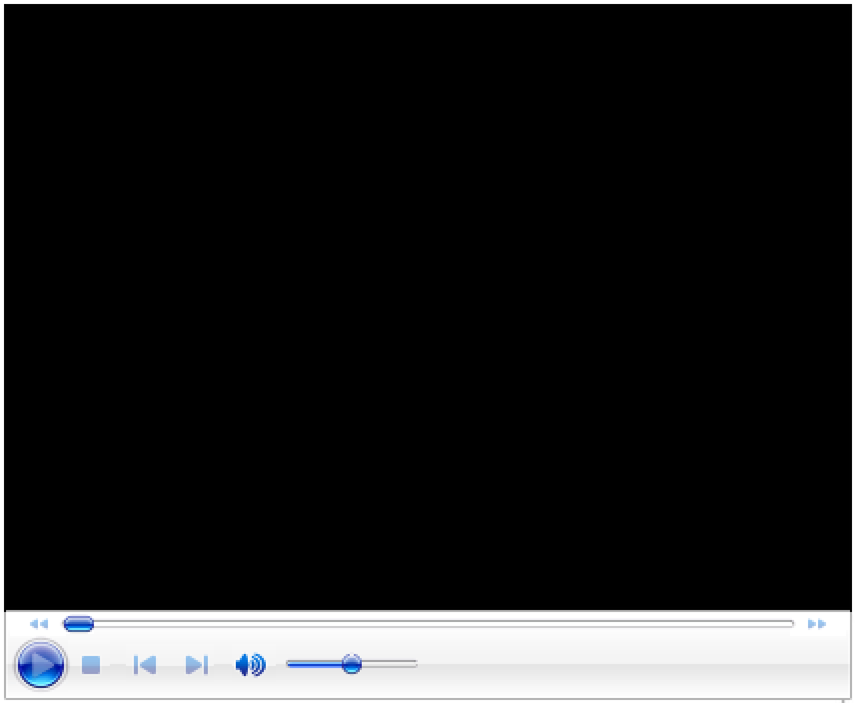
Stewart: 6 DOF/Actuators

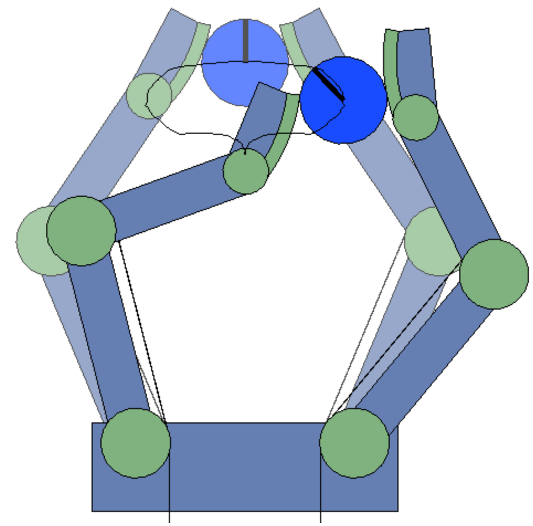
Delta: 3 DOF/Actuators

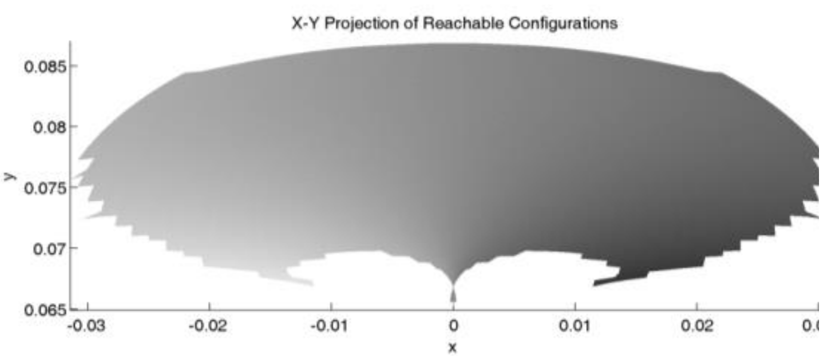
Parallel Platforms

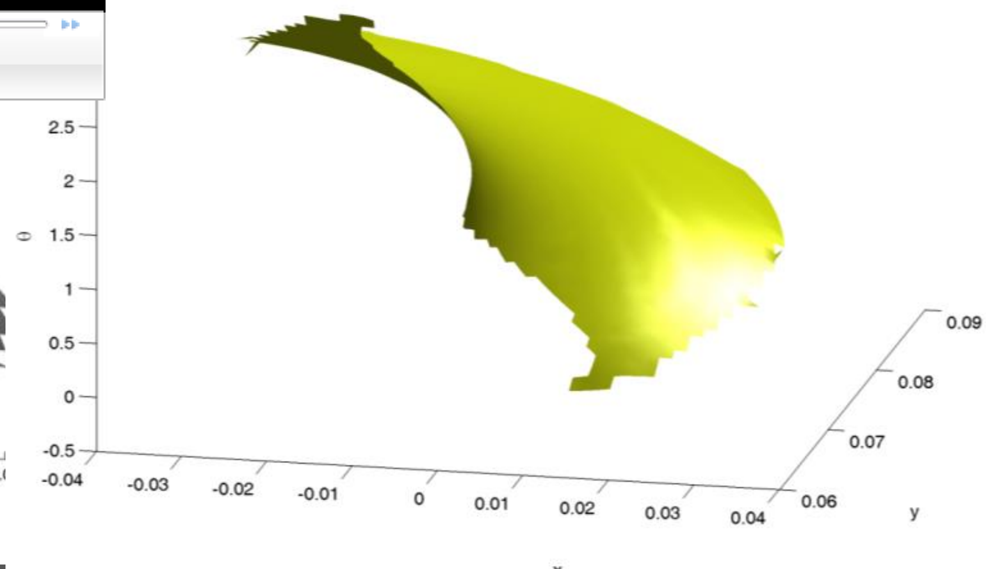
- Challenge: All “legs” must/will have same mobility as the platform
  - Makes hand design challenging as they must “stand alone”
- Solution: Underactuated Mechanisms
  - Allow fingers to be fully articulated without being fully constrained
  - 1 DOF of manipulation for every 1 <u>hand</u> actuator

Planar Precision Manipulation



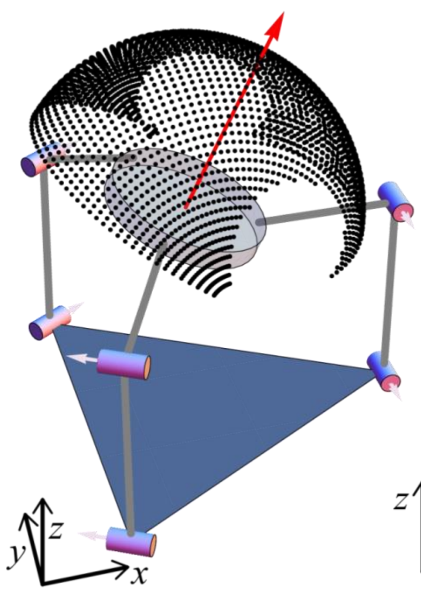


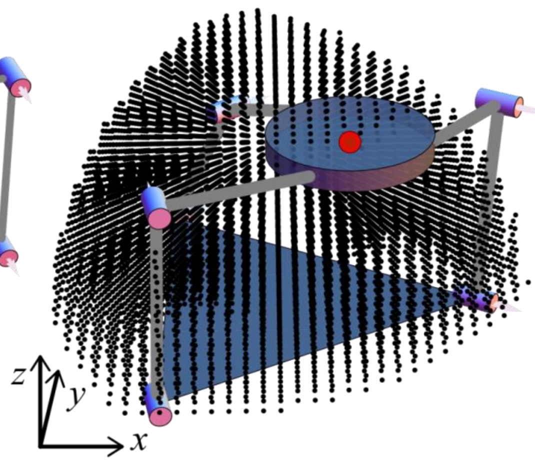


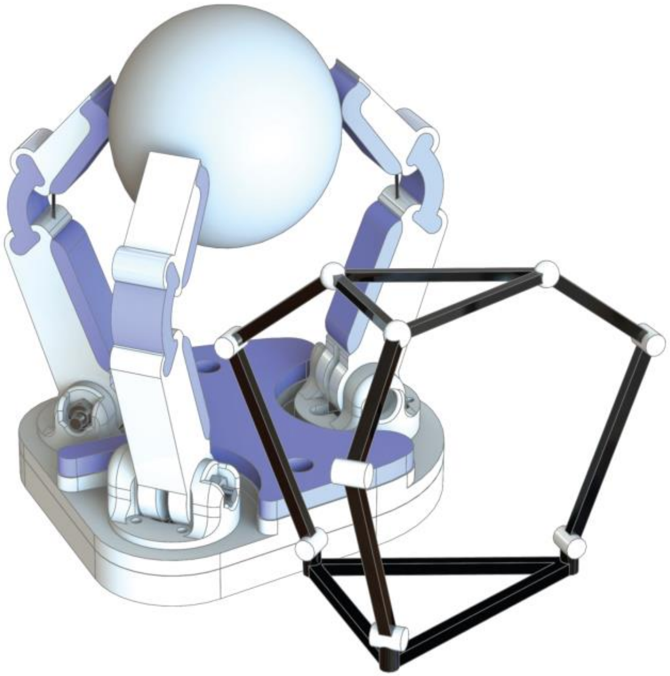


Design for Dexterous Manipulation

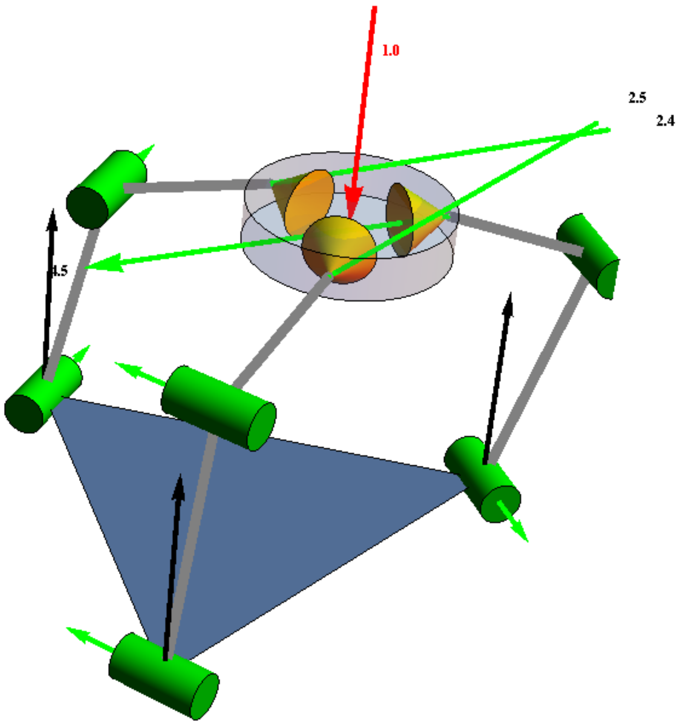
- Dexterous manipulation is a closed kinematic chain
- Can be modeled as a parallel manipulator
  - Deep research literature

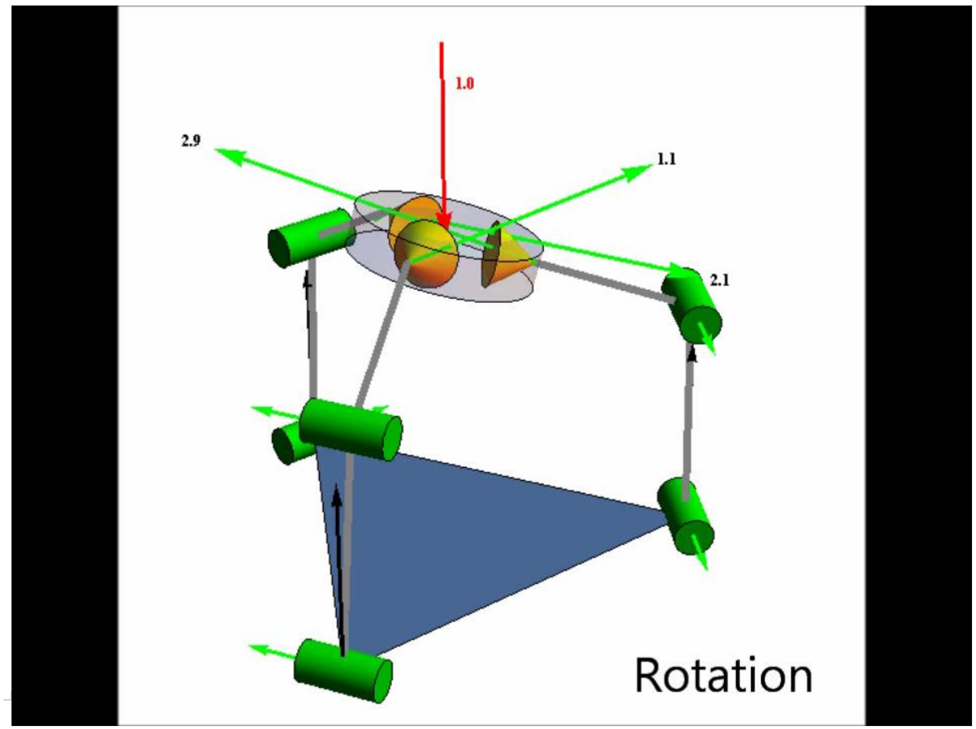






Dexterous Manipulation





DARPA ARM Program

- Three Hand teams (Hardware Track)
  - iRobot/Yale/Harvard
  - SRI/MEKA/Stanford
  - Sandia/Stanford
- Cut down after 2 years to 1 winner
- Supply hands for additional DARPA projects

Dr. Robert Kohout

Prof. Rob Howe

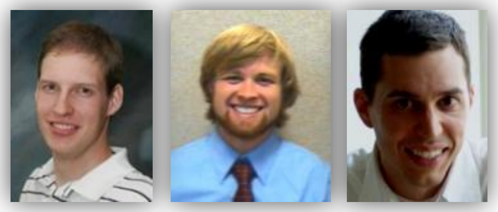
Prof. Aaron Dollar

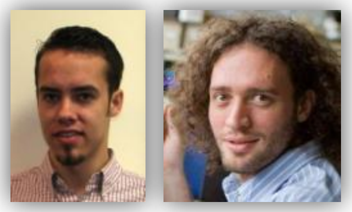
iRobot

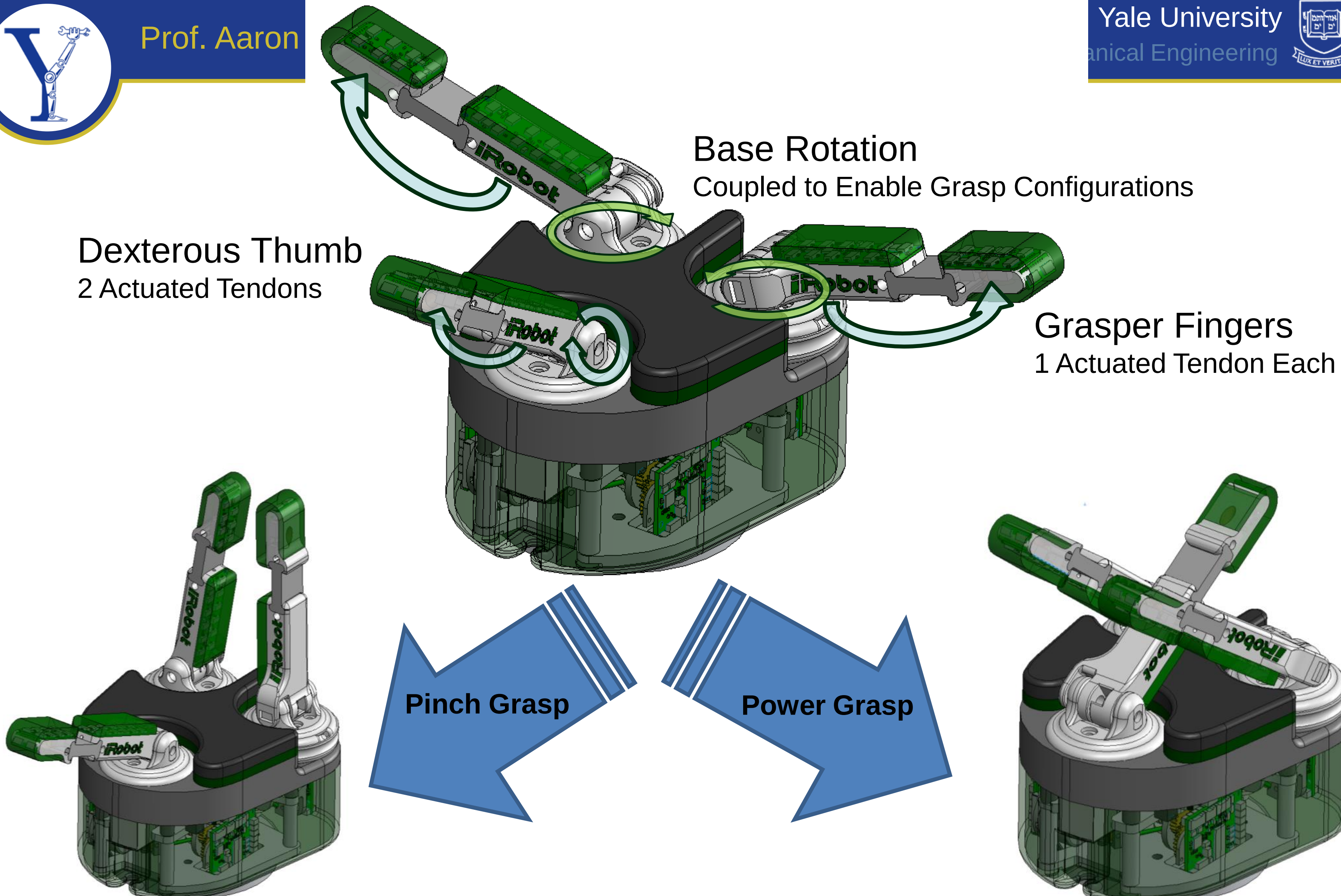
Mark Claffee
Nick Corson
Dr. Erik Steltz

Leif Jentoft
Dr. Yaroslav Tenzer

Dr. Lael Odhner
Raymond Ma

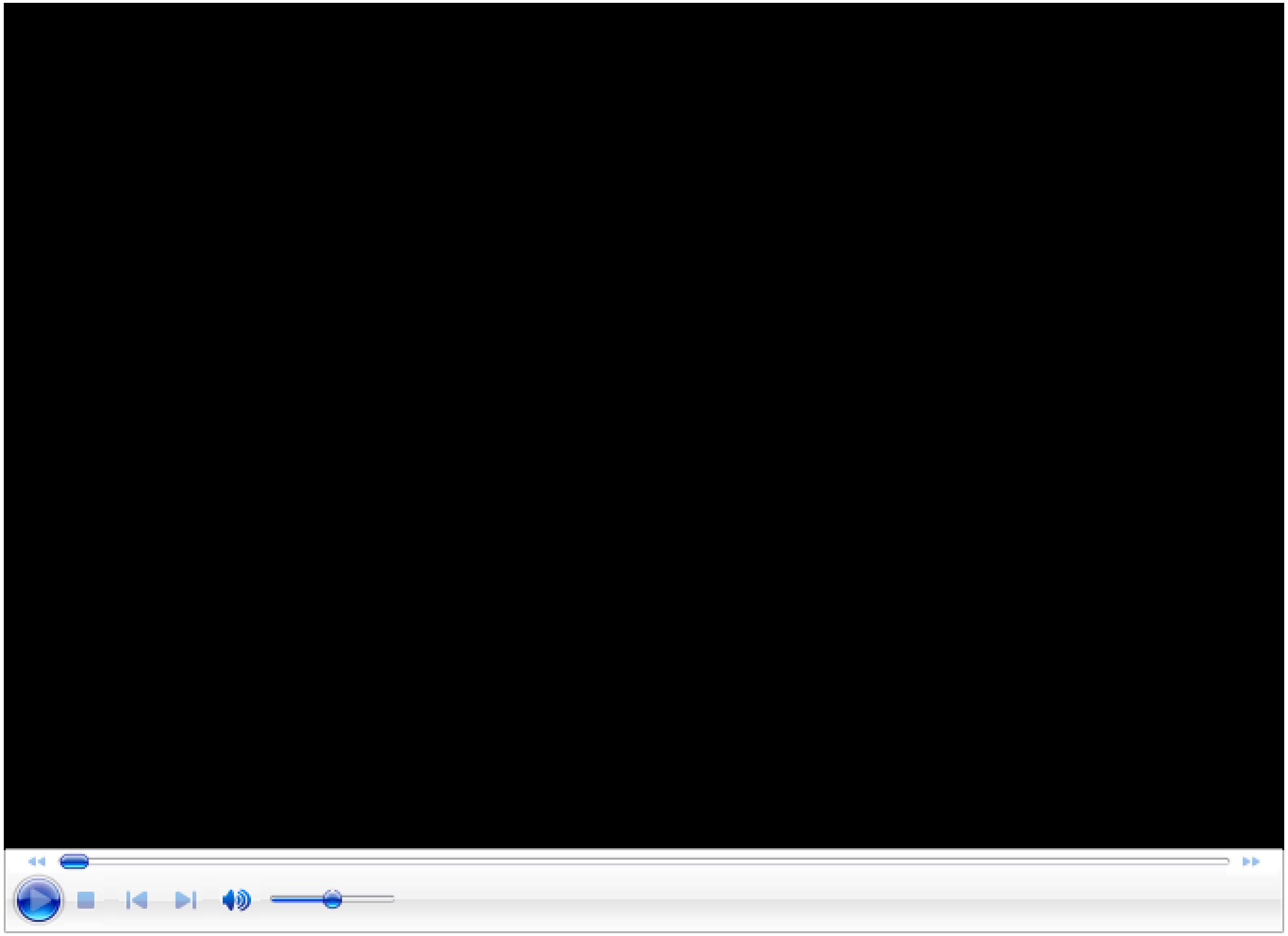






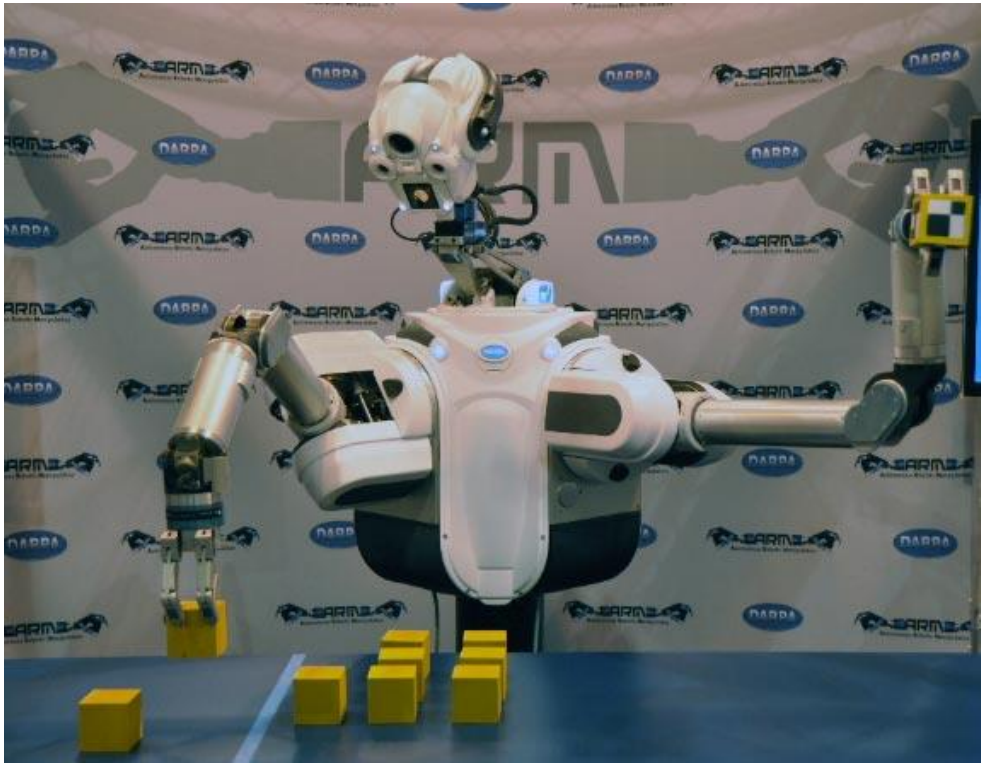
Grasper Fingers form Compliant Fingertip Grasp

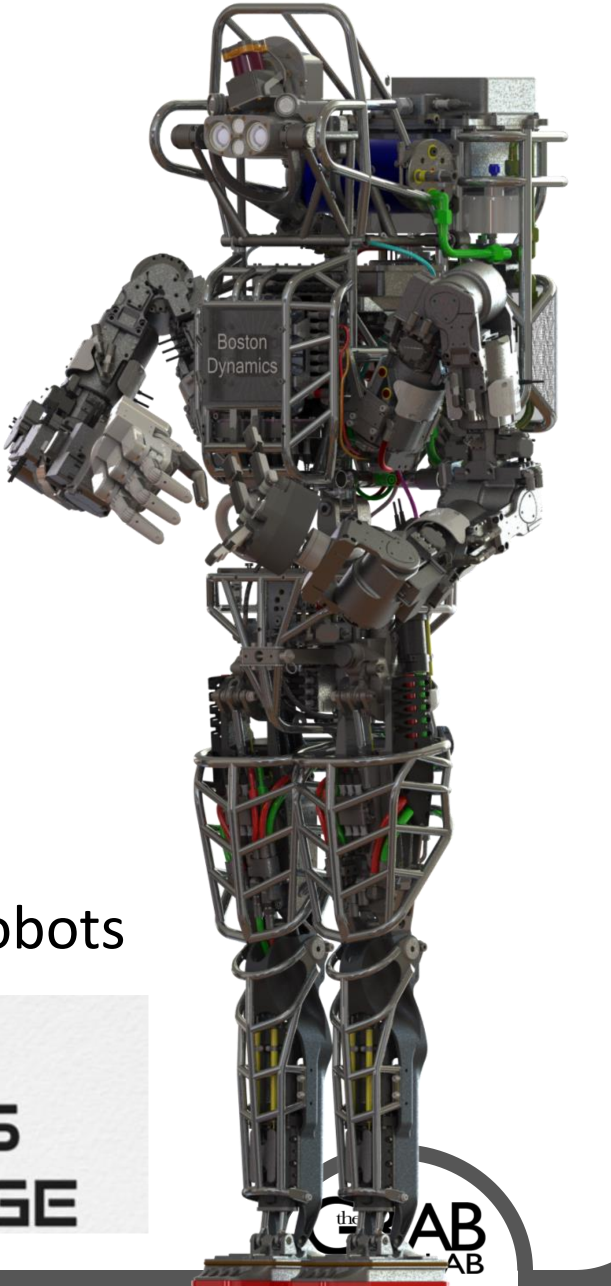
Fingers Interlace for Power Grasp



ARM
Autonomous Robotic Manipulation

the GRAB LAB

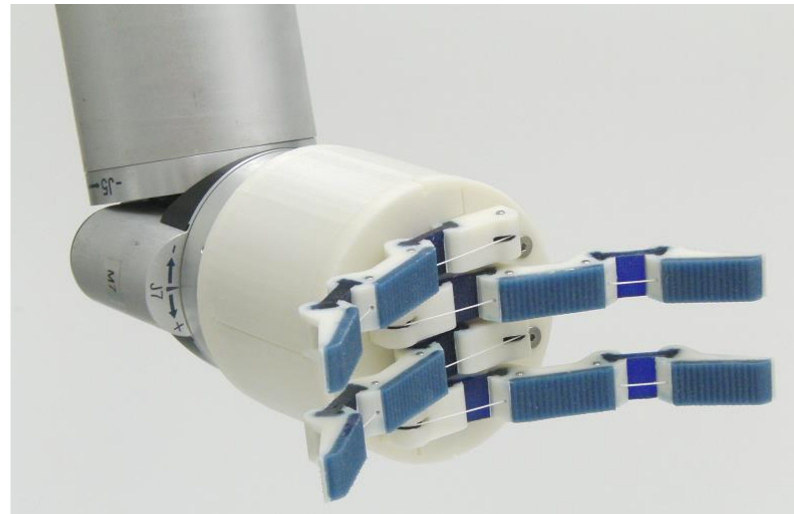




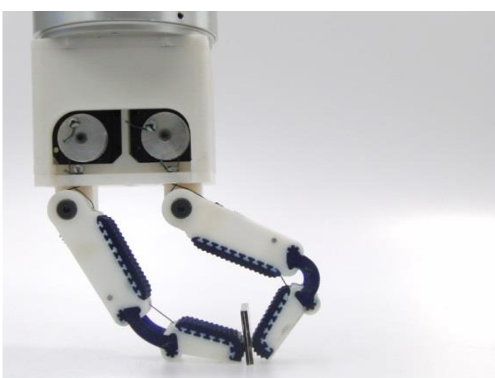
Those hands now on DARPA ARM-H/ DRC Robots

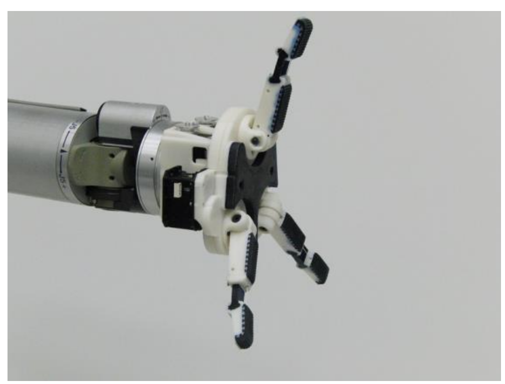
Yale OpenHand Project

All our experimental hand projects now use similar rapidly prototyped designs



Why not start releasing hands for free?

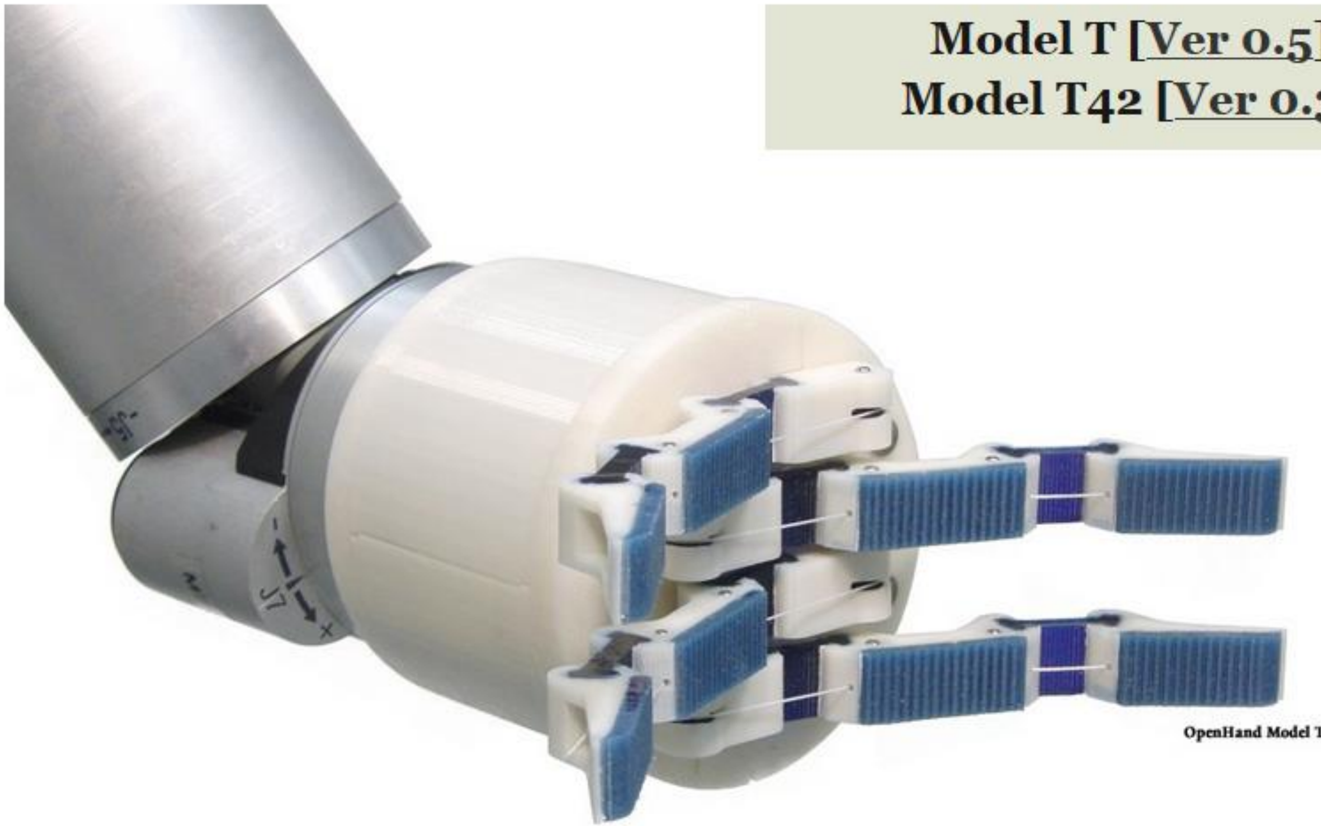




Yale OpenHand Project

About | Design | Hands | Contact

Model T [Ver 0.5]
Model T42 [Ver 0.3]

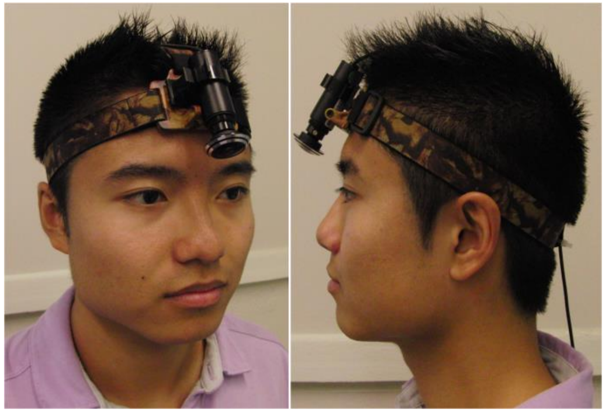


Adaptive - Robust - Open-Source

Human Grasping

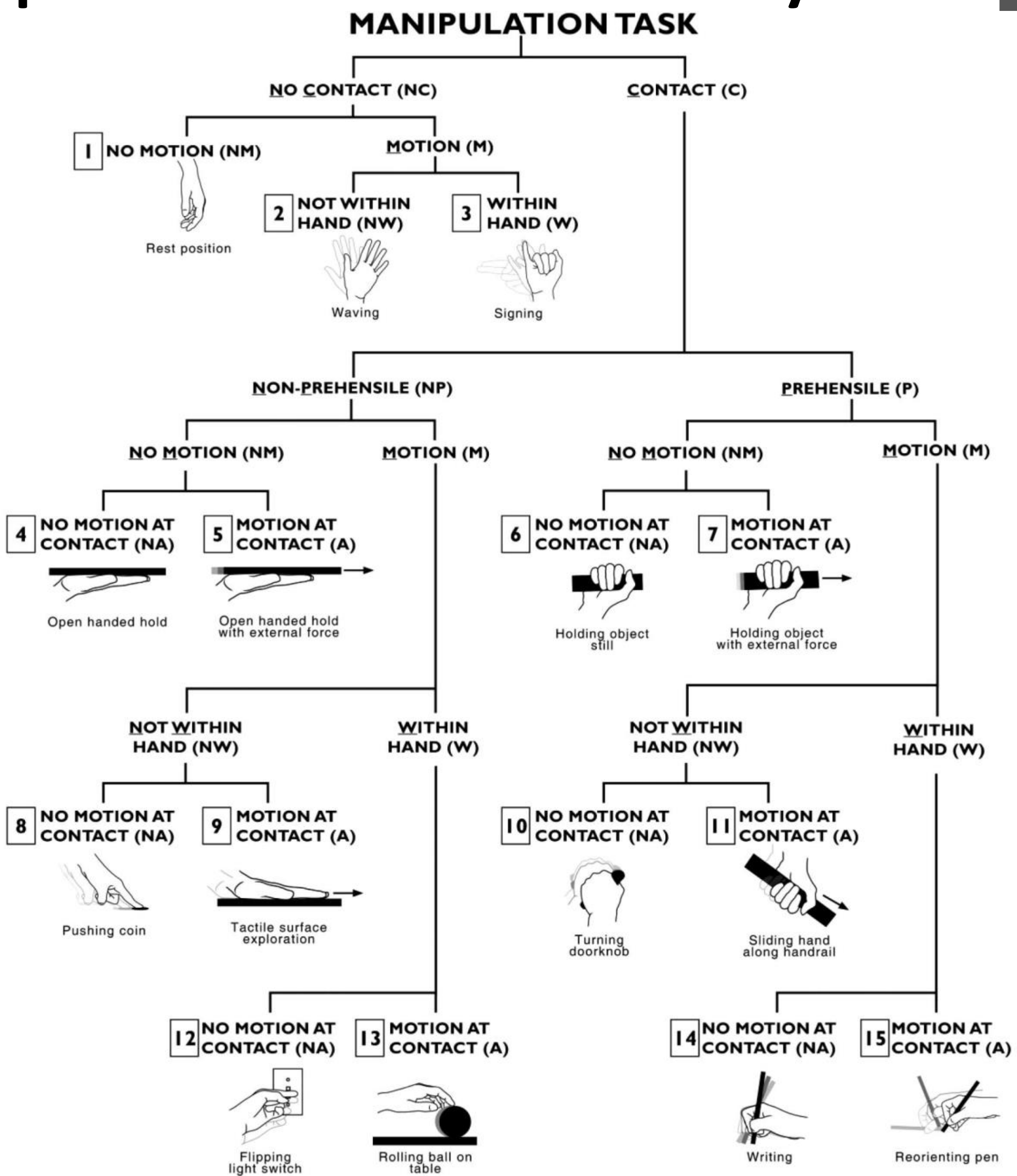
Human Grasp Use

- Head-mounted cameras on human subjects
- Investigated grasp frequency and object/task properties



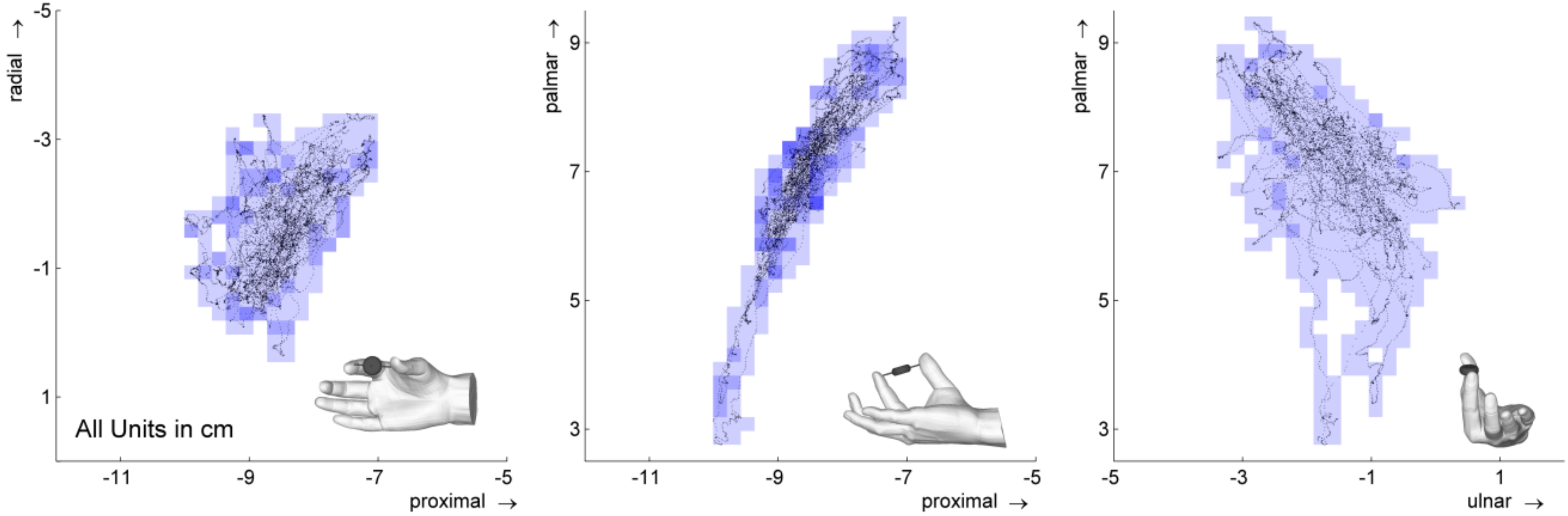
Dexterous Manipulation Taxonomy

- General-purpose, complete* taxonomy for classifying hand use



Human Precision Manipulation

- Measuring workspace of fingertip-based manipulation



RightHand Robotics

- We started a company!
  - Ok – mostly Leif Jentoft (Harvard), Yaro Tenzer (Harvard), and Lael Odhner (Yale)
  - “ReFlex Hand”
    - Version of ur DARPA ARM/DRC hand
  - www.righthandrobotics.com

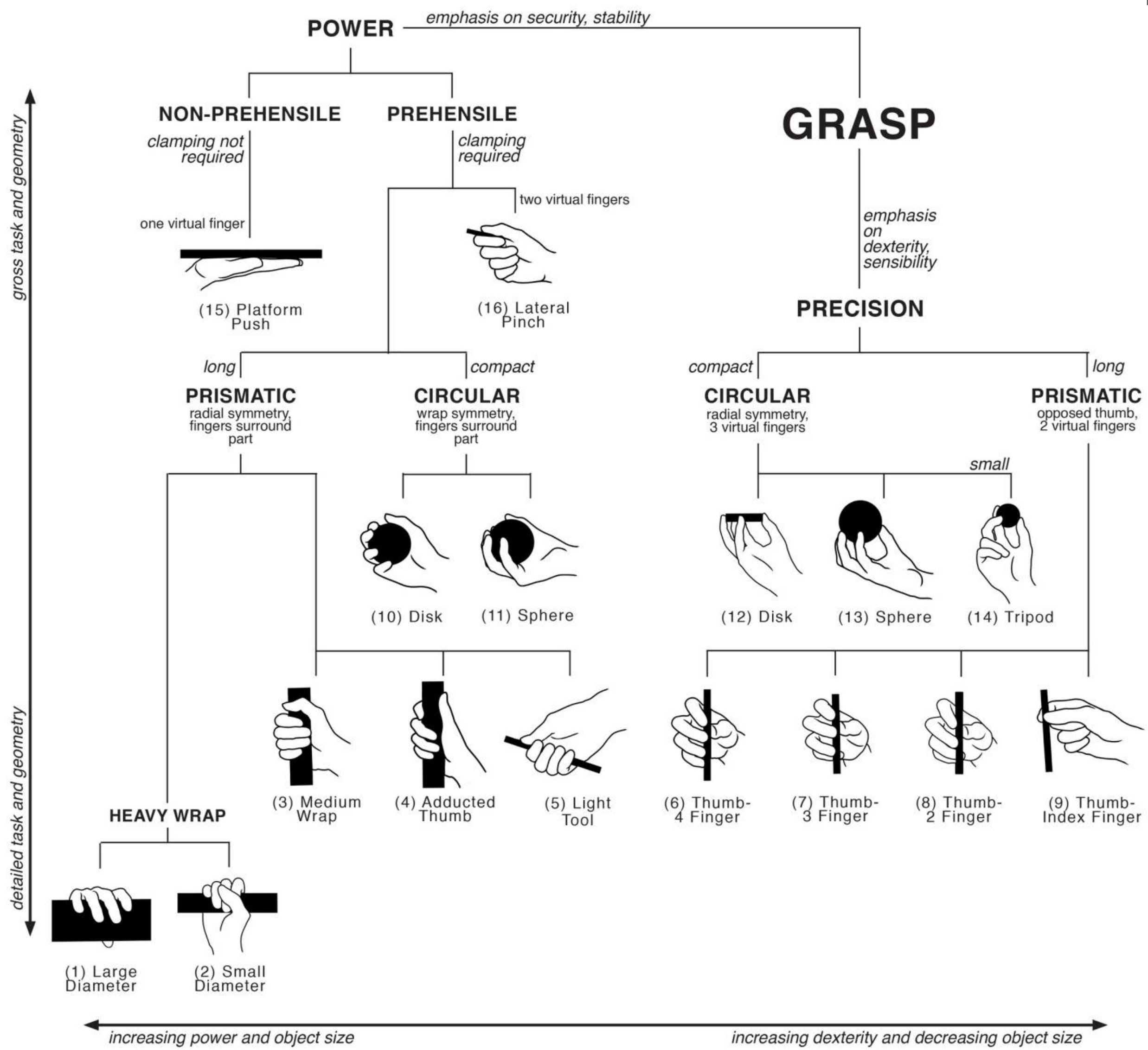
Acknowledgments

- Funding for the presented work
  - NSF CAREER
  - Office of Naval Research
  - DARPA (Advancing Robotic Manipulation)
- GRAB Lab Staff who did the work:
  - Lael Odhner, Raymond Ma, Julia Borras-Sol, Ian Bullock, Thomas Feix

Questions?

Motivation

- Not all grasps are created equally…



[Bullock et. Al, TOH 2013]

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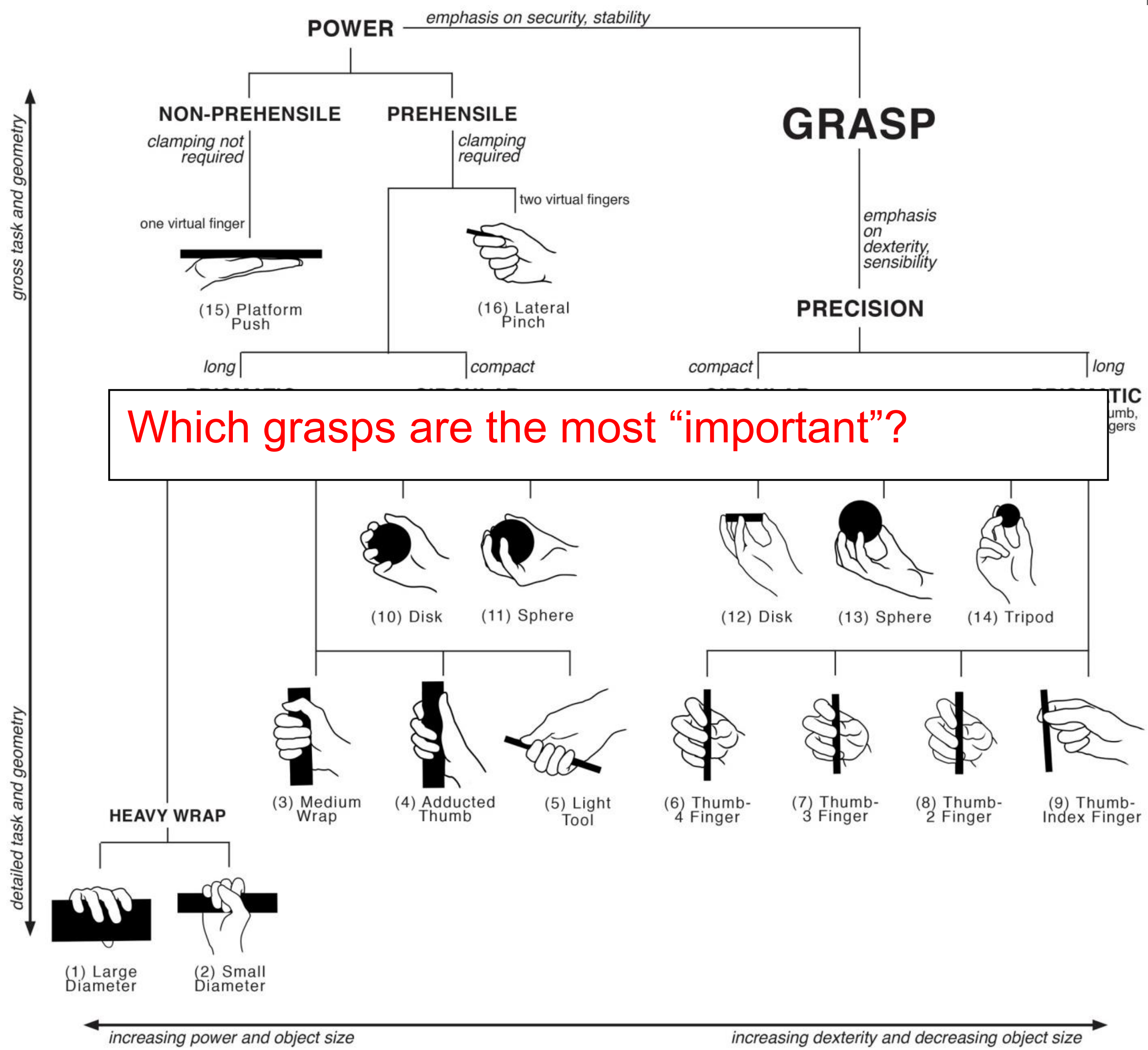
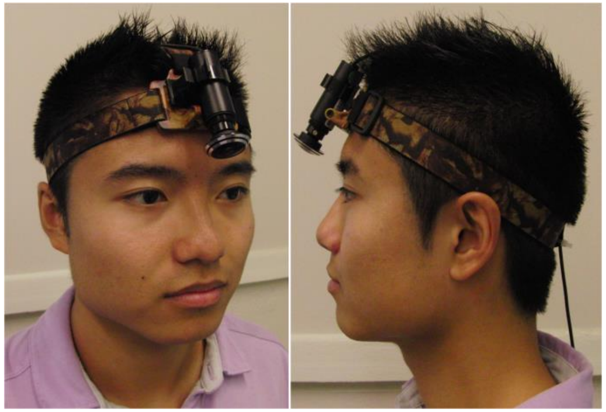


[Zheng and Dollar, ICRA 2011]

Protocol

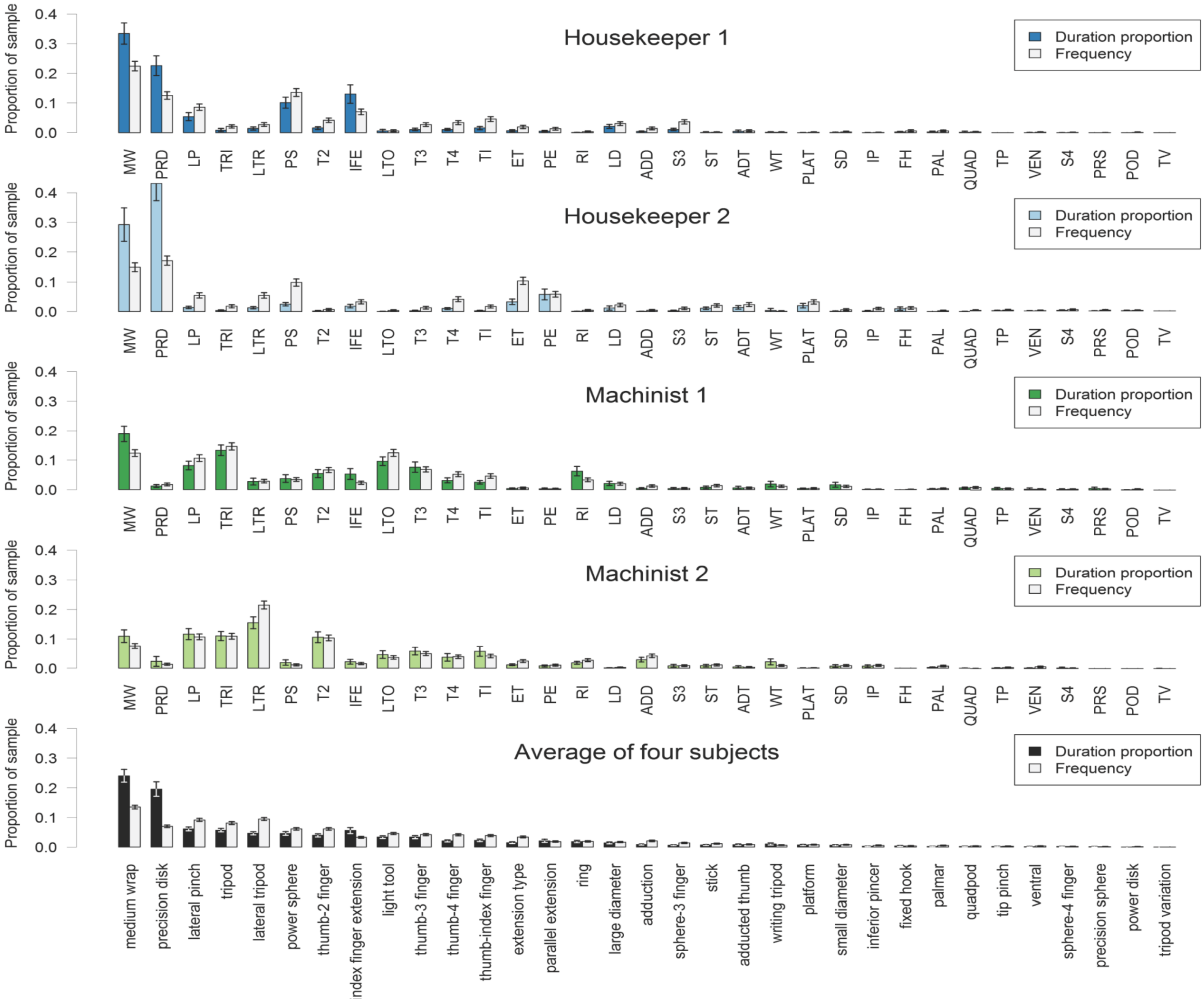
- Head-mounted camera w/wide angle lens



[Zheng and Dollar, ICRA 2011]

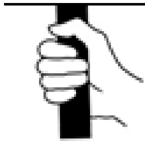
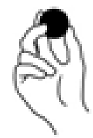
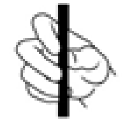
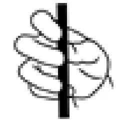
Protocol

- Tested professionals:
  - 2 Housekeepers
  - 2 Machinists
- 7.5 hours of video analyzed each
- Subjects performed common, non-repetitive tasks


Housekeeper 1
Housekeeper 2
Machinist 1
Machinist 2
Average of four subjects
Duration proportion
Frequency
Proportion of sample
0.0
0.1
0.2
0.3
0.4
MW PRD LP TRI LTR PS T2 IFE LTO T3 T4 TI ET PE RI LD ADD S3 ST ADT WT PLAT SD IP FH PAL QUAD TP VEN S4 PRS POD TV
medium wrap
precision disk
lateral pinch
tripod
lateral tripod
power sphere
thumb-2 finger
index finger extension
light tool
thumb-3 finger
thumb-4 finger
thumb-index finger
extension type
parallel extension
ring
large diameter
adduction
sphere-3 finger
stick
adducted thumb
writing tripod
platform
small diameter
inferior pincer
fixed hook
palmar
quadpod
tip pinch
ventral
sphere-4 finger
precision sphere
power disk
tripod variation

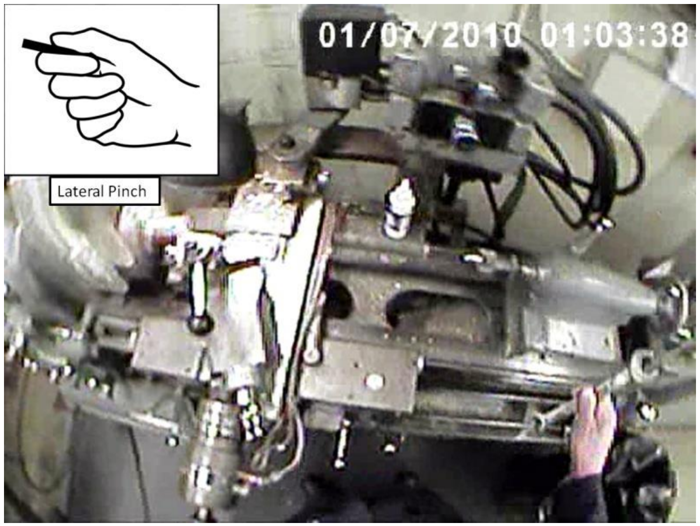
Top 10

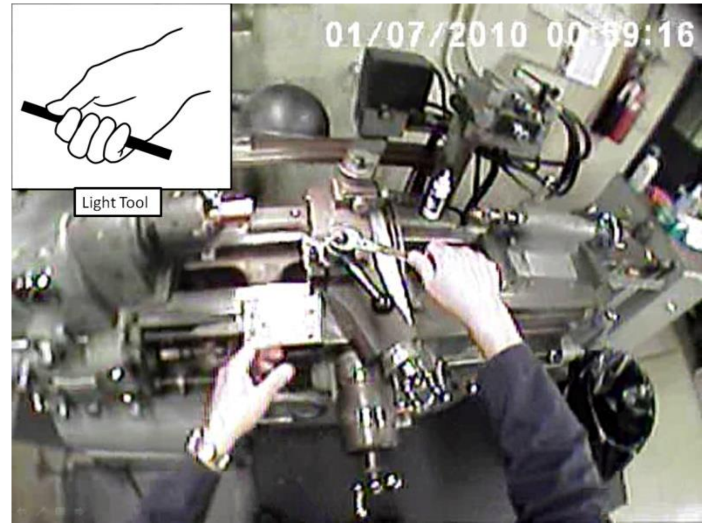
TOP 10 GRASPS WITH AVERAGES FOR THE FOUR SUBJECTS

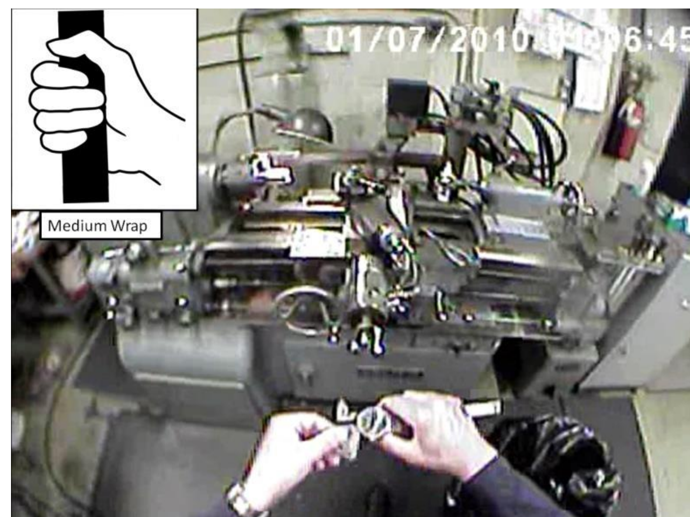
	Grasp	Duration Proportion	Frequency	Mean Duration Per Grasp
	medium wrap	23 ± 1%	14.0 ± 0.3%	12 s
	precision disk	17 ± 1%	8.2 ± 0.2%	19 s
	lateral pinch	6.7 ± 0.3%	8.9 ± 0.3%	4.5 s
	tripod	6.4 ± 0.3%	7.4 ± 0.3%	4.8 s
	lateral tripod	5.3 ± 0.3%	8.2 ± 0.3%	3.3 s
	power sphere	4.6 ± 0.3%	7.0 ± 0.2%	5.1 s
	thumb-2 finger	4.5 ± 0.3%	5.5 ± 0.2%	4.3 s
	index finger extension	5.6 ± 0.5%	3.6 ± 0.2%	11 s
	light tool	3.7 ± 0.2%	4.3 ± 0.2%	5.0 s
	thumb-3 finger	3.7 ± 0.3%	4.0 ± 0.2%	5.4 s

Examples: Housekeeper

Examples: Machinist

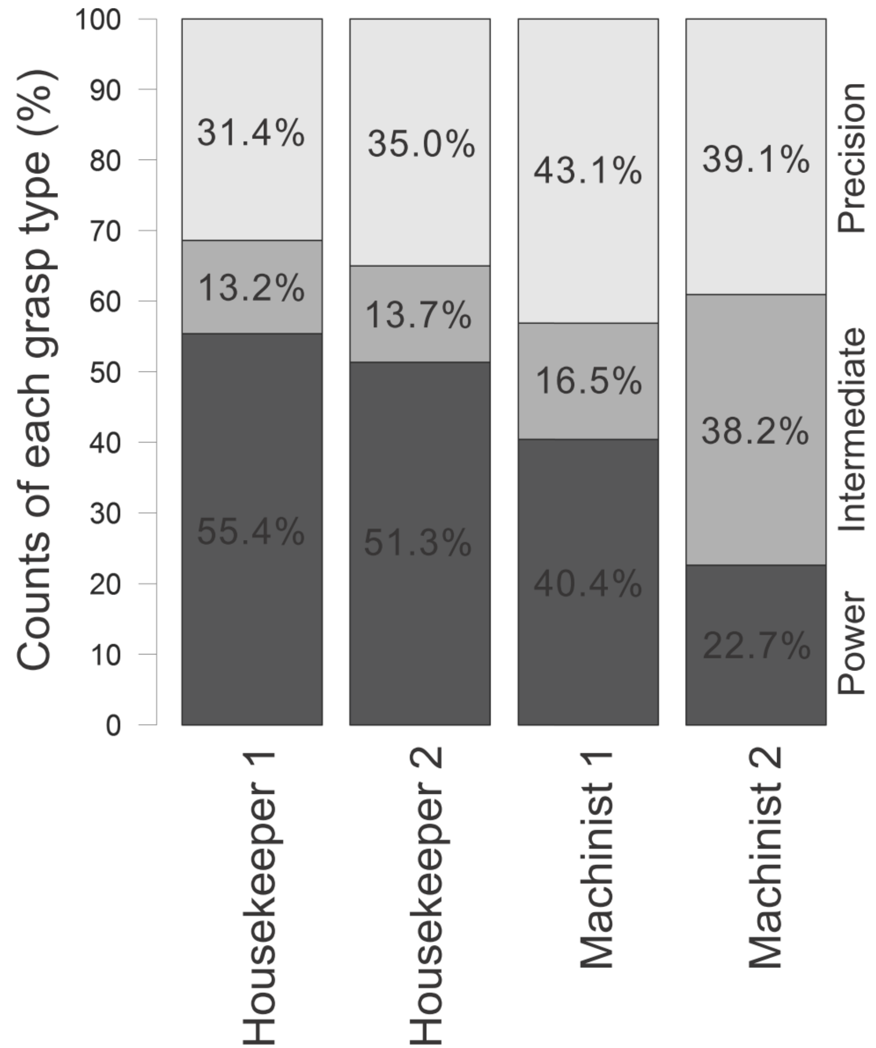




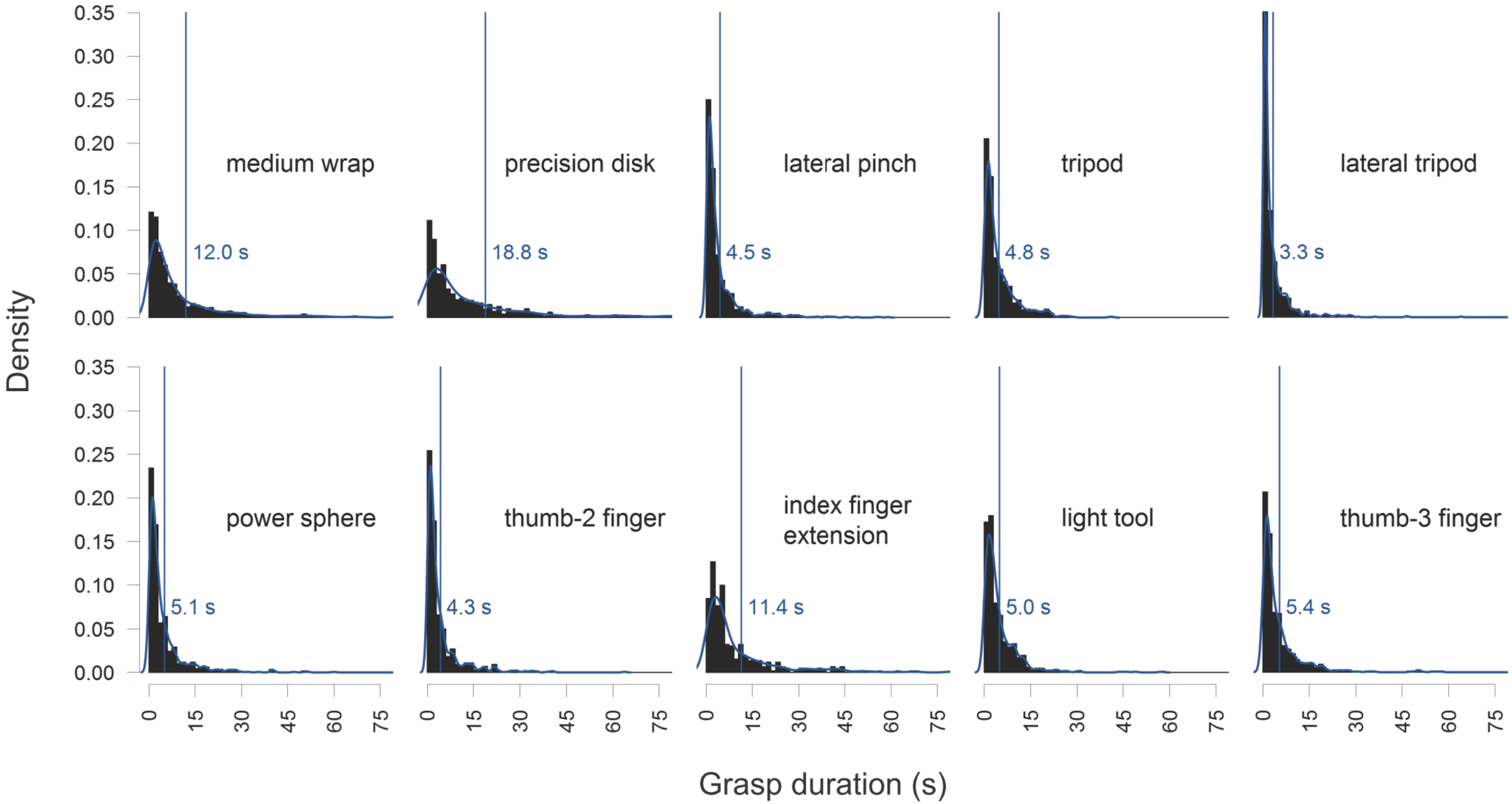


Results

- Grasp Class results



Results


Density
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
medium wrap
12.0 s
precision disk
18.8 s
lateral pinch
4.5 s
tripod
4.8 s
lateral tripod
3.3 s
power sphere
5.1 s
thumb-2 finger
4.3 s
index finger extension
11.4 s
light tool
5.0 s
thumb-3 finger
5.4 s
0
15
30
45
60
75
Grasp duration (s)