



# Robotics

Miao Li

Fall 2023, Wuhan University

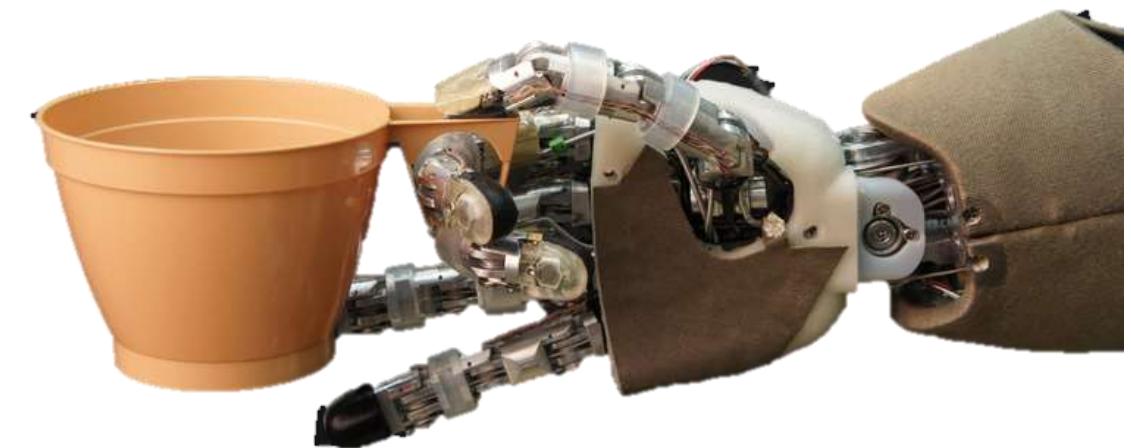
WeChat: [15527576906](#)

Email: [limiao712@gmail.com](mailto:limiao712@gmail.com)



# Today

- Design and Modelling of typical robotic arm/hand
- DH parameters
- Kinematics, IK, Jacobian
- Soft hand
- Grasp planning
- Simulation tool introduction
- Group list





# Why robotic hand and grasping?



Grasping and manipulation is an essential skill for humans



# Why robotic hand and grasping?



Understanding  
human behavior

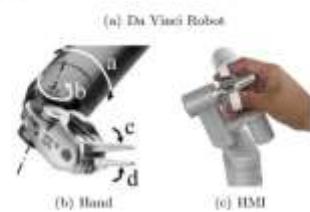


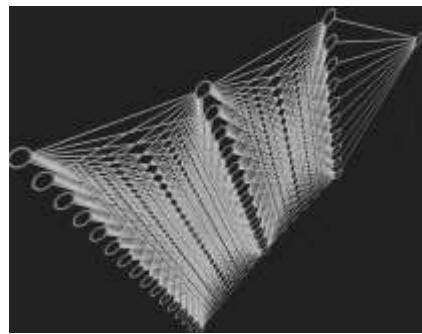
“..... If there is something that is so natural for humans or animals to do well, but it is so hard for us to control such an engineer system, that most likely means this is the **correct challenge** that deserves our investigation.....”

----- Russ Tedrake

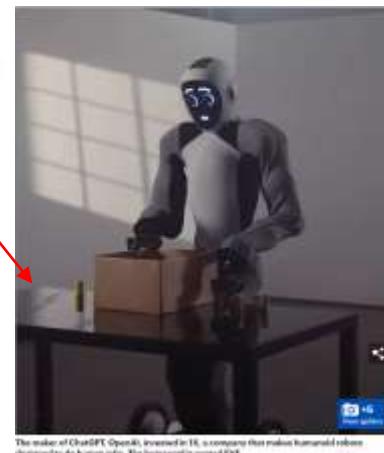


# Why robotic hand and grasping?





# Why hand?



The maker of ChatGPT, OpenAI, invested in EX, a company that makes humanoid robots designed to do human jobs. The humanoid is named EXI.



# Why hand?

• Safety First.



1X tests every EVE in real-world scenarios before they're deployed and ensures that every operator is trained to work with them. EVE's soft, organically-inspired mechanics make them safer from the inside out, so they're ready for your workplace.

• Balanced Performance.



EVE moves like us, so they can meet your needs. 1X engineers EVE for high precision and gentle strength, with wheels and gripper hands, so they can open your doors, take your elevators, and fit into your work in a natural, intuitive way.

• Smart Behavior.

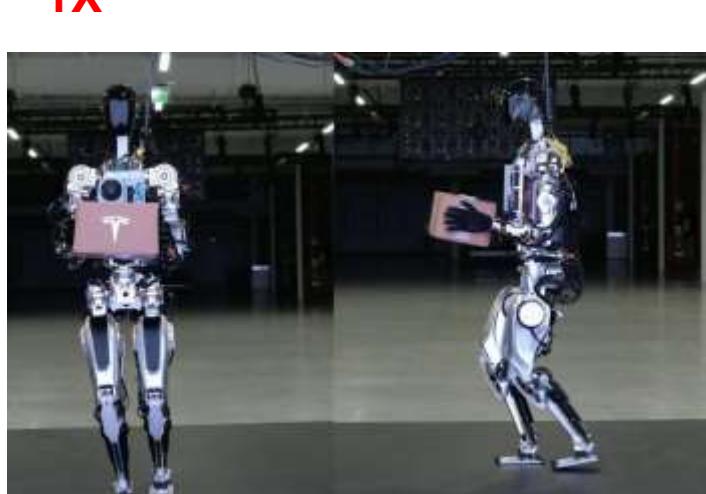


Androids embody artificial intelligence. 1X combines thoughtfully-designed bodies with advanced AI minds, so they can move throughout your space and you can control them from a distance.

**1X**



**Boston Dynamics**



**Tesla Bot**



**Sanctuary**

[https://www.youtube.com/watch?v=YHk7Cztk6Lg&ab\\_channel=SanctuaryAI](https://www.youtube.com/watch?v=YHk7Cztk6Lg&ab_channel=SanctuaryAI)



# Why hand?

RODNEY BROOKS

*Robots, AI, and other stuff*

BLOG MIT ROBUST.AI



POST: RESEARCH NEEDED ON ROBOT HANDS

JANUARY 30, 2017 — QUICK TAKES

Research Needed on Robot Hands

[rodneybrooks.com/research-needed-on-robot-hands/](https://rodneybrooks.com/research-needed-on-robot-hands/)

*This is a short piece I wrote for a workshop on what are good things to work on in robotics research.*

One measure of success of robots is how many of them get deployed doing real work in the real world. One way to get more robots deployed is to reduce the friction that comes up during typical deployments. For intelligent robots in factories there are many sources of friction, some sociological, some financial, some concerning takt time, some concerning PLCs and other automation, **but perhaps the most friction that can be attributed to a lack of relevant research results is the problem of getting a gripper suitable for a particular task.**

Today in factories the most commonly used grippers are either a set of custom configured suction cups to pick up a very particular object, or one of a myriad of parallel jaw grippers varying over a large number of parameters, and custom fingers, again carefully selected for a particular object. In both cases just one grasp is used for that particular object. Getting the right gripper for initial deployment can be a weeks long source of friction, and then changing the gripper when new objects are to be handled is another source of friction. Furthermore, grip failure can be a major source of run time errors.

Human hands just work. Give them an object from a very wide class of objects and they grip that object, usually with a wide variety of possible grips. They sense when the grip is failing and adjust. They work reliably and quickly.

Search ...

## RECENT POSTS

What Will Transformers Transform?

Predictions Scorecard, 2023 January 01

Where are the crewed eVTOL videos?

My IEEE Spectrum Columns and Articles

No front seat occupants; adventures in autonomous ride services

## CATEGORIES

Dated Predictions

Essays

Quick Takes



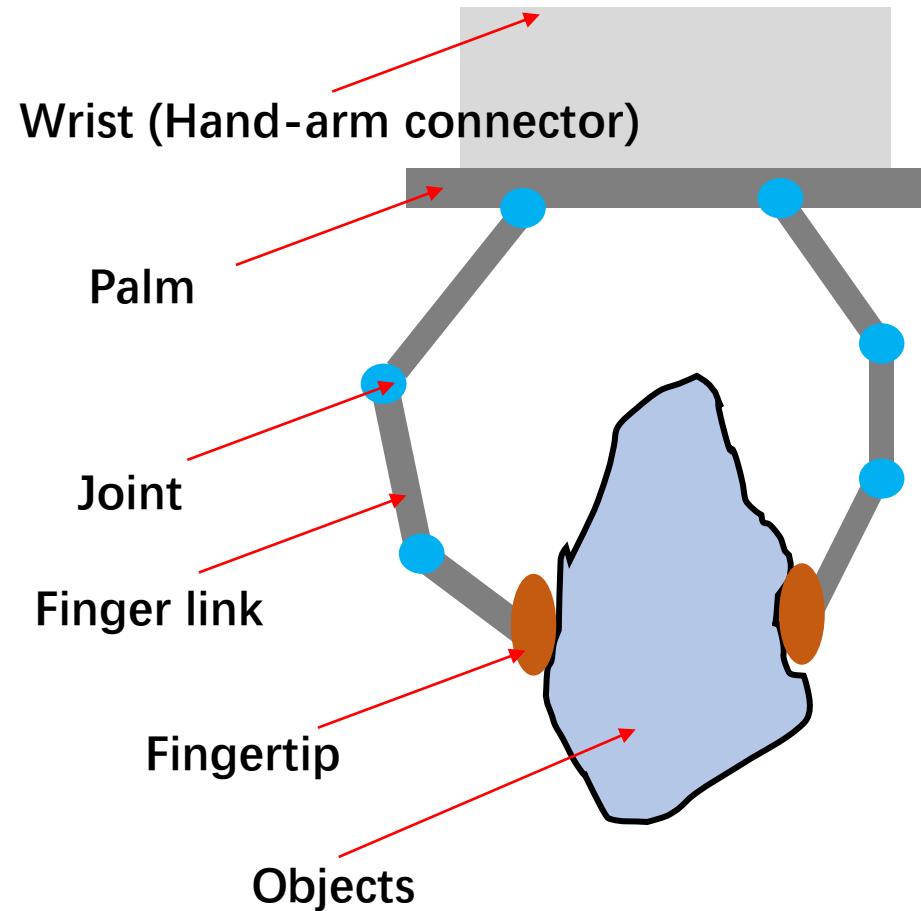
My strawman is that we will need concurrent progress in at least five areas, each feeding off the other, in order to come up with truly useful and general robot hands:

- ✓ new (low cost) mechanisms for both kinematics and force control
- ✓ materials to act as a skin (grasp properties and longevity)
- ✗ long life sensors that can be embedded in the skin and mechanism
- ✗ algorithms to dynamically adjust grasps based on sensing
- ✓ learning mechanisms on visual/3D data to inform hands for pregrasp

<https://rodneybrooks.com/research-needed-on-robot-hands/>



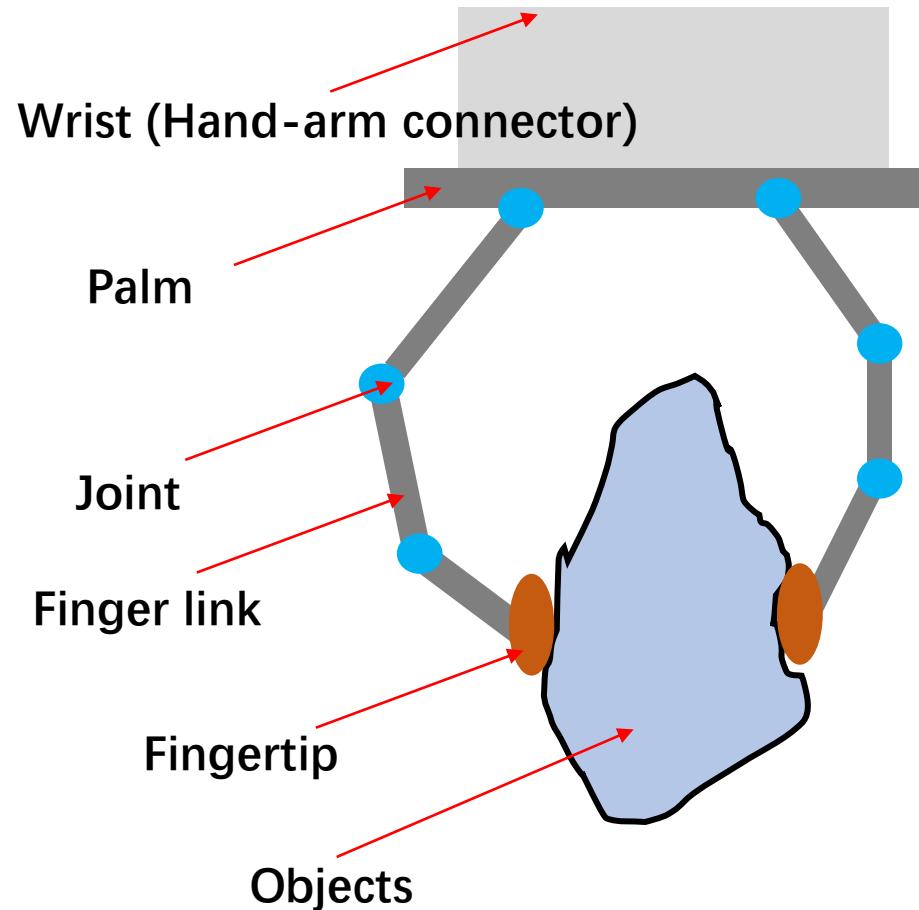
# A robotic grasping system



How to design, model, and control a robotic hand?



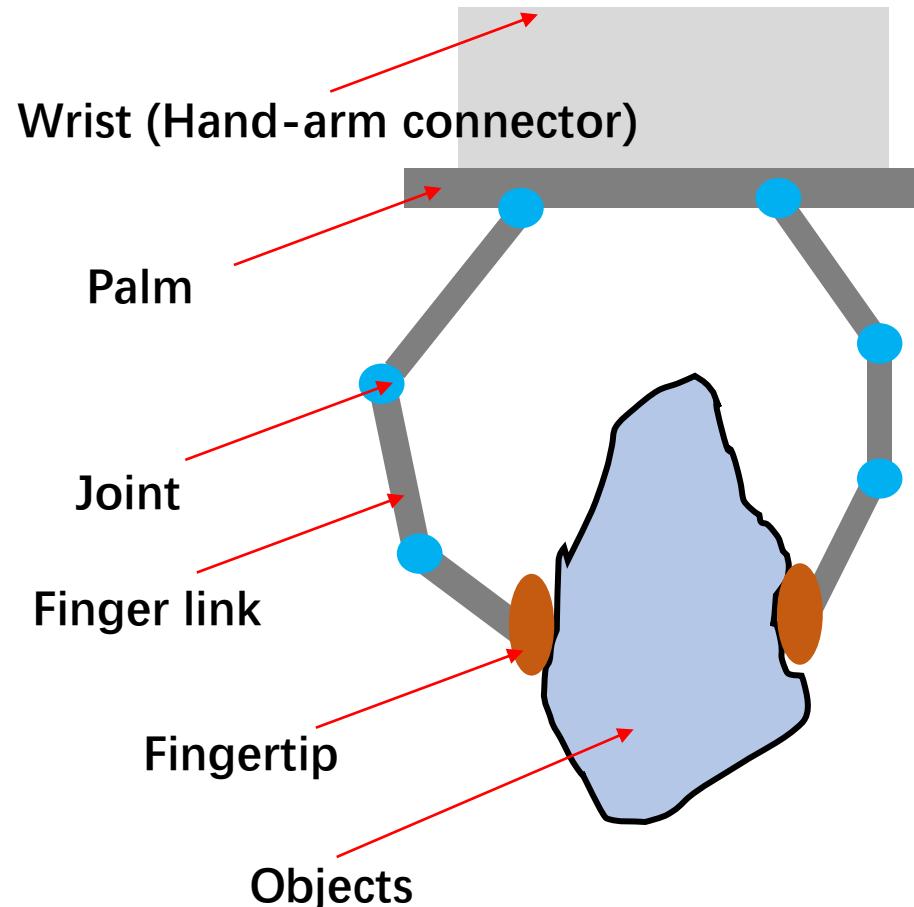
# A robotic grasping system



- How to design the hardware including the palm, finger link, finger joint and fingertip?
- How to integrate a proper sensor for a hand, especially a tactile sensor?
- How to choose the configuration of the fingers, including the degree of freedoms for each finger?
- How to model the kinematics of the finger and the hand?
- How to model the contact between the fingertips and the object?
- How to plan a suitable/optimal grasp for different objects?
- How to control the hand for a given task ?
- How to dexterously manipulate an object?



# A robotic grasping system



Journals & Magazines > IEEE Robotics & Automation Ma... > Volume: 28 Issue: 2 ⓘ

## A Novel Soft Robotic Hand Design With Human-Inspired Soft Palm: Achieving a Great Diversity of Grasps

Publisher: IEEE

Cite This

PDF

nature communications

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nature > nature communications > articles > article

Article | Open Access | Published: 14 December 2021

## Integrated linkage-driven dexterous anthropomorphic robotic hand

Uikyum Kim✉, Dawoon Jung, Heeyeon Jeong, Jongwoo Park, Hyun-Mok Jung, Joono Cheong, Hyouk Ryeol Choi, Hyunmin Do & Chanhun Park

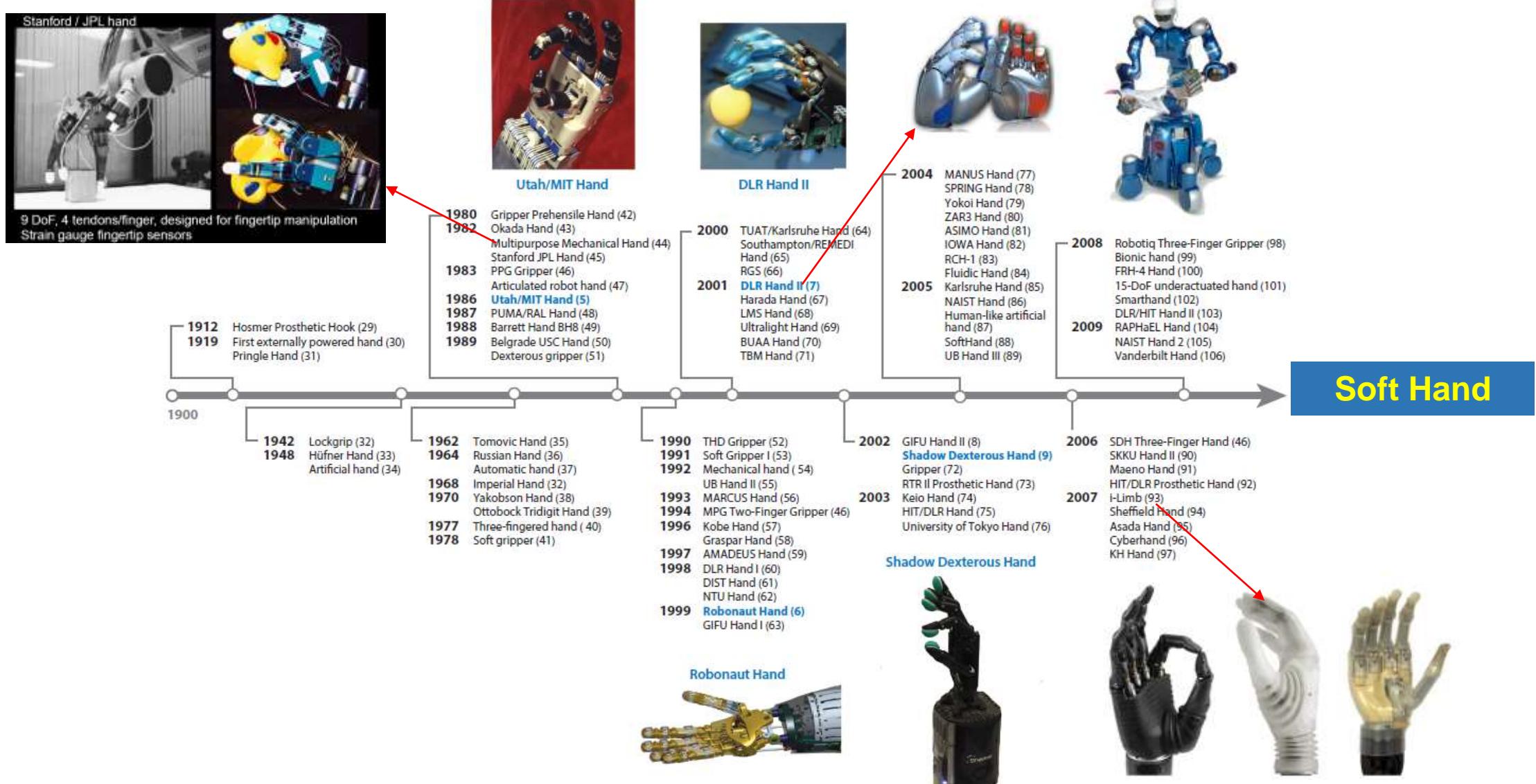
*Nature Communications* 12, Article number: 7177 (2021) [this article](#)

28k Accesses | 34 Citations | 289 Altmetric | Metrics

Still a hot topic in robotics

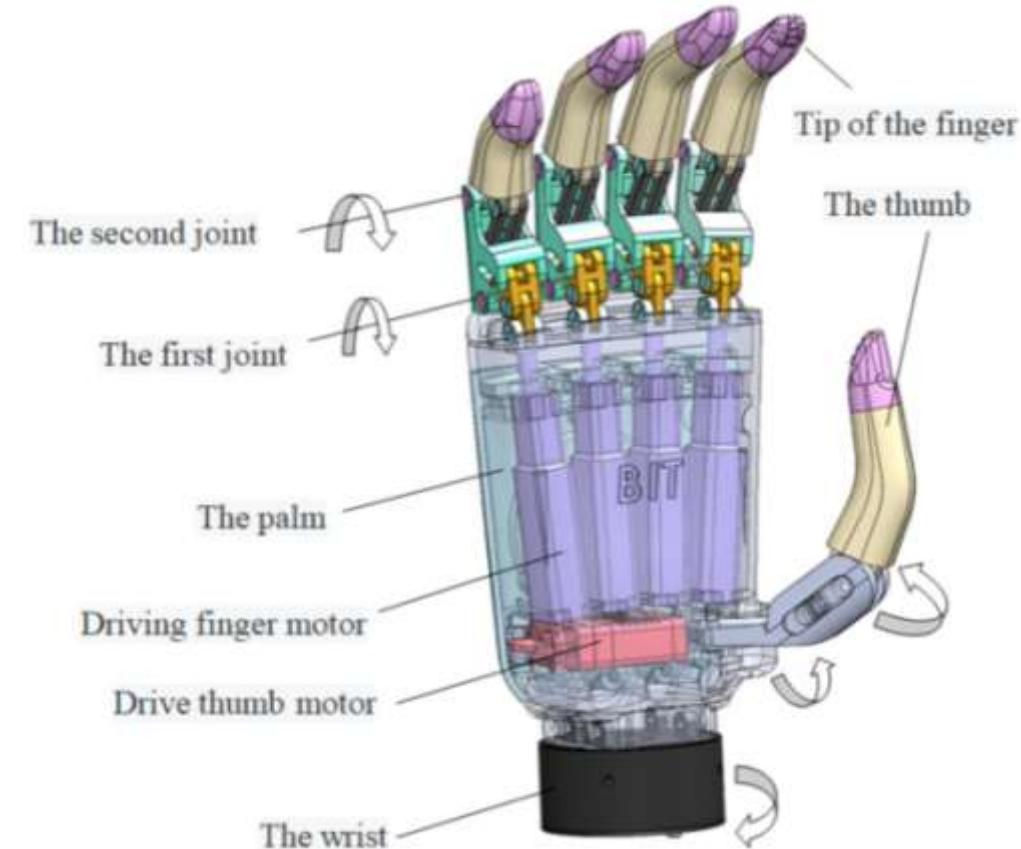
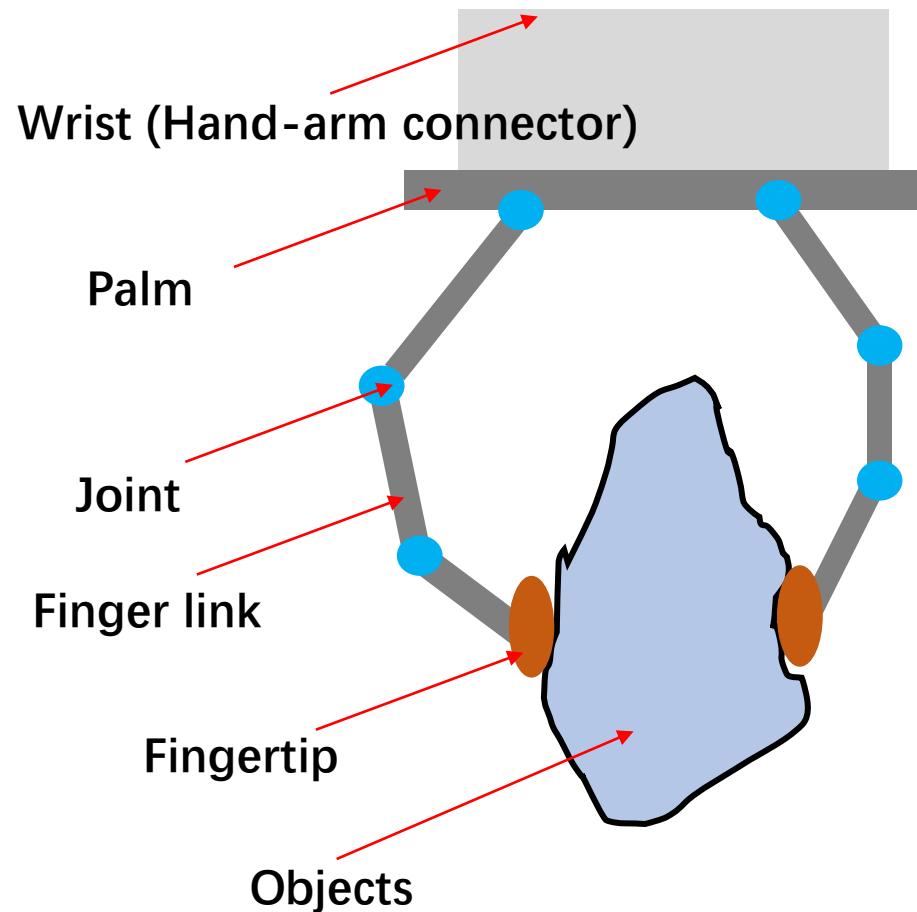


# A robotic grasping system



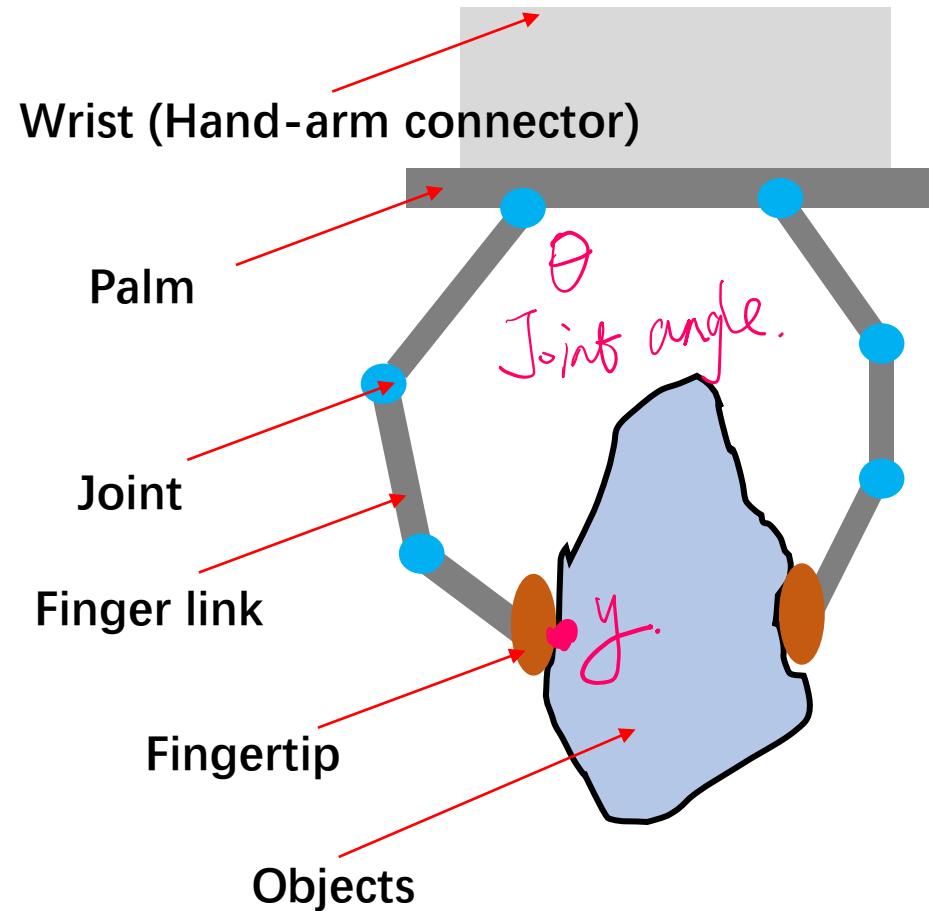


# A robotic grasping system





# Hand Kinematics



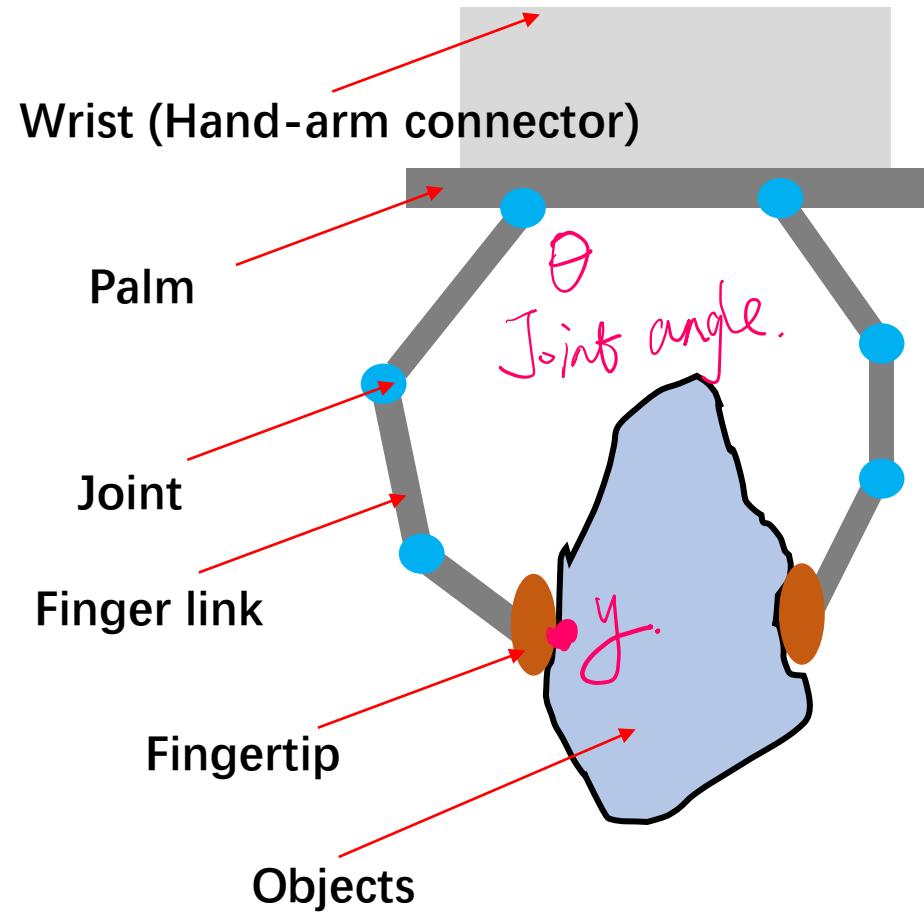
$$y = f(\theta)$$

↓                    ↓

pos of fingertip      Joint Angle.



# Hand Kinematics



$y = f(\theta)$

↓      ↓

pos of fingertip      Joint Angle.

★ How to get this mapping?

We need a coordinate frame!



# Hand Kinematics

We are interested in **two kinematics topics**

## Forward Kinematics (angles to position)

What you are given:

- The length of each link
- The angle of each joint

What you can find:

- The position of any point  
(i.e. it's  $(x, y, z)$  coordinates)

## Inverse Kinematics (position to angles)

What you are given:

- The length of each link
- The position of some point on the robot

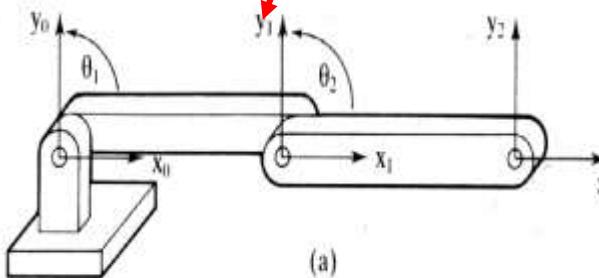
What you can find:

- The angles of each joint needed to obtain that position

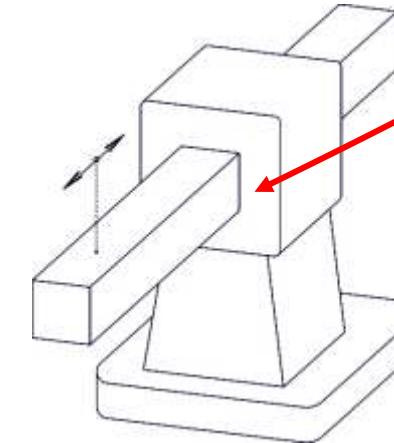


# Hand Kinematics- Joints

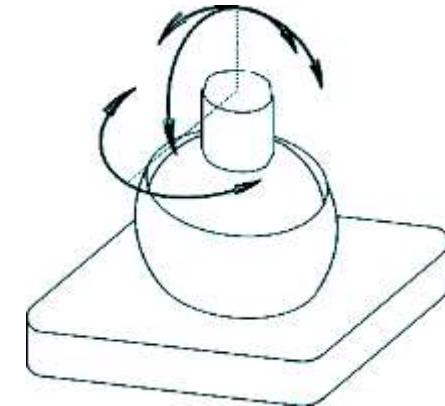
$$q_i = \begin{cases} \theta_i & : \text{joint } i \text{ revolute} \\ d_i & : \text{joint } i \text{ prismatic} \end{cases}$$



Revolute Joint  
1 DOF



Prismatic Joint  
1 DOF (linear)

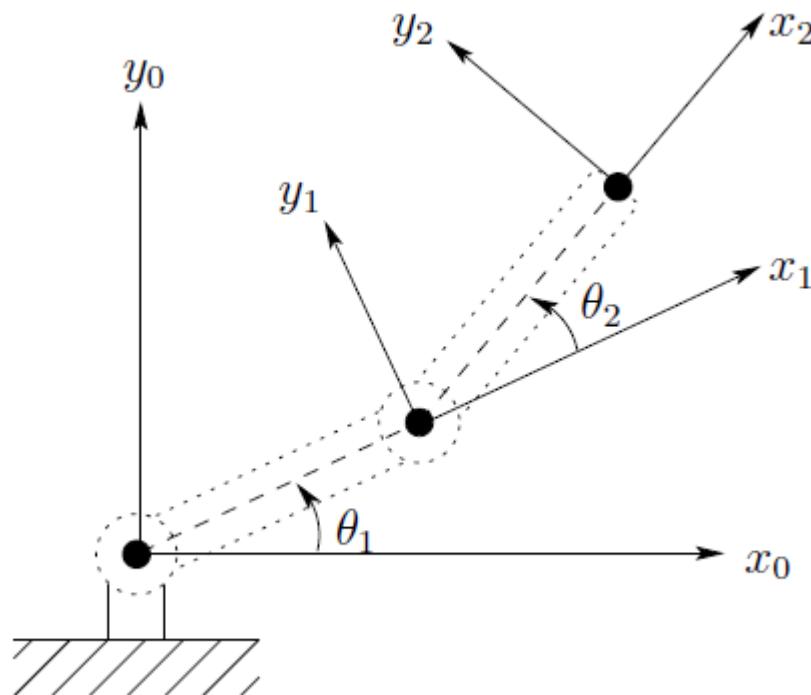


Spherical Joint  
3 DOF





# Hand Kinematics- An 2D example



Position

$$\begin{aligned}x &= x_2 = \alpha_1 \cos \theta_1 + \alpha_2 \cos(\theta_1 + \theta_2) \\y &= y_2 = \alpha_1 \sin \theta_1 + \alpha_2 \sin(\theta_1 + \theta_2),\end{aligned}$$

Orientation Matrix

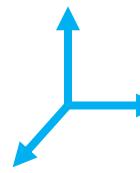
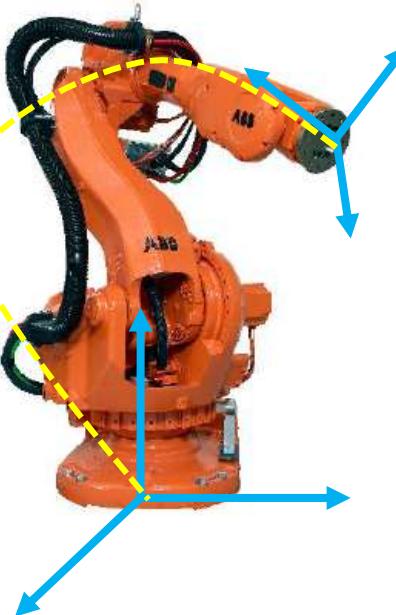
$$\begin{aligned}x_2 \cdot x_0 &= \cos(\theta_1 + \theta_2); & x_2 \cdot y_0 &= \sin(\theta_1 + \theta_2) \\y_2 \cdot x_0 &= \sin(\theta_1 + \theta_2); & y_2 \cdot y_0 &= \sin(\theta_1 + \theta_2)\end{aligned}$$



$$\begin{bmatrix} x_2 \cdot x_0 & y_2 \cdot x_0 \\ x_2 \cdot y_0 & y_2 \cdot y_0 \end{bmatrix} = \begin{bmatrix} \cos(\theta_1 + \theta_2) & -\sin(\theta_1 + \theta_2) \\ \sin(\theta_1 + \theta_2) & \cos(\theta_1 + \theta_2) \end{bmatrix}$$



# Hand Kinematics- FK



$$H = \begin{bmatrix} R & d \\ 0 & 1 \end{bmatrix}; R \in SO(3).$$

$q_i = \begin{cases} \theta_i & : \text{joint } i \text{ revolute} \\ d_i & : \text{joint } i \text{ prismatic} \end{cases}$

$$A_i = A_i(q_i) \rightarrow o_i x_i y_i z_i \text{ with respect to } o_{i-1} x_{i-1} y_{i-1} z_{i-1}$$

$$T_j^i = A_{i+1} A_{i+2} \dots A_{j-1} A_j \text{ if } i < j$$

$$T_j^i = I \text{ if } i = j \quad o_j x_j y_j z_j \text{ with respect to } o_i x_i y_i z_i$$

$$T_j^i = (T_i^j)^{-1} \text{ if } j > i.$$



$$H = \begin{bmatrix} R_n^0 & o_n^0 \\ 0 & 1 \end{bmatrix}$$

$$H = T_n^0 = A_1(q_1) \cdots A_n(q_n)$$

$$A_i = \begin{bmatrix} R_i^{i-1} & o_i^{i-1} \\ 0 & 1 \end{bmatrix}$$

All about FK ?



# Hand Kinematics

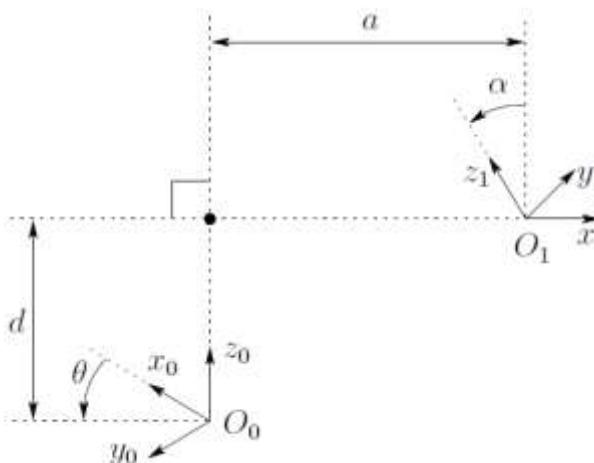
## DH Parameters

$$A_i = \begin{bmatrix} R_i^{i-1} & o_i^{i-1} \\ 0 & 1 \end{bmatrix}$$

?

How many parameters?

~~6~~  
4



(DH1) The axis  $x_1$  is perpendicular to the axis  $z_0$

(DH2) The axis  $x_1$  intersects the axis  $z_0$

1. Denavit, Jacques; Hartenberg, Richard Scheunemann (1955). "A kinematic notation for lower-pair mechanisms based on matrices". *Trans ASME J. Appl. Mech.* **23**: 215–221.
2. Hartenberg, Richard Scheunemann; Denavit, Jacques (1965). *Kinematic synthesis of linkages*. McGraw-Hill series in mechanical engineering. New York: McGraw-Hill. p. 435. [Archived from the original on 2013-09-28](#). Retrieved 2012-01-13.



# Hand Kinematics- FK

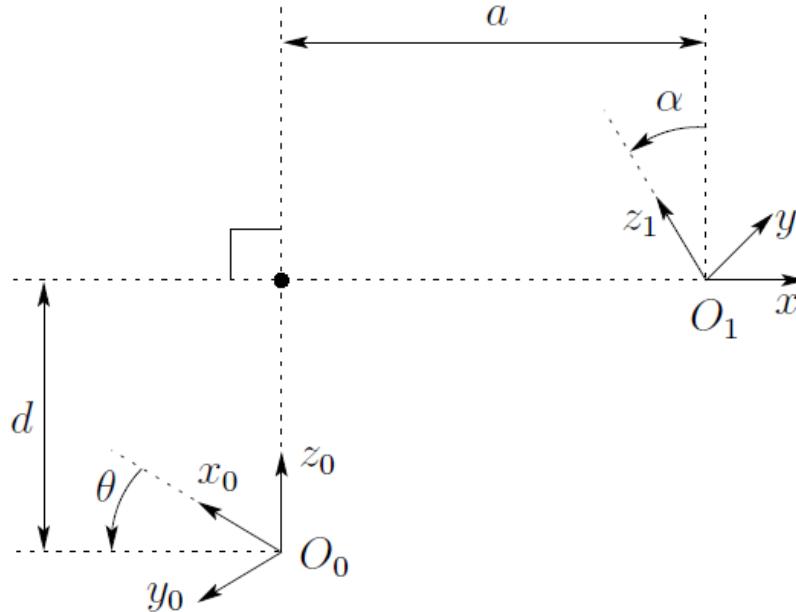


Exist only 4 params (Spong 1989)

(DH1) The axis  $x_1$  is perpendicular to the axis  $z_0$

(DH2) The axis  $x_1$  intersects the axis  $z_0$

$$A = Rot_{z,\theta} Trans_{z,d} Trans_{x,a} Rot_{x,\alpha}$$

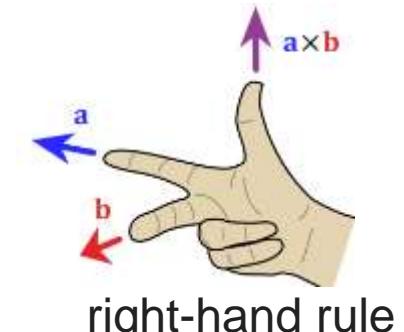
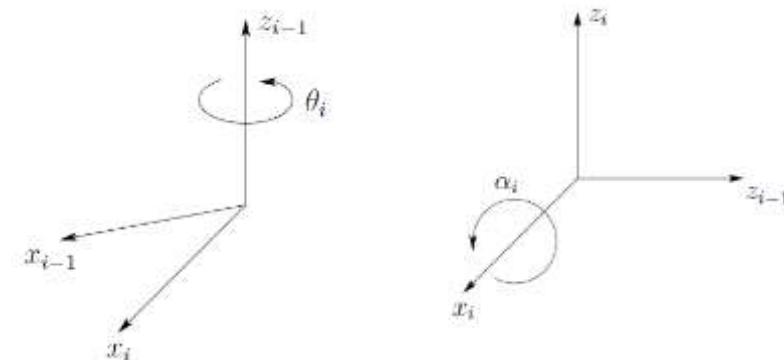


$\theta_i$  = the angle between  $x_{i-1}$  and  $x_i$  measured about  $z_{i-1}$

$d_i$  = distance along  $z_{i-1}$  from  $o_{i-1}$  to the intersection of the  $x_i$  and  $z_{i-1}$  axes.  $d_i$  is variable if joint  $i$  is prismatic.

$a_i$  = distance along  $x_i$  from  $o_i$  to the intersection of the  $x_i$  and  $z_{i-1}$  axes.

$\alpha_i$  = the angle between  $z_{i-1}$  and  $z_i$  measured about  $x_i$





# Hand Kinematics- FK



$$A_i = \begin{bmatrix} R_i^{i-1} & o_i^{i-1} \\ 0 & 1 \end{bmatrix}$$

?

$$A = Rot_{z,\theta} Trans_{z,d} Trans_{x,a} Rot_{x,\alpha}$$

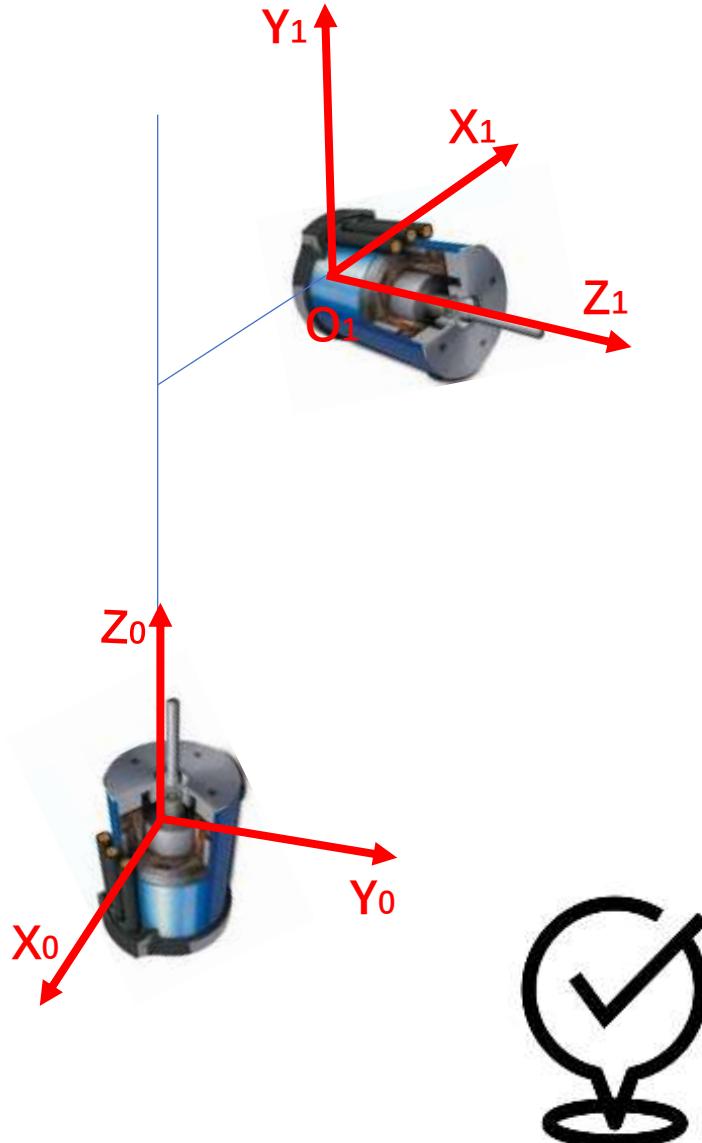
$$A_i = Rot_{z,\theta_i} Trans_{z,d_i} Trans_{x,a_i} Rot_{x,\alpha_i}$$

$$= \begin{bmatrix} c_{\theta_i} & -s_{\theta_i} & 0 & 0 \\ s_{\theta_i} & c_{\theta_i} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & a_i \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & c_{\alpha_i} & -s_{\alpha_i} & 0 \\ 0 & s_{\alpha_i} & c_{\alpha_i} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} c_{\theta_i} & -s_{\theta_i}c_{\alpha_i} & s_{\theta_i}s_{\alpha_i} & a_i c_{\theta_i} \\ s_{\theta_i} & c_{\theta_i}c_{\alpha_i} & -c_{\theta_i}s_{\alpha_i} & a_i s_{\theta_i} \\ 0 & s_{\alpha_i} & c_{\alpha_i} & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$



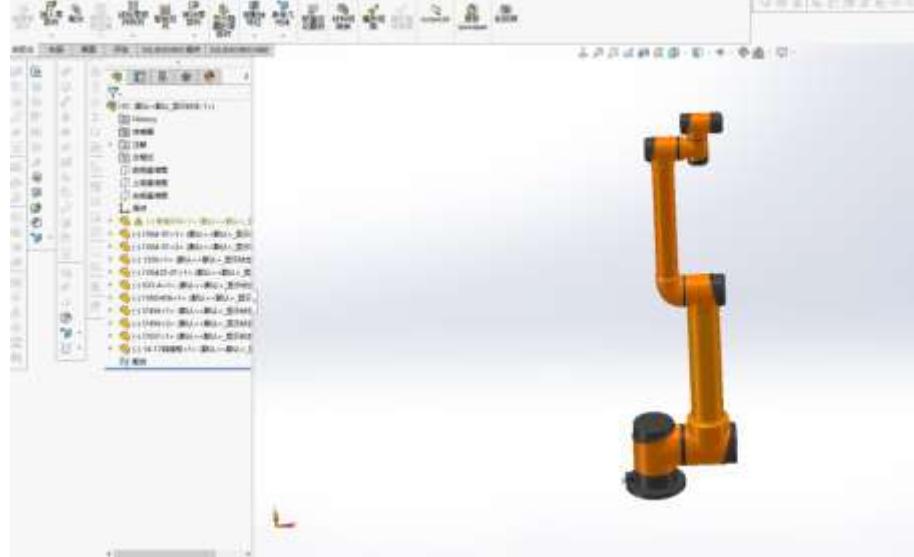
# Hand Kinematics- DH param procedure



- 1 Step 1: Locate and label the joint axes  $z_0, \dots, z_{n-1}$ .
- 2 Step 2: Establish the base frame. Set the origin anywhere on the  $z_0$ -axis. The  $x_0$  and  $y_0$  axes are chosen conveniently to form a right-hand frame.  
For  $i = 1, \dots, n - 1$ , perform Steps 3 to 5.
- 3 Step 3: Locate the origin  $o_i$  where the common normal to  $z_i$  and  $z_{i-1}$  intersects  $z_i$ . If  $z_i$  intersects  $z_{i-1}$  locate  $o_i$  at this intersection. If  $z_i$  and  $z_{i-1}$  are parallel, locate  $o_i$  in any convenient position along  $z_i$ .
- 4 Step 4: Establish  $x_i$  along the common normal between  $z_{i-1}$  and  $z_i$  through  $o_i$ , or in the direction normal to the  $z_{i-1} - z_i$  plane if  $z_{i-1}$  and  $z_i$  intersect.
- 5 Step 5: Establish  $y_i$  to complete a right-hand frame.
- 6 Step 6: Establish the end-effector frame  $o_n x_n y_n z_n$ . Assuming the  $n$ -th joint is revolute, set  $z_n = a$  along the direction  $z_{n-1}$ . Establish the origin  $o_n$  conveniently along  $z_n$ , preferably at the center of the gripper or at the tip of any tool that the manipulator may be carrying. Set  $y_n = s$  in the direction of the gripper closure and set  $x_n = s \times a$ . If the tool is not a simple gripper set  $x_n$  and  $y_n$  conveniently to form a right-hand frame.
- 7 Step 7: Create a table of link parameters  $a_i, d_i, \alpha_i, \theta_i$ .

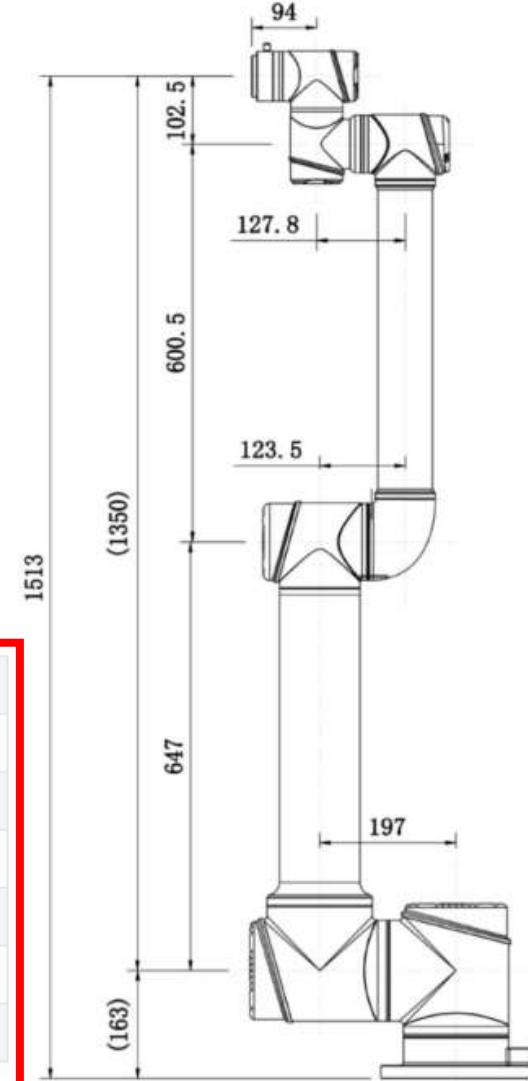


# Hand Kinematics- DH in practice

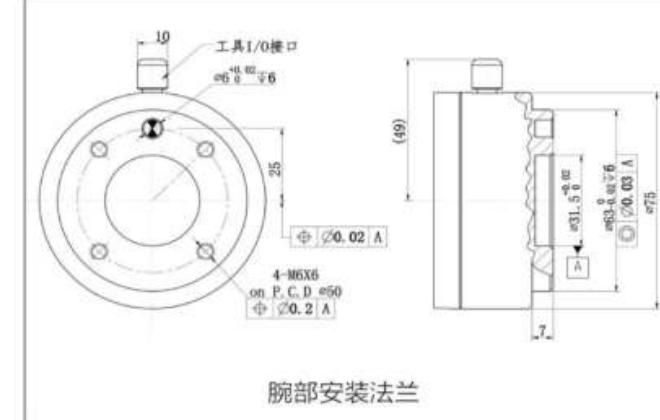


1513

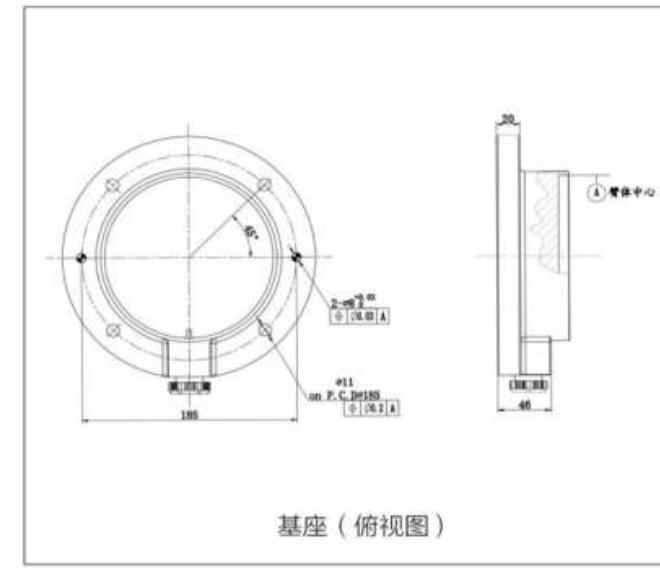
DH参数	d(m)	$\theta(^{\circ})$	a(m)	$\alpha(^{\circ})$
关节1	0	0	0	0
关节2	0.163	90	0	90
关节3	0	0	-0.647	0
关节4	0	0	-0.6005	0
关节5	0.2013	0	0	90
关节6	0.1025	0	0	-90



1513



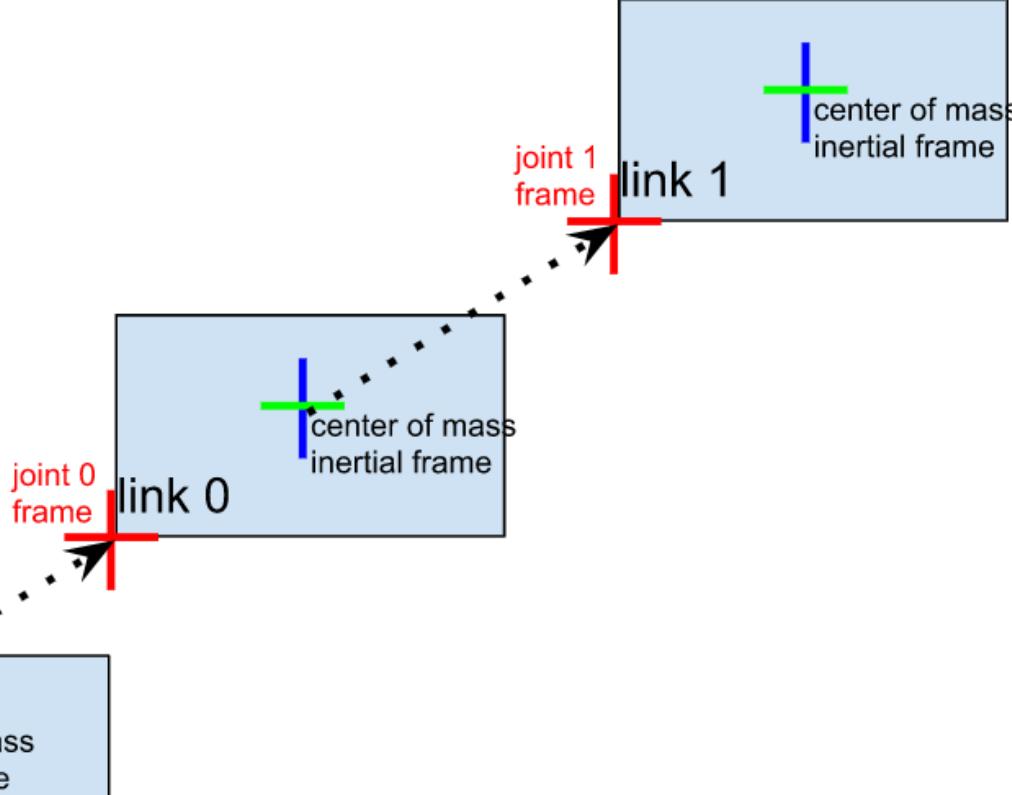
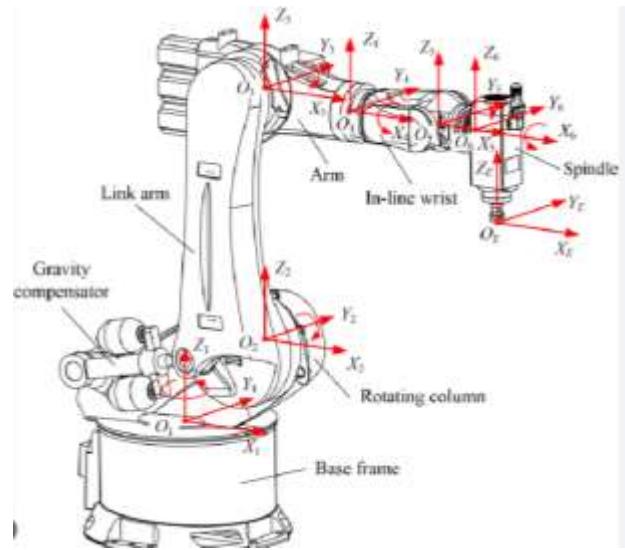
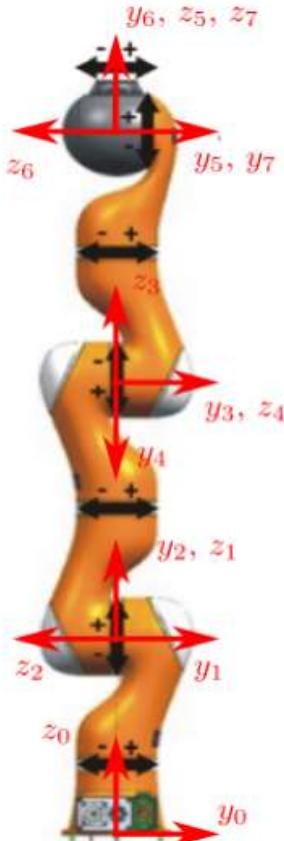
腕部安装法兰



基座 (俯视图)



# Hand Kinematics- FK in Practice



<https://docs.google.com/document/d/10sXEhzFRSnvFcI3XxNGhnD4N2SedqwdAvK3dsihxVUA/edit>



# Hand Kinematics- FK in PyBullet



Bullet Real-Time Physics Simulation

Home of Bullet and PyBullet: physics simulation for games, visual effects, robotics and reinforcement learning.

RECENT POSTS

- Kubric: a scalable dataset generator
- NeuraSim: Augmenting Differentiable Simulators with Neural Networks
- PyBullet in a colab
- Learning Agile Robotic Locomotion Skills by Imitating Animals
- Assitive gym @ ICRA 2020

SELECTED VIDEO

Top 5 AI ...

## KUBRIC: A SCALABLE DATASET GENERATOR

March 21, 2022

Kubric is an open-source Python framework that interfaces with PyBullet and Blender to generate photo-realistic scenes, with rich annotations, and seamlessly scales to large jobs distributed over thousands of machines, and generating TBs of data. Kubric can generate semi-realistic synthetic multi-object videos with rich annotations such as instance segmentation masks, depth maps, and optical flow.

You can find the [paper](#) here, or access the [source code](#) from github.

LAST TOPICS POSTS

**Bullet & Bsp**

- New engine: Ancestor Ancestor Ancestor ...  
by Typhontaur  
August 25, 2023 8:37 pm
- btMultiBodyDynamicsWorld and soft bodies  
Hi, This might sound like a stupid question... In the case one decides to use the ...  
by glasy  
August 10, 2023 10:10 am
- Unstable behavior on shapes like cylinder or box  
I will suggest you several ways to solve shape instability: You can increase the collision ...  
by sharase23  
July 6, 2023 9:02 am
- Compiling for ARM/Raspberry Pi  
Optionally, you can install the compiled Bullet library on your Ubuntu machine or the Raspberry ...  
by sharase23  
July 6, 2023 8:58 am
- Issue moving objects that are constrained together,  
Instead of moving the kinematic object abruptly from -5.f to 1.f, consider implementing a smooth ...  
by sharase23  
July 6, 2023 8:57 am

<https://docs.google.com/document/d/10sXEhzFRSnvFcI3XxNGhnD4N2SedqwdAvK3dsihxVUA/edit>

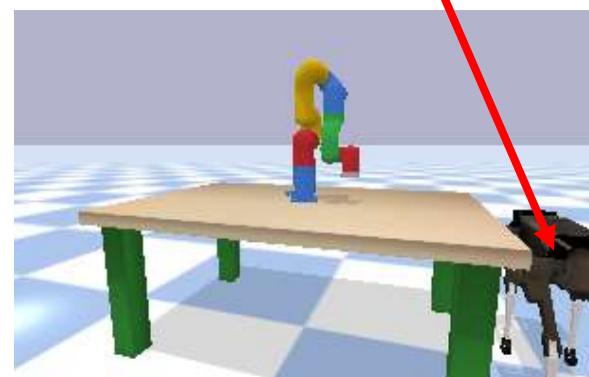
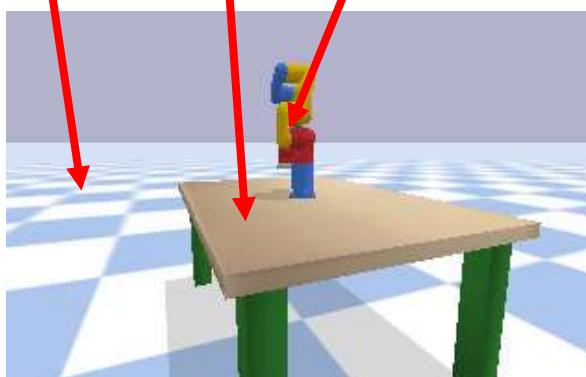


# Hand Kinematics- FK in Practice



```
p.resetSimulation()
p.configureDebugVisualizer(p.COV_ENABLE_GUI)
useFixedBase = True
flags = p.URDF_INITIALIZE_SAT_FEATURES

plane_pos = [0, 0, -0.625]
plane = p.loadURDF("plane.urdf", plane_pos, flags = flags, useFixedBase=useFixedBase)
table_pos = [0, 0, -0.625]
table = p.loadURDF("table/table.urdf", table_pos, flags = flags, useFixedBase=useFixedBase)
xarm = p.loadURDF("xarm/xarm6_robot.urdf", flags = flags, useFixedBase=useFixedBase)
xarm = p.loadURDF("laikago/laikago_toes.urdf", [1,0,-0.15], [0, 0.5, 0.5, 0], flags = flags, useFixedBase=useFixedBase)
```



<https://docs.google.com/document/d/10sXEhzFRSnvFcI3XxNGhnD4N2SedqwdAvK3dsihxVUA/edit>



# Hand Kinematics- FK in Practice



## getLinkState(s)

You can also query the Cartesian world position and orientation for the center of mass of each link using `getLinkState`. It will also report the local inertial frame of the center of mass to the URDF link frame, to make it easier to compute the graphics/visualization frame.

### getLinkState input parameters

required	bodyUniqueId	int	body unique id as returned by <code>loadURDF</code> etc
required	linkIndex	int	link index
optional	computeLinkVelocity	int	If set to 1, the Cartesian world velocity will be computed and returned.
optional	computeForwardKinematics	int	if set to 1 (or True), the Cartesian world position/orientation will be recomputed using forward kinematics.
optional	physicsClientId	int	if you are connected to multiple servers, you can pick one.

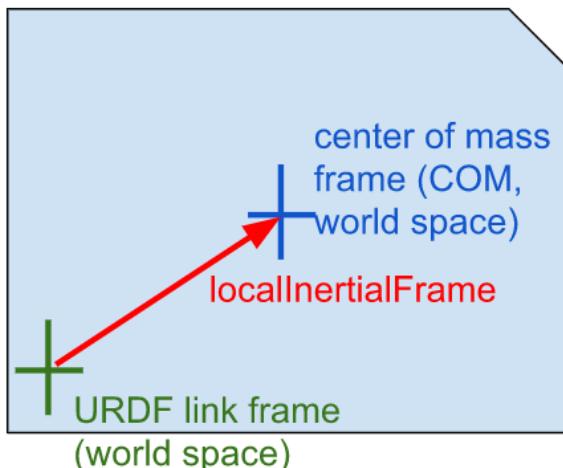
<https://docs.google.com/document/d/10sXEhzFRSnvFcI3XxNGhnD4N2SedqwdAvK3dsihxVUA/edit>



# Hand Kinematics- FK in Practice



getLinkState return values



linkWorldPosition	vec3, list of 3 floats	Cartesian position of center of mass
linkWorldOrientation	vec4, list of 4 floats	Cartesian orientation of center of mass, in quaternion [x,y,z,w]
localInertialFramePosition	vec3, list of 3 floats	local position offset of inertial frame (center of mass) expressed in the URDF link frame
localInertialFrameOrientation	vec4, list of 4 floats	local orientation (quaternion [x,y,z,w]) offset of the inertial frame expressed in URDF link frame.
worldLinkFramePosition	vec3, list of 3 floats	world position of the URDF link frame
worldLinkFrameOrientation	vec4, list of 4 floats	world orientation of the URDF link frame
worldLinkLinearVelocity	vec3, list of 3 floats	Cartesian world velocity. Only returned if computeLinkVelocity non-zero.
worldLinkAngularVelocity	vec3, list of 3 floats	Cartesian world velocity. Only returned if computeLinkVelocity non-zero.

<https://docs.google.com/document/d/10sXEhzFRSnvFcI3XxNGhnD4N2SedqwdAvK3dsihxVUA/edit>



# Hand Kinematics- FK in Practice

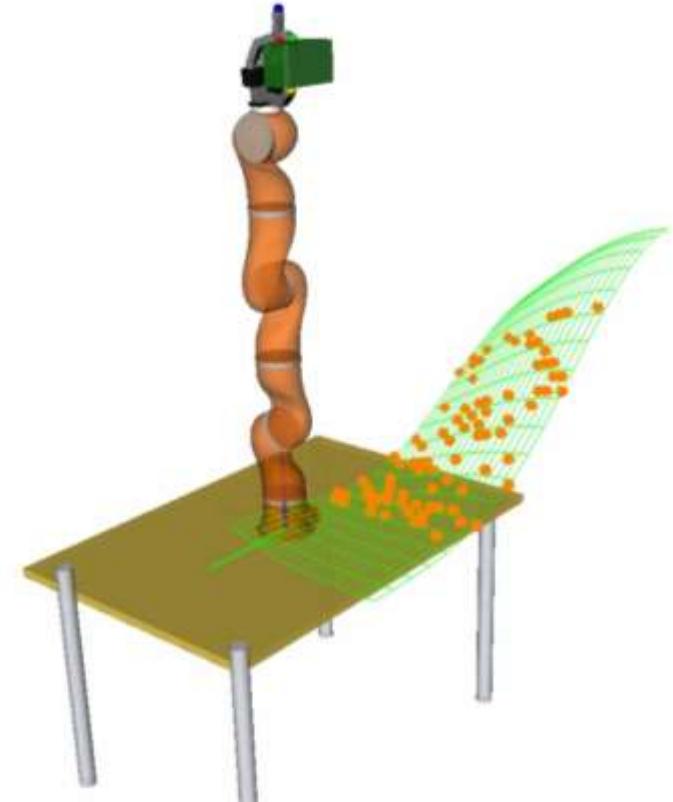


## PyBullet Quickstart Guide

[Erwin Coumans](#), [Yunfei Bai](#), 2016-2023

Visit [desktop doc](#), [forums](#), [github discussions](#) and star [Bullet!](#)

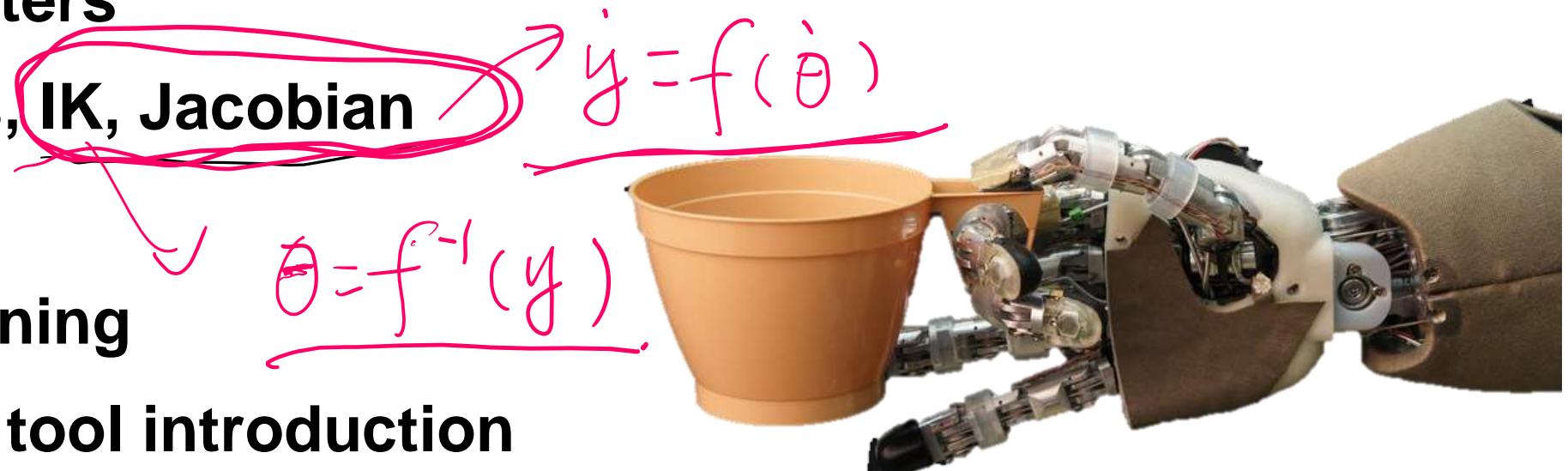
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# Today

- Design and Modelling of typical robotic arm/hand
- DH parameters
- Kinematics, IK, Jacobian
- Soft hand
- Grasp planning
- Simulation tool introduction
- Group list

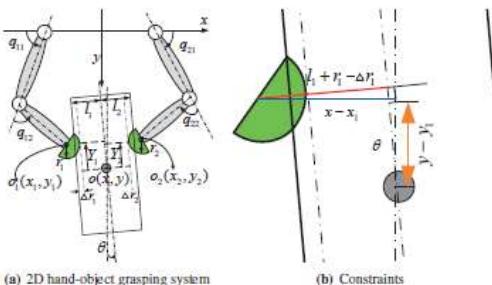




# Robotic Hand Dynamics

## STABILITY OF VARIABLE GRASP STIFFNESS CONTROL

In this part, we address the control stability of varying stiffness in robotic grasping using a two-fingered example, as shown in Fig. B.1(a). To this end, a detailed formulation for the dynamics of the constraints and the soft fingertip deformation is given. The formulation is based on the grasp kinematics and the contact model of the soft fingertip. The goal is to grasp the object stably and to derive the proof of convergence.



**Figure B.1:** (a) The hand-object system in 2D. Each finger has 2 DOFs with soft fingertips. (b) The constraint that the fingertip should keep contact with the object's surface.

### B.1 DYNAMICS

In this part, we first consider the contact model of the fingertips and the constraints involved in the hand-object system. Then the overall dynamics of the system is formulated. The notations in this section are explained in Fig. B.1 to simplify the understanding of the grasping dynamics.

#### B.1.1 CONTACT MODEL OF SOFT FINGERTIP

$$f = c_1(\Delta r)^2 + c_2 \frac{d}{dt} \Delta r \quad (\text{B.1})$$

where  $c_1$  and  $c_2$  are positive constant parameters which depend on the material of the fingertip, and  $\Delta r$  is the deformation at the fingertip. The fingertip should keep contact with the object surface, as shown in Fig. B.1(b), which can be expressed as follows

$$l_1 + r_1 - \Delta r_1 = (x - x_1) \cos \theta - (y - y_1) \sin \theta \quad (\text{B.2})$$

$$l_2 + r_2 - \Delta r_2 = -(x - x_2) \cos \theta + (y - y_2) \sin \theta \quad (\text{B.3})$$

#### B.1.2 ROLLING CONSTRAINTS

## Complicated with many assumptions

$$Y_1 = (x_1 - x) \sin \theta + (y_1 - y) \cos \theta \quad (\text{B.5})$$

$$q_{11} + q_{12} + \phi_1 = \pi + \theta \quad (\text{B.6})$$

$$q_{21} + q_{22} + \phi_2 = \pi - \theta \quad (\text{B.7})$$

#### B.1.3 OVERALL DYNAMICS

The total kinetic energy for the overall system can be described as follows

$$K = \sum_{i=1,2} \frac{1}{2} \dot{\mathbf{q}}_i^T H_i \dot{\mathbf{q}}_i + \frac{1}{2} M(\dot{x}^2 + \dot{y}^2) + \frac{1}{2} I \dot{\theta}^2 \quad (\text{B.8})$$

where  $\mathbf{q}_i = [q_{11}, q_{12}]^T$  is the vector of finger joints and  $H_i \in \mathbb{R}^{2 \times 2}$  is the inertia matrix for each finger,  $M$  and  $I$  are the mass and inertia matrix of the object respectively.

The total potential energy from deformation can be given as:

$$P = \sum_{i=1,2} \int_0^{\Delta r_i} c_1 \eta^2 d\eta \quad (\text{B.9})$$

Then from the Hamilton's principle, we have

$$\int_{t_0}^{t_1} [\delta(K - P) - \sum_{i=1,2} c_2 \Delta \dot{r}_i \frac{\partial \Delta r_i}{\partial X^T} \delta X + \sum_{i=1,2} \lambda_i [(r_i - \Delta r_i) \frac{\partial \phi_i}{\partial X^T} + \frac{\partial Y_i}{\partial X^T}] \delta X + \sum_{i=1,2} \mathbf{u}_i^T \delta \mathbf{q}_i] dt = 0 \quad (\text{B.10})$$

where  $X = [\mathbf{q}_1^T, \mathbf{q}_2^T, x, y, \theta]^T$ .

Then we have the overall dynamics for the object-hand system as follows

$$H_1(\mathbf{q}_1) \ddot{\mathbf{q}}_1 + \left( \frac{1}{2} \dot{H}_1 + S_1 \right) \dot{\mathbf{q}}_1 + f_1 \frac{\partial \Delta r_1}{\partial \mathbf{q}_1^T} - \lambda_1 [(r_1 - \Delta r_1) \frac{\partial \phi_1}{\partial \mathbf{q}_1^T} + \frac{\partial Y_1}{\partial \mathbf{q}_1^T}] = \mathbf{u}_1 \quad (\text{B.11})$$

$$M \ddot{x} + \sum_{i=1,2} [f_i \frac{\partial \Delta r_i}{\partial x} - \lambda_i \frac{\partial Y_i}{\partial x}] = 0 \quad (\text{B.12})$$

$$M \ddot{y} + \sum_{i=1,2} [f_i \frac{\partial \Delta r_i}{\partial y} - \lambda_i \frac{\partial Y_i}{\partial y}] = 0 \quad (\text{B.13})$$

$$I \ddot{\theta} + \sum_{i=1,2} [f_i \frac{\partial \Delta r_i}{\partial \theta} - \lambda_i ((r_i - \Delta r_i) \frac{\partial \phi_i}{\partial \theta} + \frac{\partial Y_i}{\partial \theta})] = 0 \quad (\text{B.14})$$

With the identities in section B.5, the overall dynamics can be simplified as

$$\begin{aligned} M \ddot{x} - (f_1 - f_2) \cos \theta + (\lambda_1 + \lambda_2) \sin \theta &= 0 & (\text{B.15}) \\ M \ddot{y} - (f_1 - f_2) \sin \theta + (\lambda_1 + \lambda_2) \cos \theta &= 0 & (\text{B.16}) \\ I \ddot{\theta} - f_1 Y_1 + f_2 Y_2 + I_1 \lambda_1 - I_2 \lambda_2 &= 0 & (\text{B.17}) \end{aligned}$$

### B.2 VARIABLE GRASP STIFFNESS CONTROL

Motivated by the analysis of the overall system dynamics, the following control law is adopted for each finger to achieve stable grasp

$$u_i = -D_i \dot{\mathbf{q}}_i + k_i \mathbf{q}_i^T (\mathbf{x}_i - \mathbf{x}_d) \quad (\text{B.19})$$

$$\mathbf{x}_i = \begin{bmatrix} x_i \\ y_i \end{bmatrix} \quad \mathbf{x}_d = \frac{1}{2} \begin{bmatrix} x_1 + x_2 \\ y_1 + y_2 \end{bmatrix} \quad (\text{B.20})$$

where  $D_i$  is a diagonal positive definite matrix representing the damping gain,  $k \in \mathbb{R}^+$  represents the variable stiffness for each fingertip ( $k$  is the same value for the two-finger grasp to ensure force balance).

### B.3 STABILITY PROOF-1

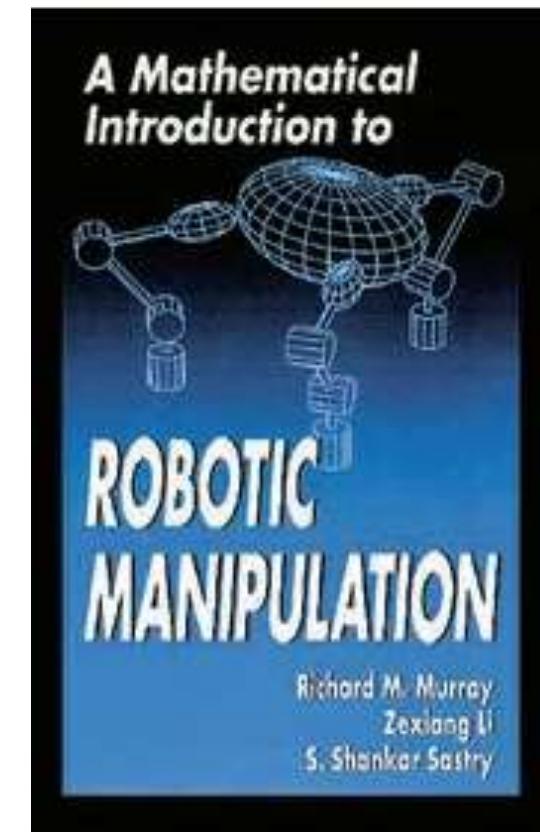
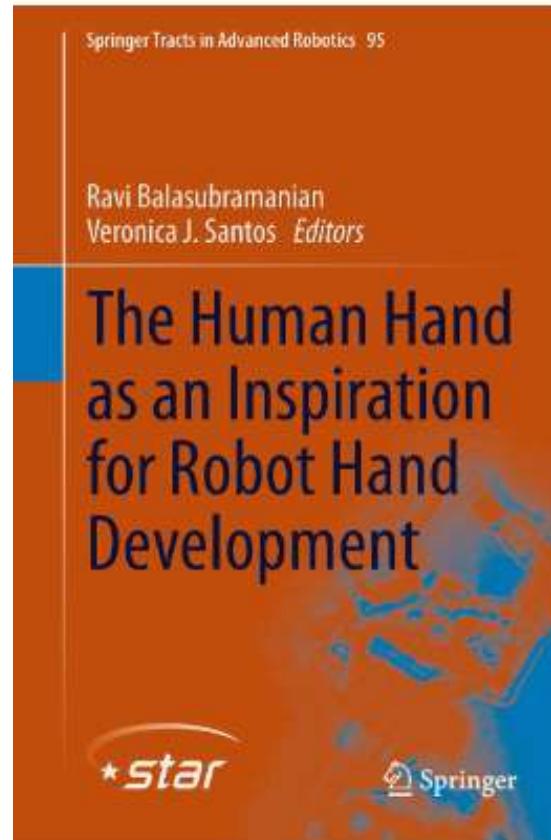
Taking the sum of inner product of Eq. (B.15) with  $\dot{\mathbf{q}}_i$ ,  $i = 1, 2$ , Eq. (B.16) with  $\dot{x}$ , Eq. (B.17) with  $\dot{y}$ , Eq. (B.18) with  $\dot{\theta}$ , we have

$$\frac{d}{dt} E = - \sum_{i=1,2} (\dot{\mathbf{q}}_i^T D_i \dot{\mathbf{q}}_i + c_2 \Delta \dot{r}_i^2) + \frac{k}{4} (\mathbf{x}_1 - \mathbf{x}_2)^T (\mathbf{x}_1 - \mathbf{x}_2) \quad (\text{B.21})$$

$$E = K + V + P \quad (\text{B.22})$$

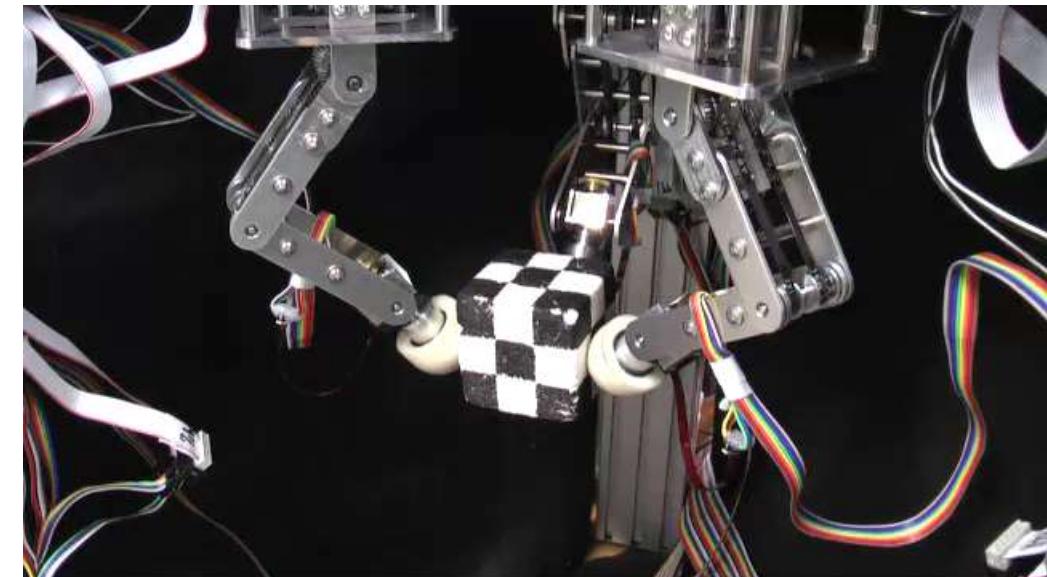
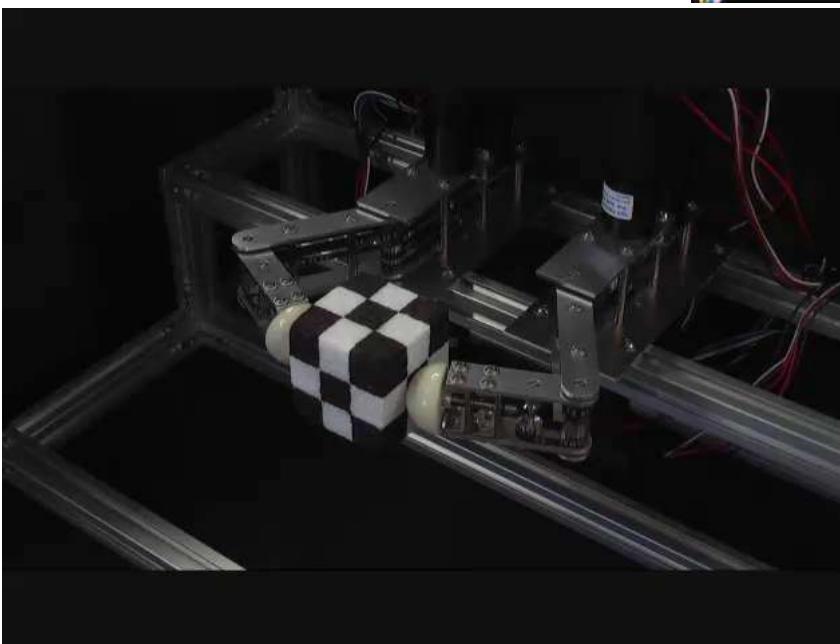
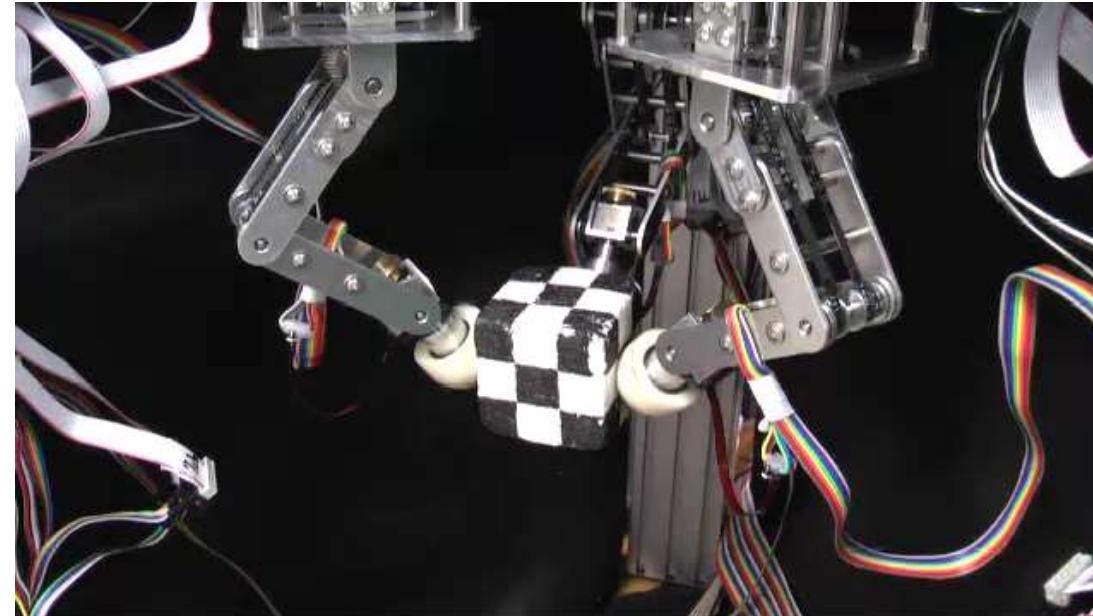
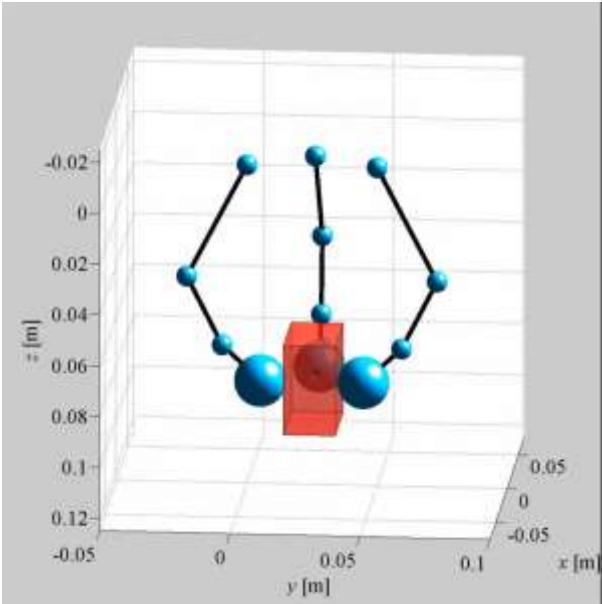


# Robotic Hand Dynamics





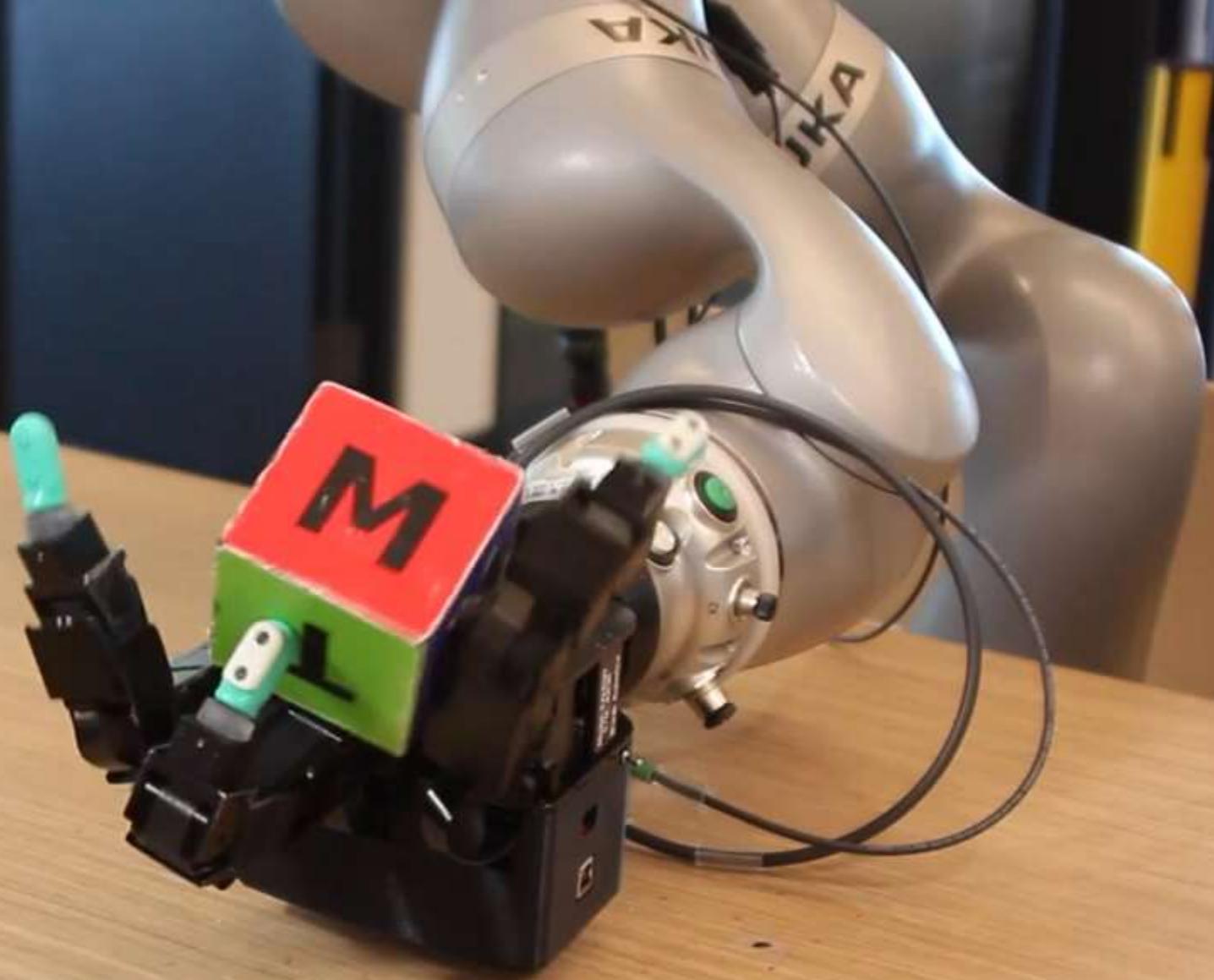
# Robotic Hand Dynamics





# Opening thoughts on robot hands

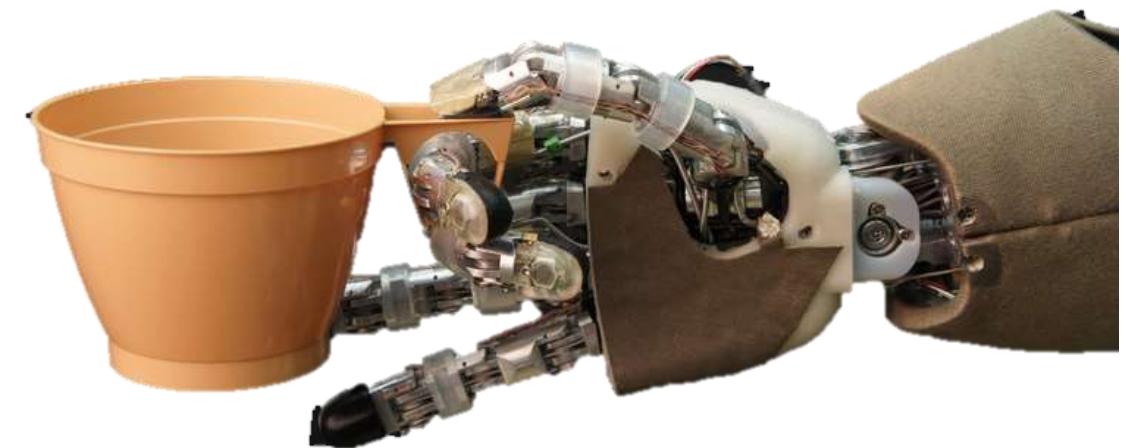
- We have had high degree of freedom robot hands in humanlike form since the 80's. What is missing?
- There have been many exciting new ideas about hand design throughout the past decades.
- Yet we still do not have highly dexterous robotic hand.
- What are the gaps?
- How can we close them?





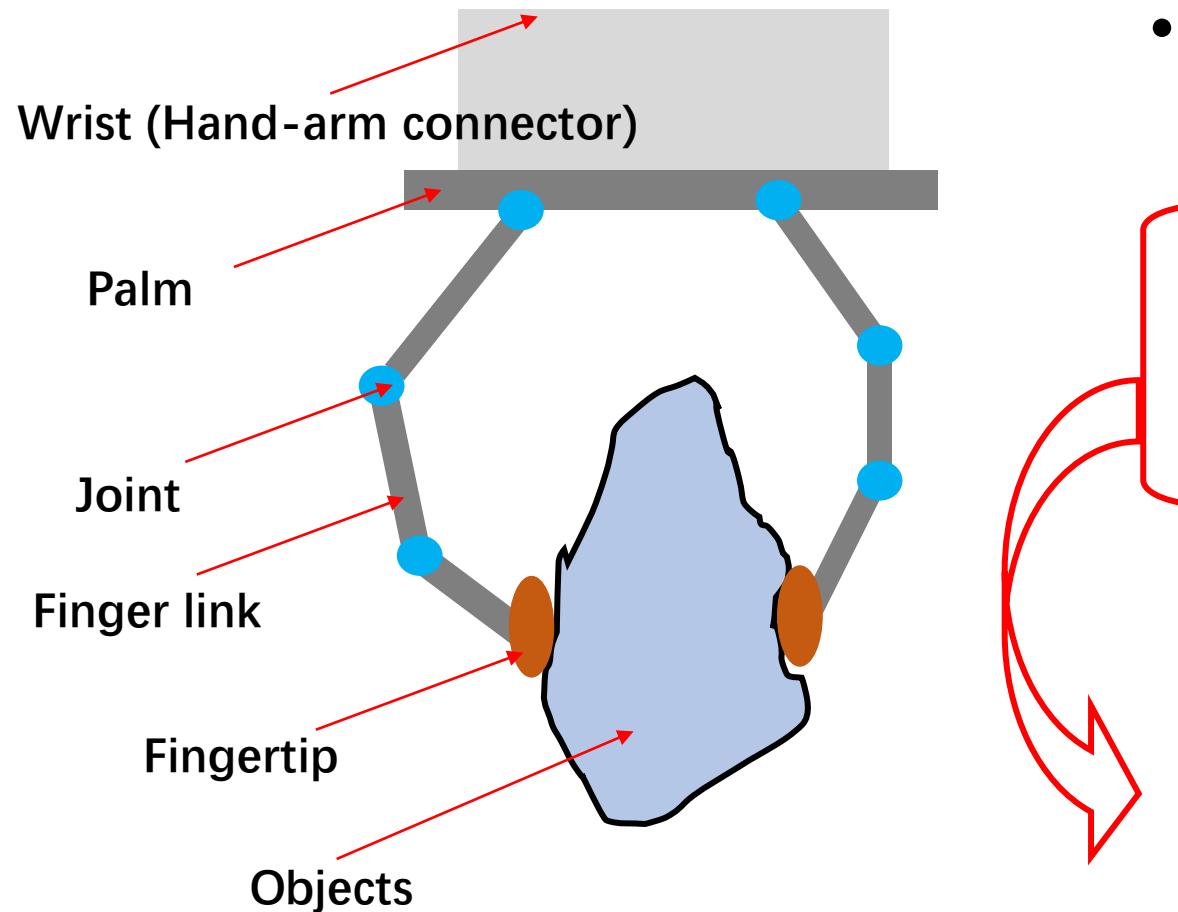
# Today

- Design and Modelling of typical robotic arm/hand
- DH parameters
- Kinematics, IK, Jacobian
- **Soft hand**
- Grasp planning
- Simulation tool introduction
- Group list





# A robotic grasping system



- **Complex hands = Complicated!**

- **Difficult to control**

- **Expensive**

- **Fragile**

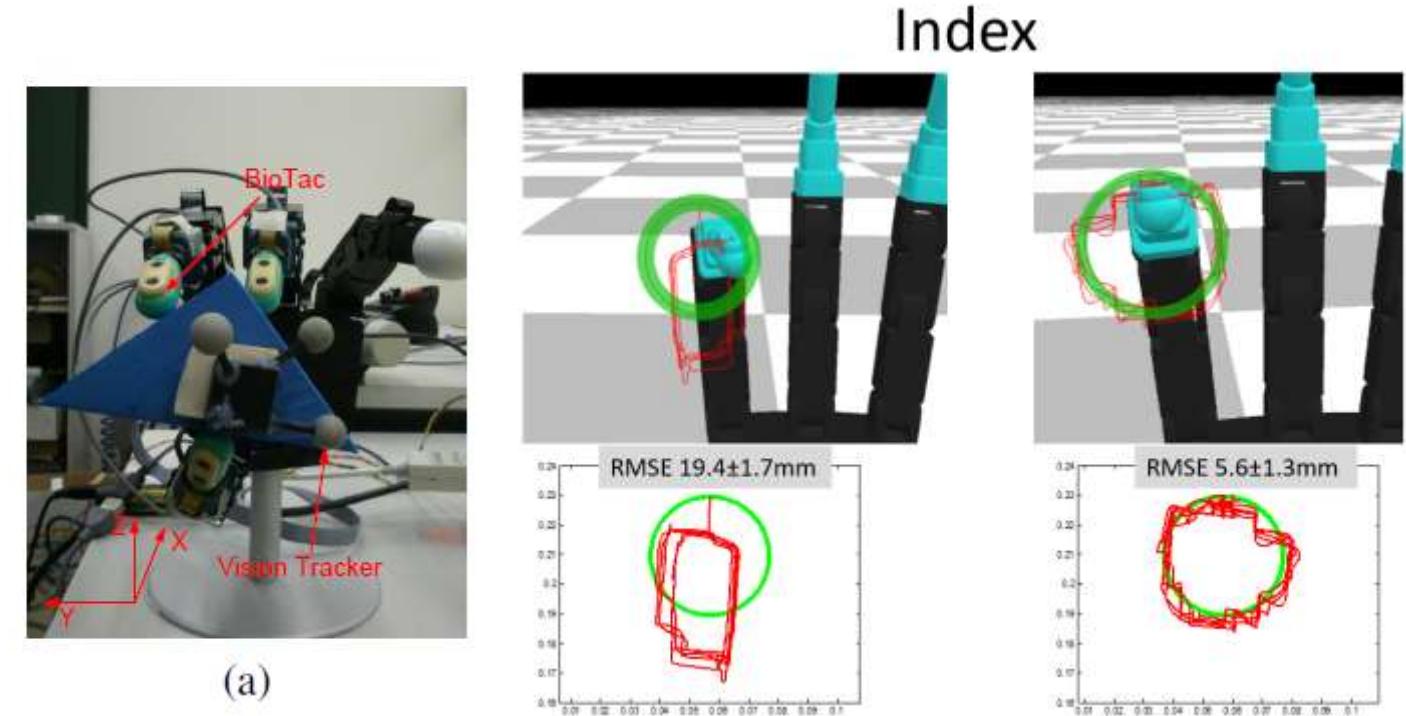
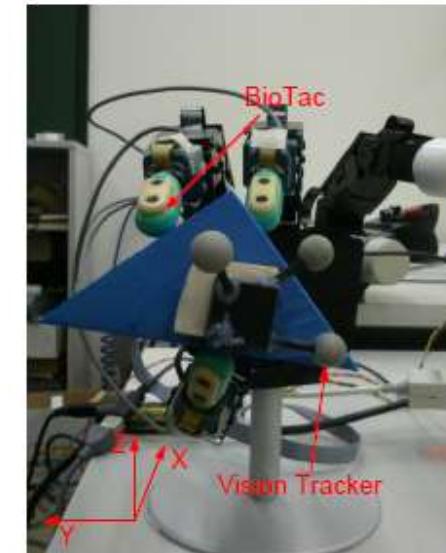
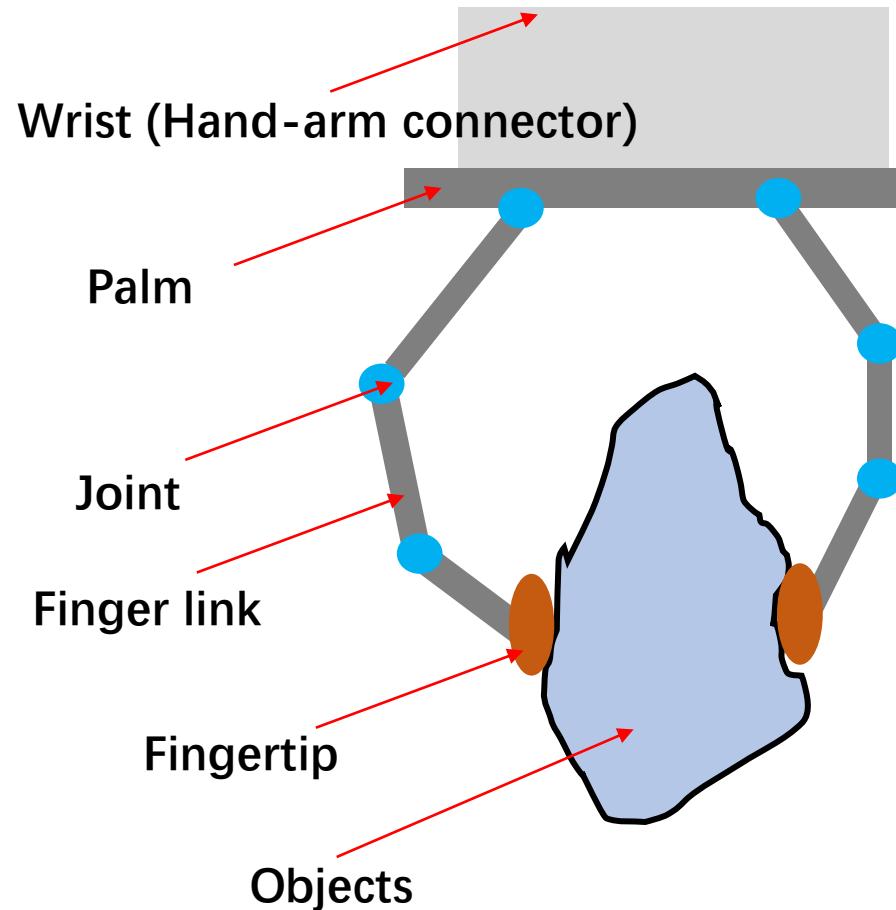


Utah/MIT hand  
[robonaut.jsc.nasa.gov](http://robonaut.jsc.nasa.gov)

**They don't work reliably!**



# A robotic grasping system

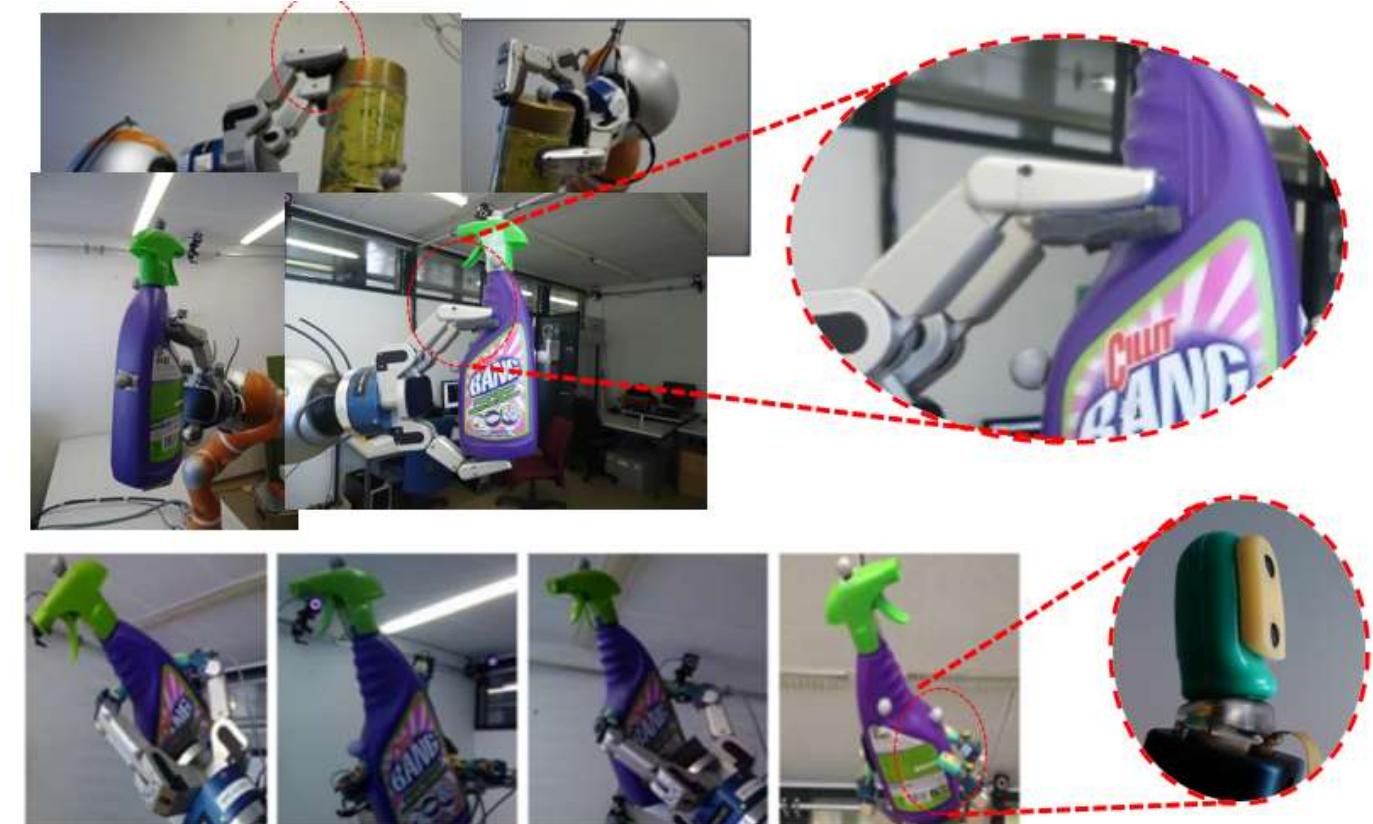
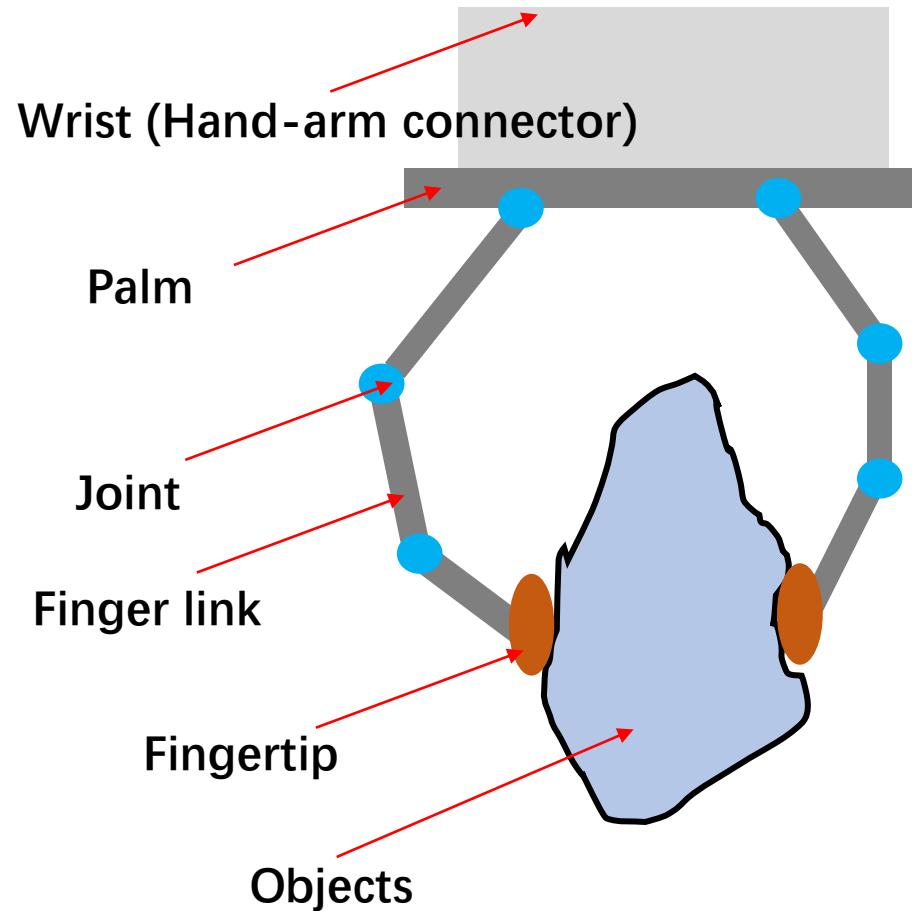


How to deal with “poor” sensing?

- Errors in positioning, finger placement
- Can’t control contact forces

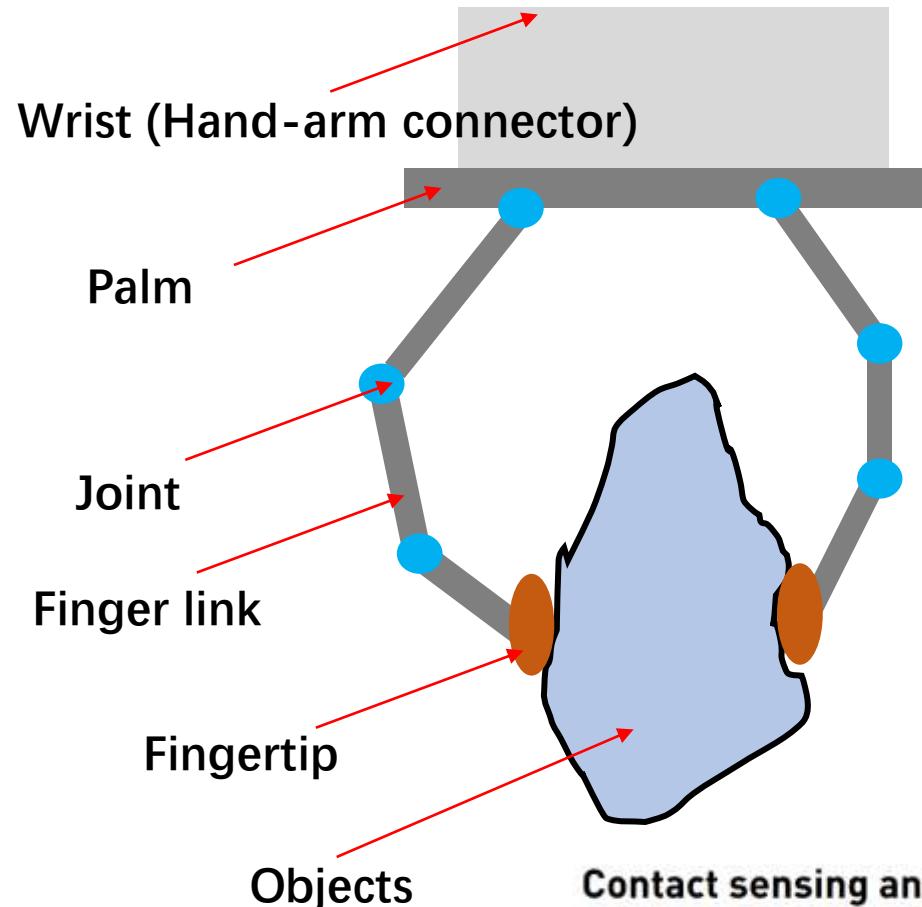


# A robotic grasping system



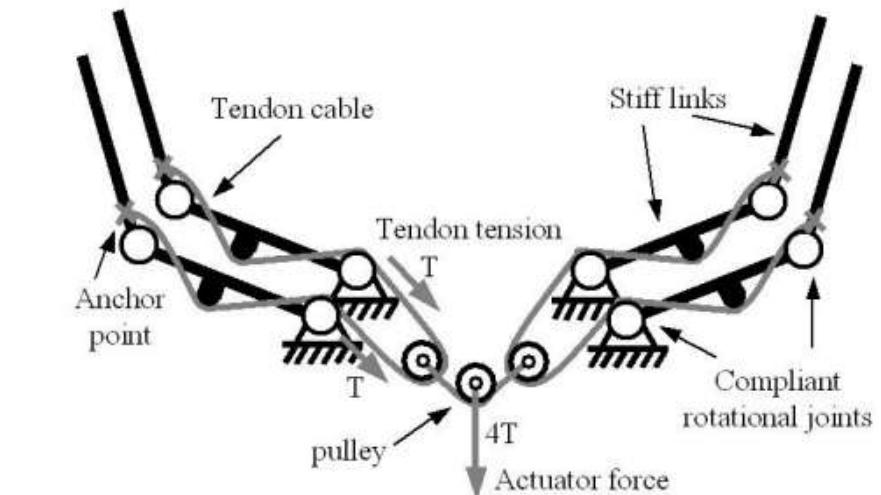
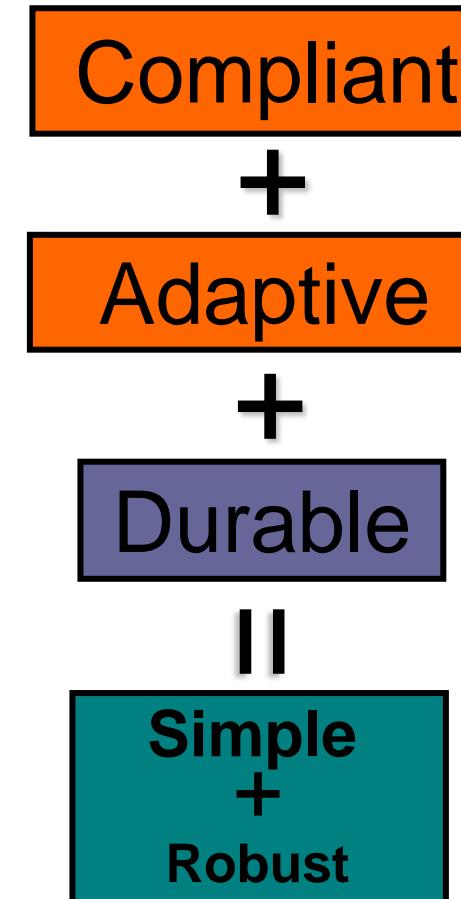


# A new robotic grasping system



## Citation

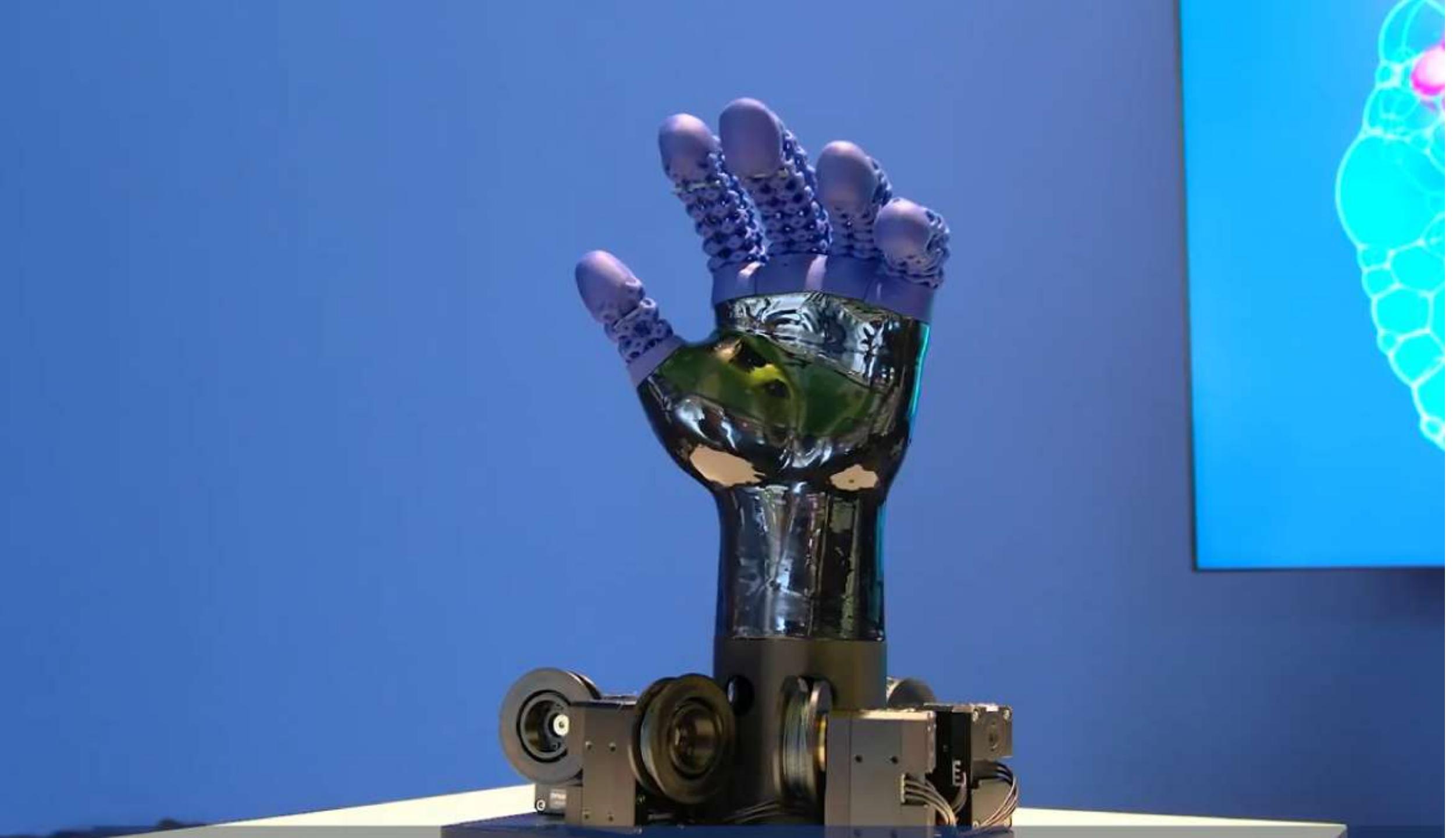
Dollar, Aaron M., Leif P. Jentoft, Jason H. Gao, and Robert D. Howe. 2009. "Contact Sensing and Grasping Performance of Compliant Hands." *Auton Robot* 28 (1) [August 26]: 65–75. doi:10.1007/s10514-009-9144-9.





# A toy example



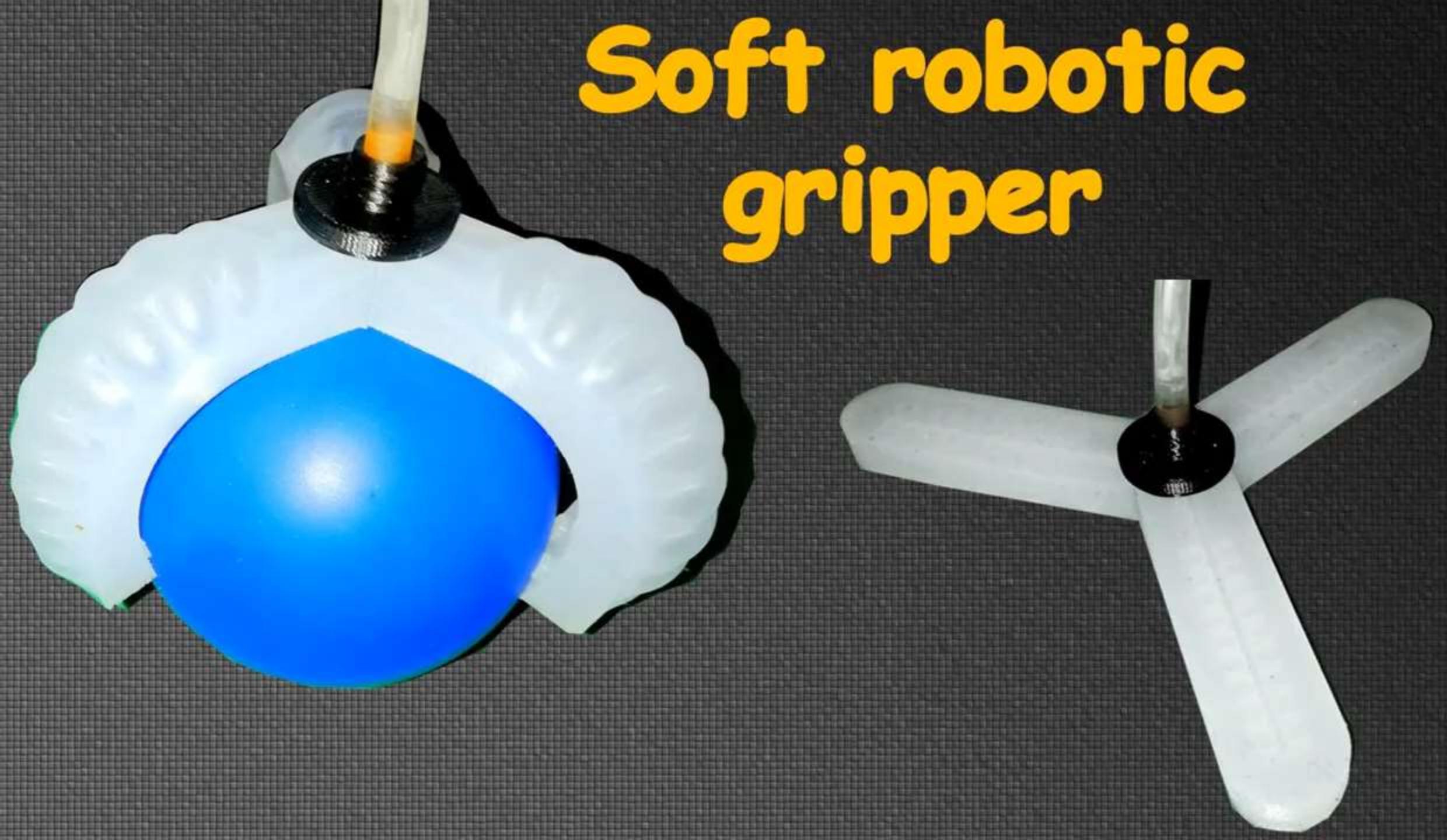


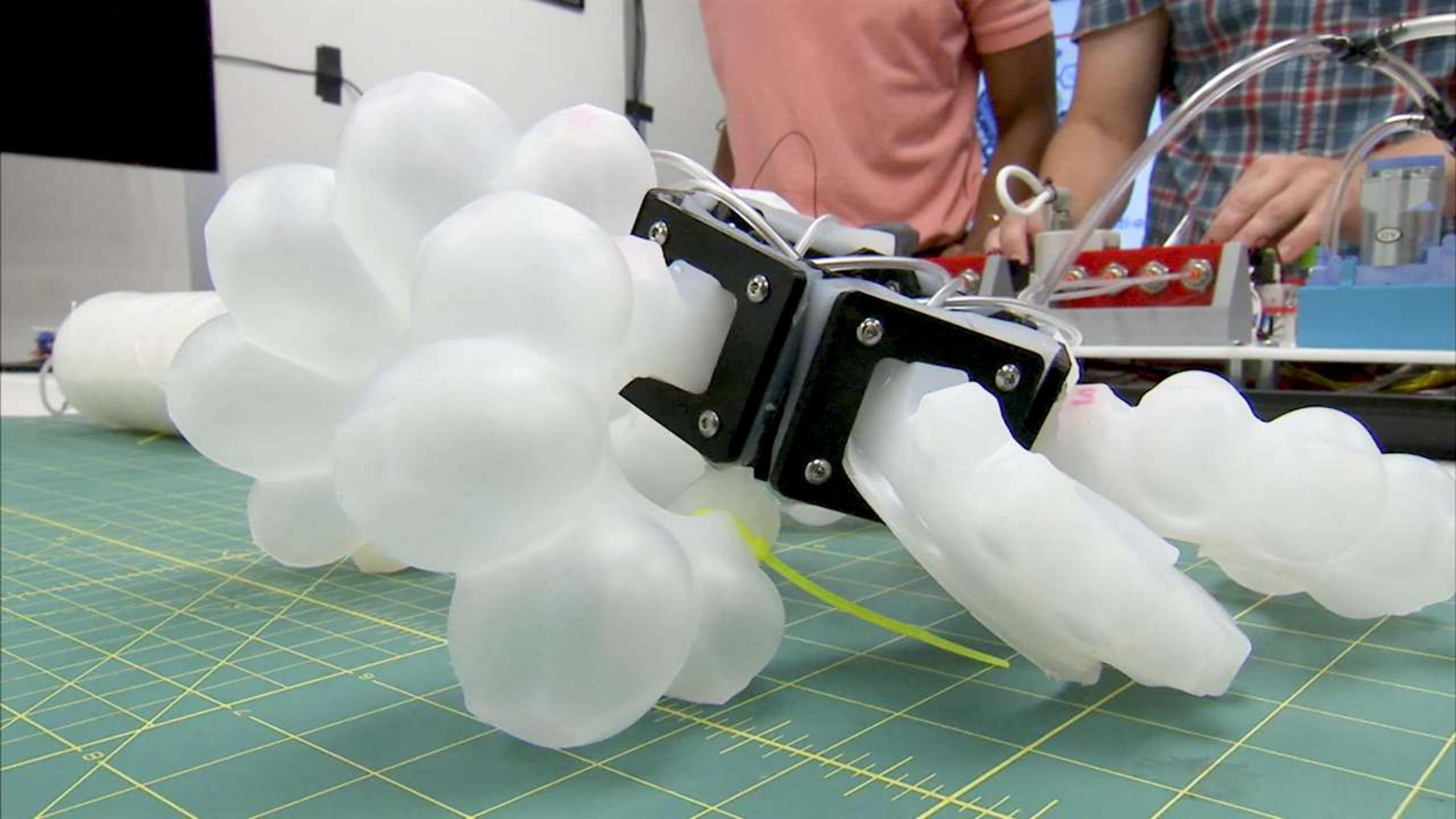
**Video  
(2 mins)**

Video  
(7 mins)

# Soft Robotics

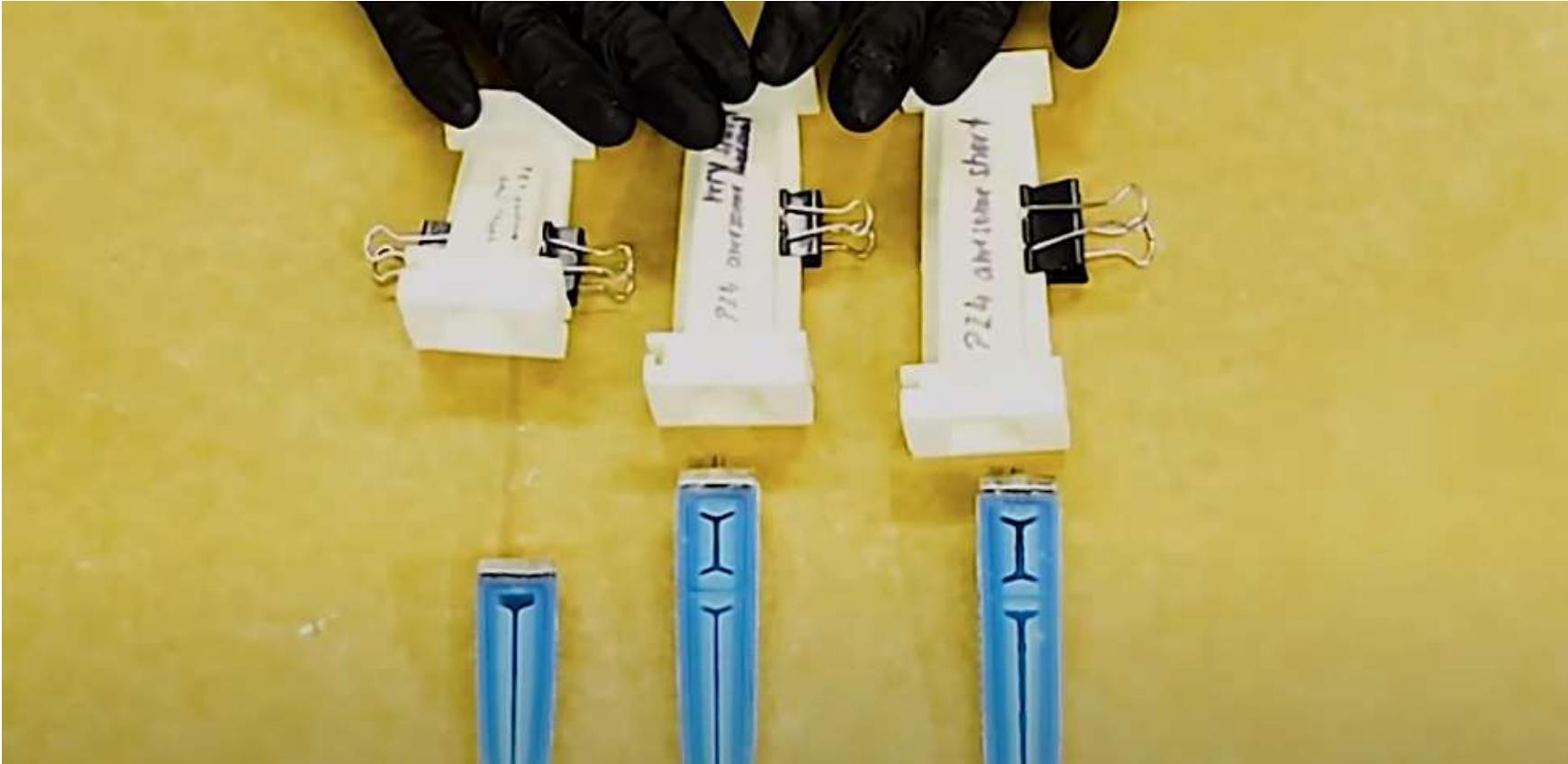
# Soft robotic gripper







# Soft Hands

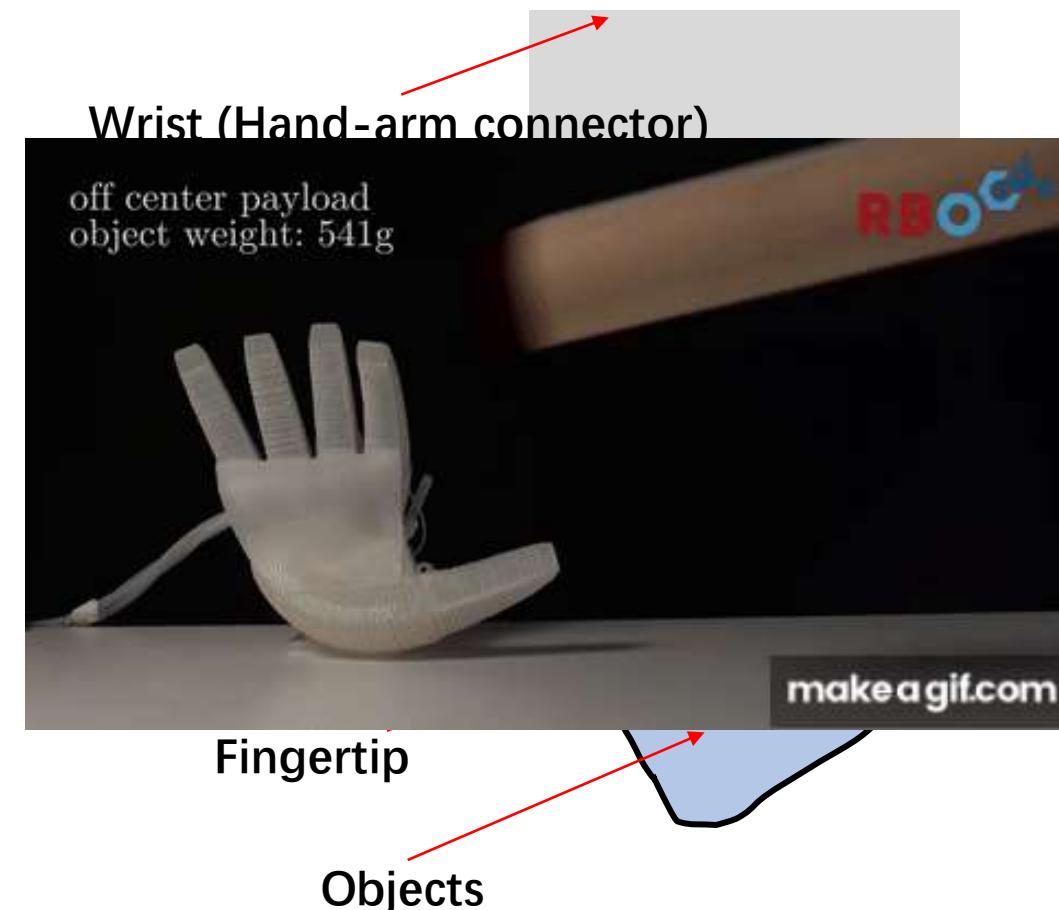


**How to build Soft Robotics Fingers, Pulps and Gloves**

[https://www.youtube.com/watch?v=HE4MGYLkXjk&ab\\_channel=RBOTUBerlin](https://www.youtube.com/watch?v=HE4MGYLkXjk&ab_channel=RBOTUBerlin)



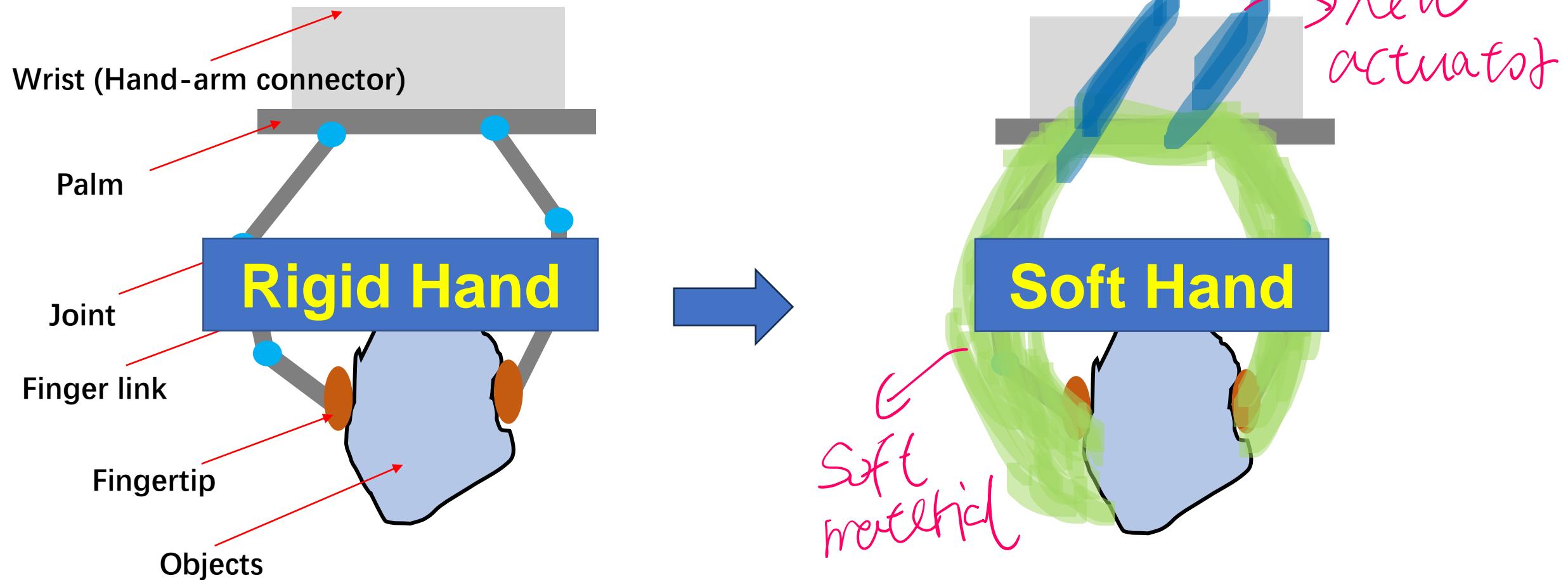
# A robotic grasping system



## Deformation



# A robotic grasping system



**How to design and control the deformation?**

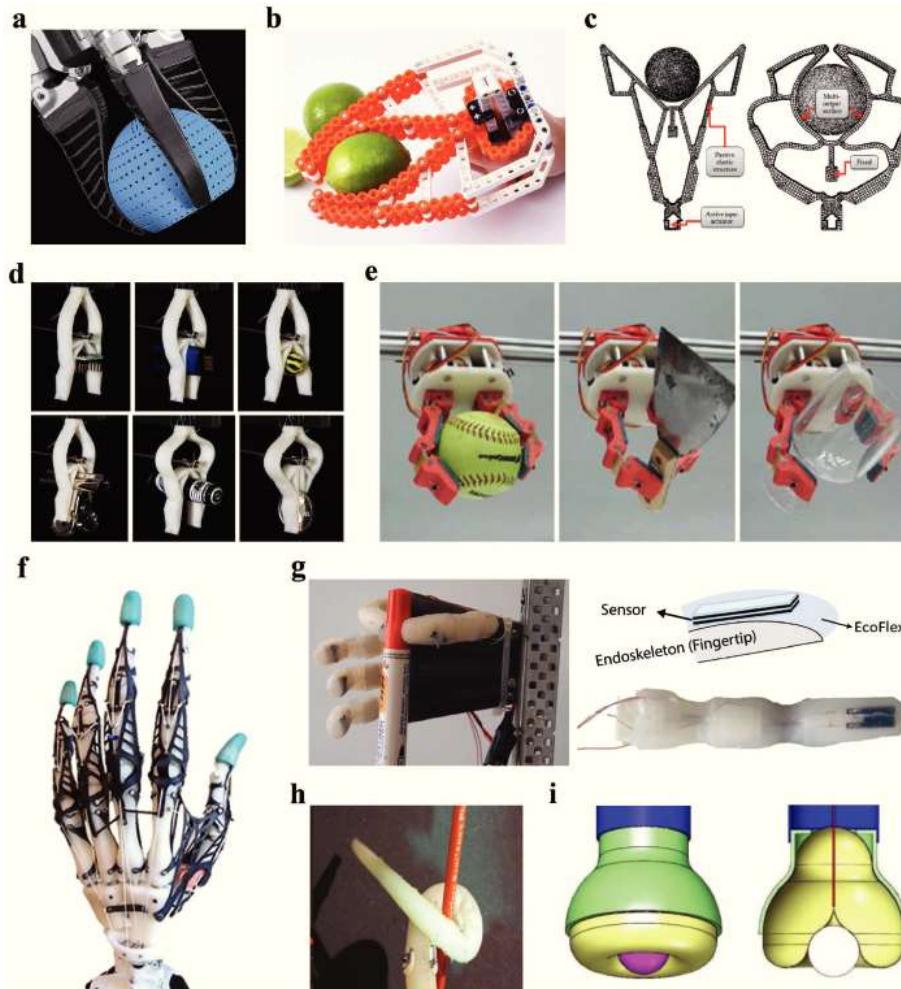


# Soft Hands

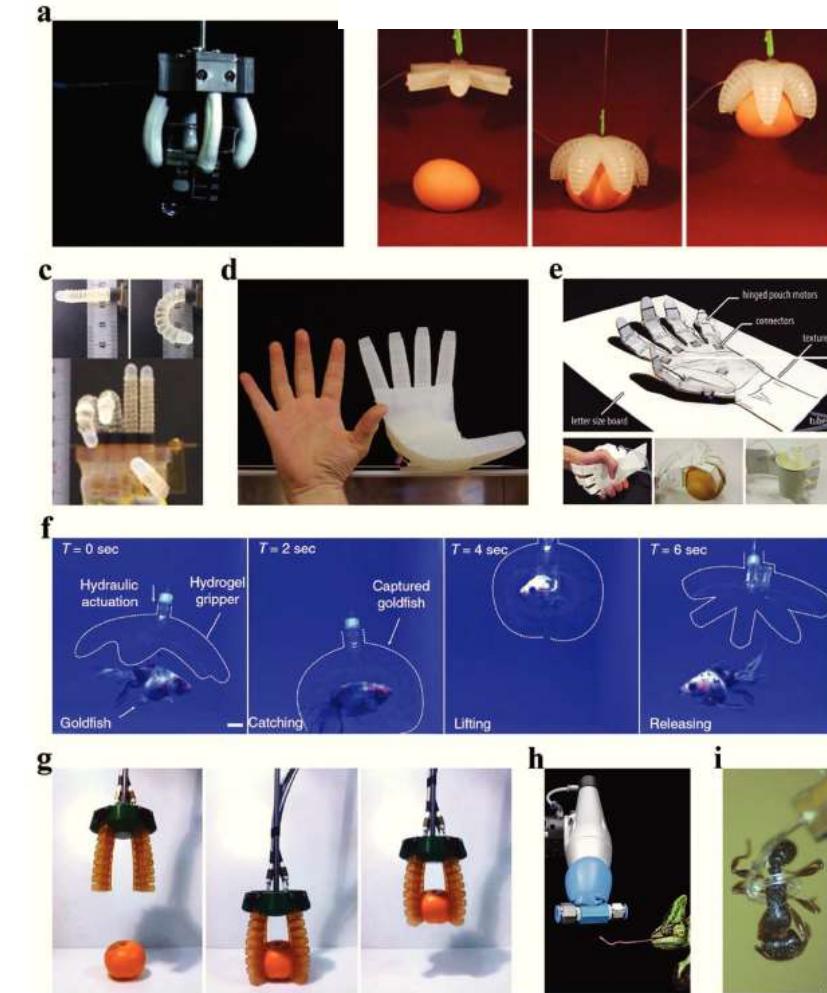
<b>Soft Exo-suit</b> A black, articulated suit designed to fit over a person's torso and arms, with mechanical components visible at the joints.	<b>Octopus-inspired robot</b> A clear plastic dome-shaped robot with tentacle-like appendages extending from its base, resembling an octopus.	<b>Universal gripper</b> A blue and green robotic gripper mechanism holding a small wooden object.	<b>Fluid-drive origami-inspired artificial muscles</b> A blue, articulated arm-like structure with a segmented, flexible end, demonstrating fluid-driven movement.	
<b>X-RHex</b> A white and black hexagonal robot with multiple legs and a central body, showing internal mechanical components.	<b>Soft griper</b> A red and blue soft robotic gripper mechanism, likely made of a flexible elastomer.	<b>Origami robot</b> A complex, multi-link origami-based robot with a golden-yellow and black patterned design.	<b>Rehabilitation glove</b> A black glove with sensors and actuators attached to the fingers, designed for medical rehabilitation.	<b>Octobot</b> A small, pink and purple soft robotic octopus-like robot with tentacle-like appendages.
Mostly stiff Few selective compliant elements			Entirely soft	
<i>Soft robots with different degree of stiffness</i>				

How to design and control the deformation?

# Soft Hands



**Soft grippers using passive structure with external motors**



**Soft grippers using fluidic elastomer actuators**

## REVIEW

Soft Grippers

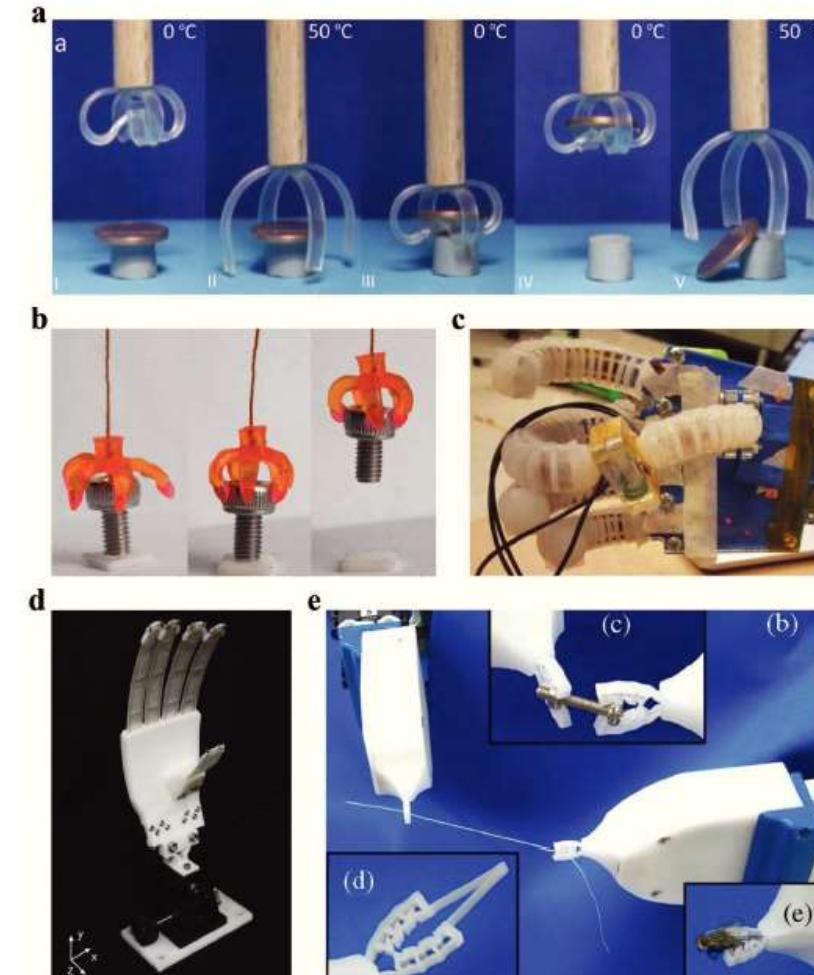
### Soft Robotic Grippers

Jun Shintake, Vito Cacucciolo, Dario Floreano, and Herbert Shea<sup>\*</sup>

# Soft Hands



**Soft grippers using dielectric elastomer actuators**



**Soft grippers using shape memory materials**

## REVIEW

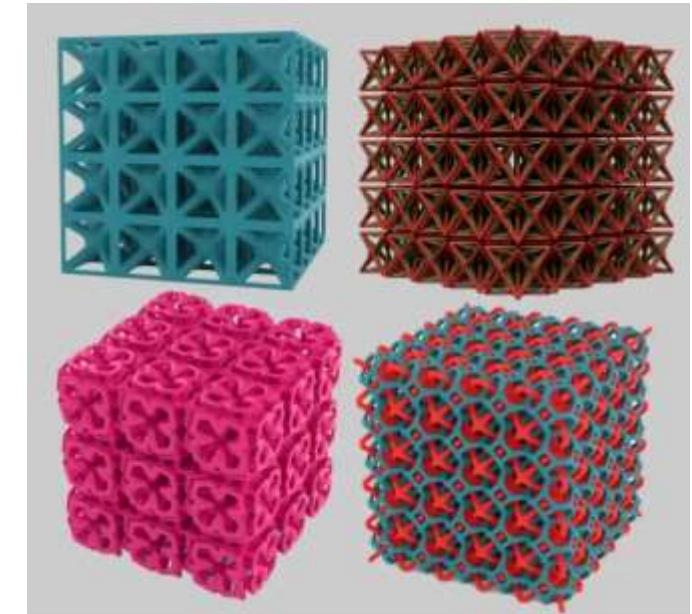
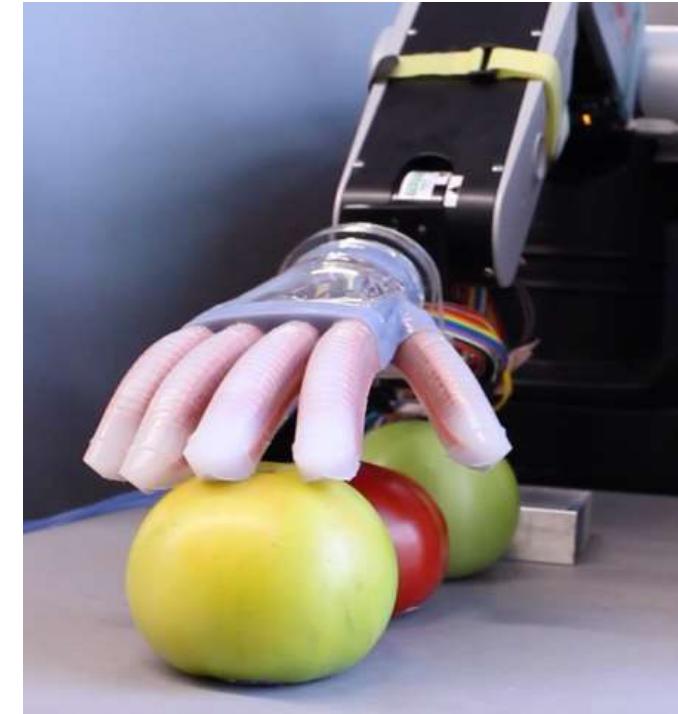
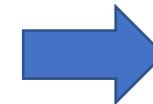
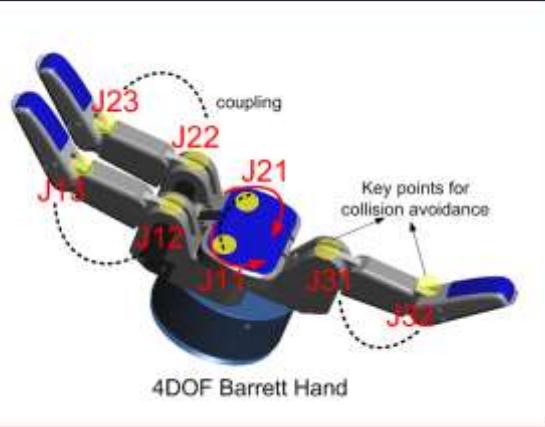
Soft Grippers

### Soft Robotic Grippers

Jun Shintake, Vito Cacucciolo, Dario Floreano, and Herbert Shea<sup>\*†</sup>



# New Material



Steel → Rubber...→ Meta Material

# Grasping without Squeezing: Shear Adhesion Gripper with Fibrillar Thin Film

E.W. Hawkes, D.L. Christensen, A.K. Han, H. Jiang, and M.R. Cutkosky  
Stanford University

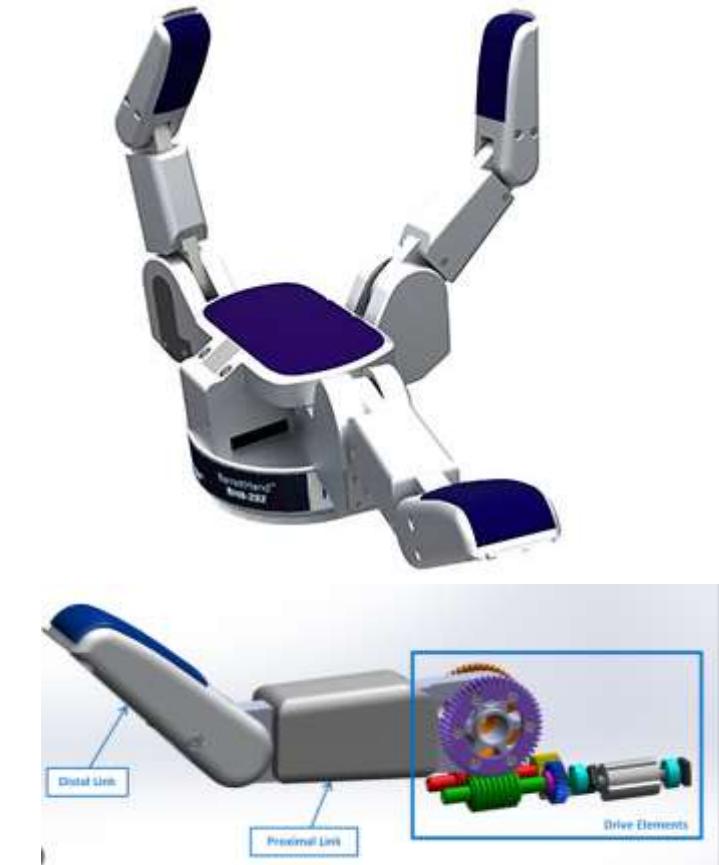
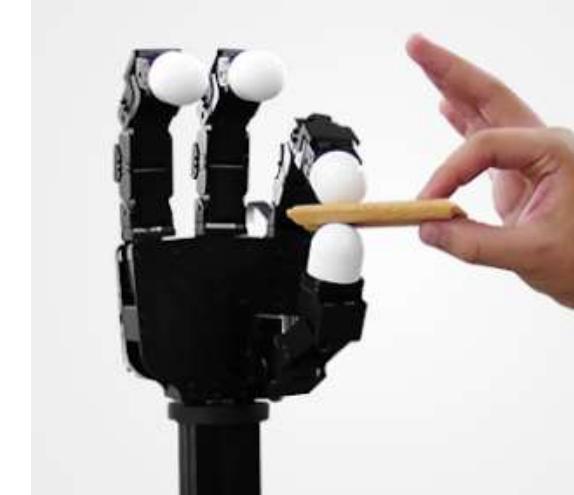


# Design, Fabrication, and Evaluation of Tendon-Driven Foam Manipulators

Jonathan P. King, Dominik Bauer, Cornelia Schlagenhauf,  
Kai-Hung Chang, Daniele Moro, Nancy Pollard, and Stelian Coros

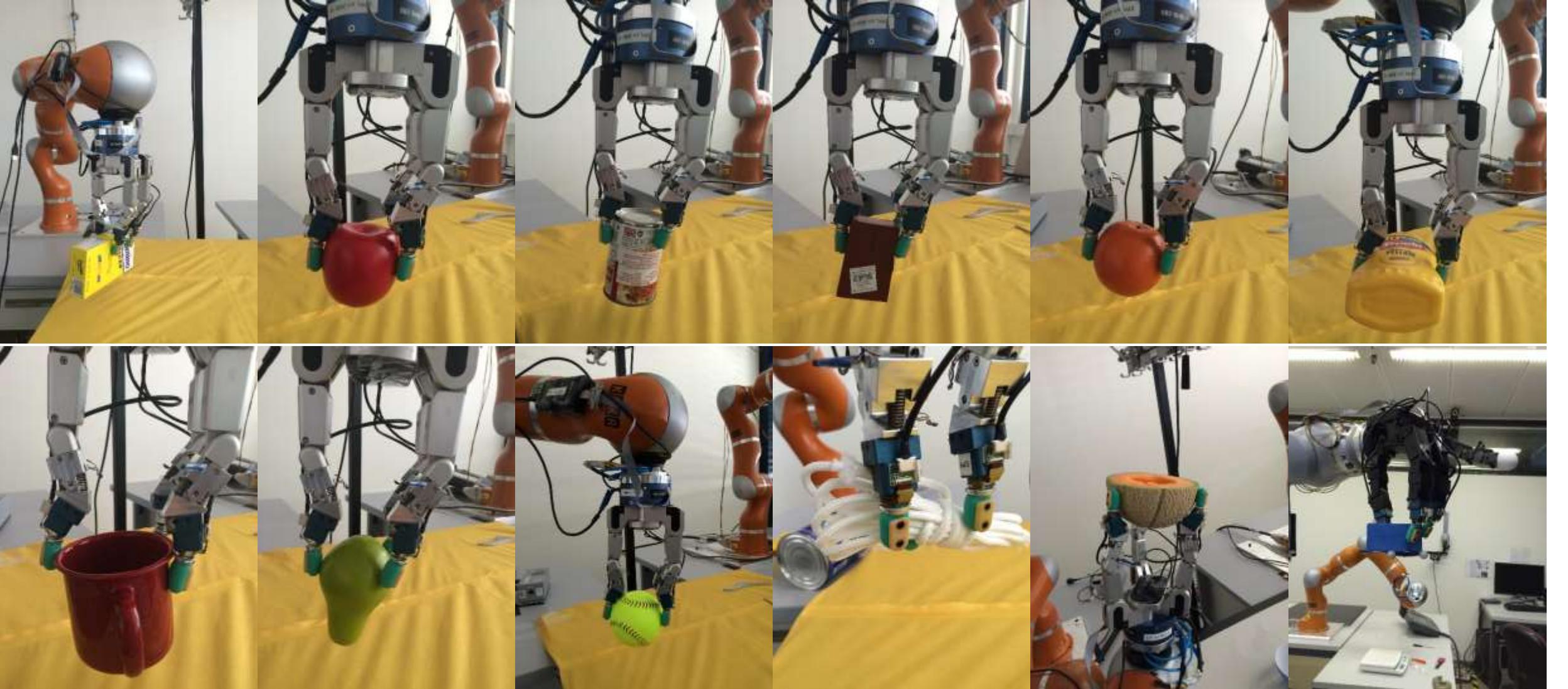


# Motion Transmission

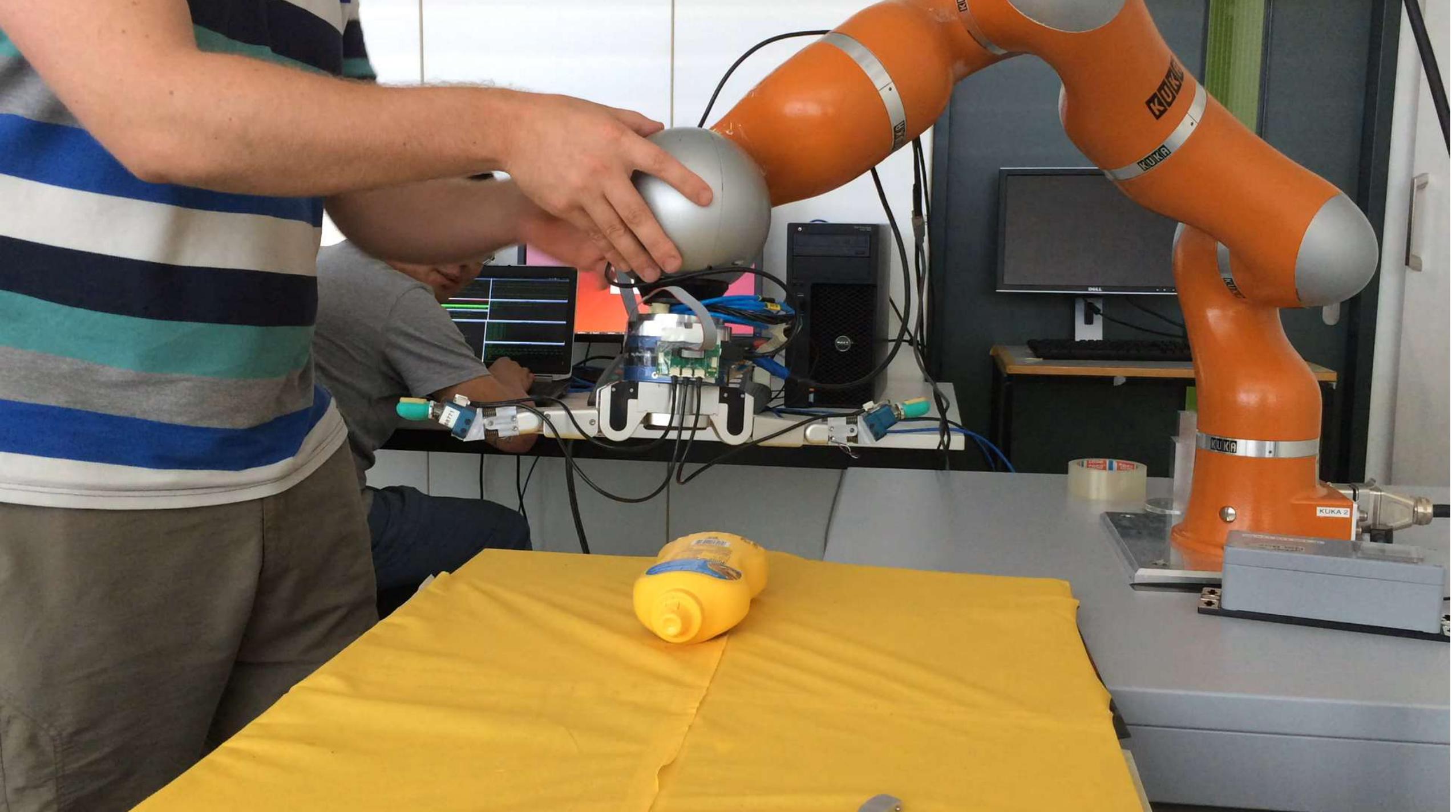


**No(few) Deformation!**

**Back-drivable is already good enough  
for rigid hand!**

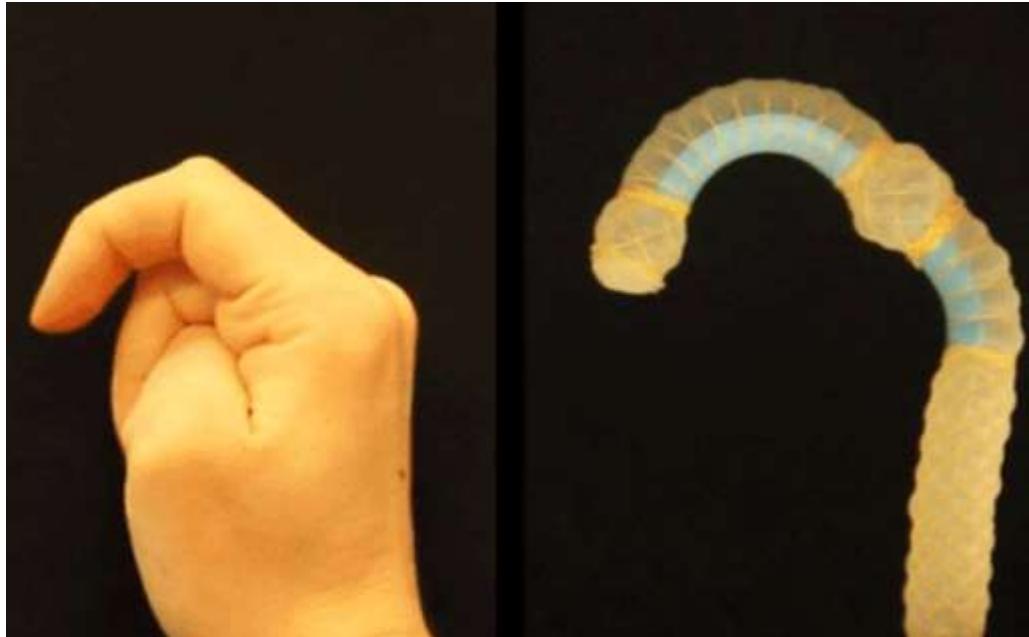


Add some deformation to right hand!





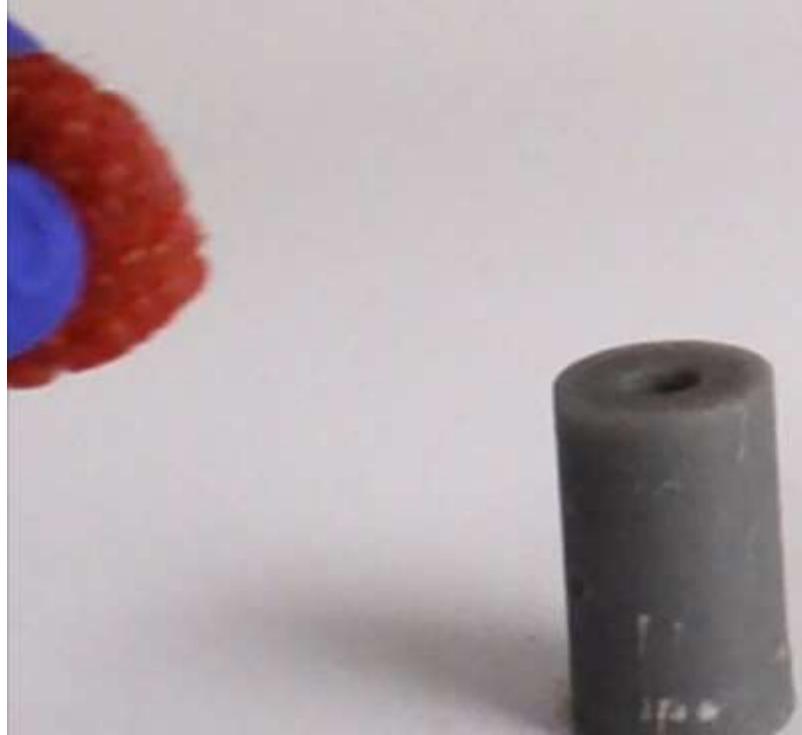
# Motion Transmission



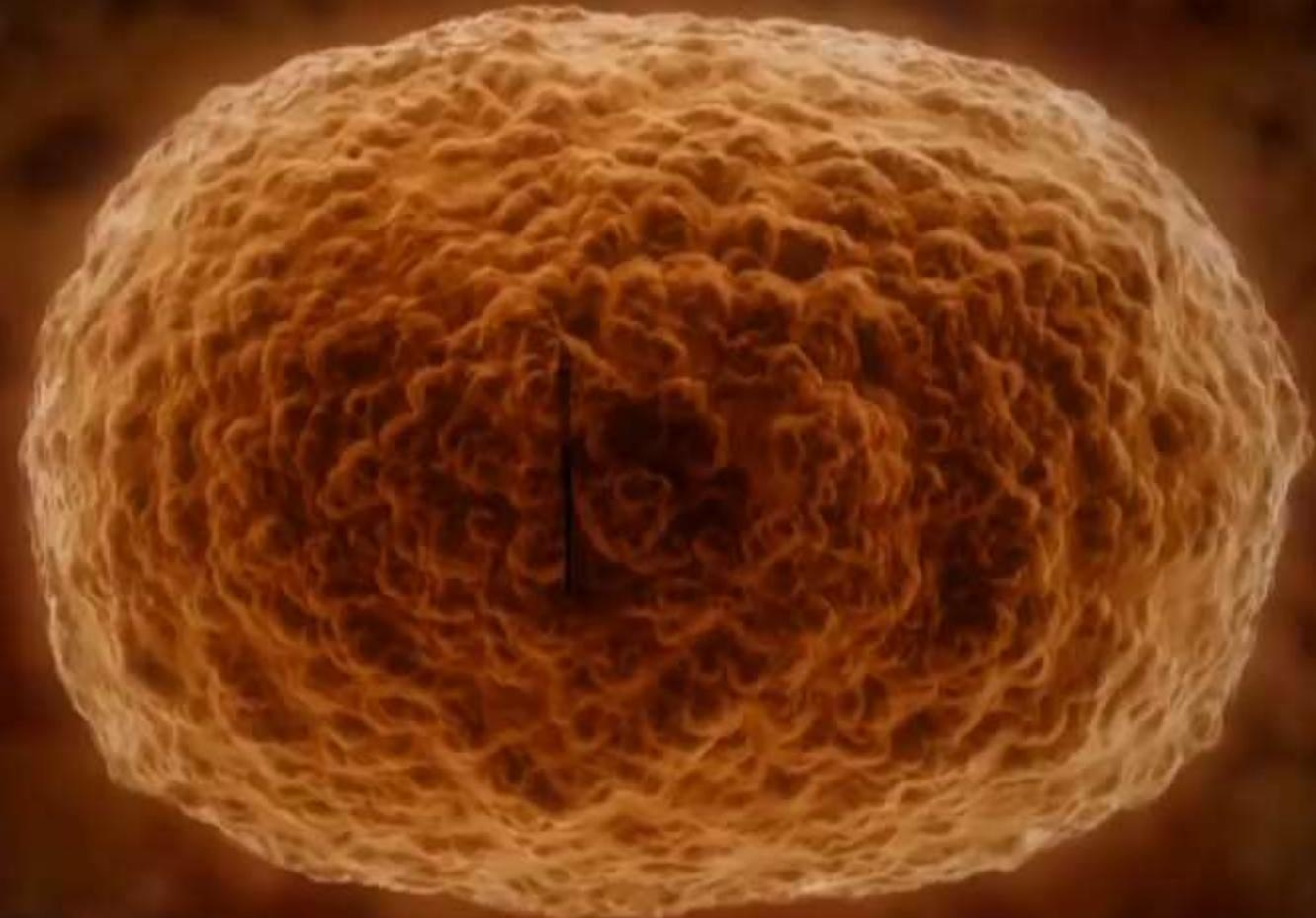
**Deformation is motion!  
Shape is function!**

Video  
(1 mins)

# HOW DOES A ROBOT PICK UP A RASPBERRY WITHOUT SQUISHING IT?



Video  
(2 mins)



**Video  
(1 mins)**



**But this gripper  
relies on simple  
inflation to  
entangle objects  
and doesn't  
require any  
sensing, planning,  
or feedback  
control.**



**Video  
(1 mins)**





# Actuator

- electric motors;
- pneumatic actuators;
- hydraulic actuators;
- shape memory alloys (SMA).

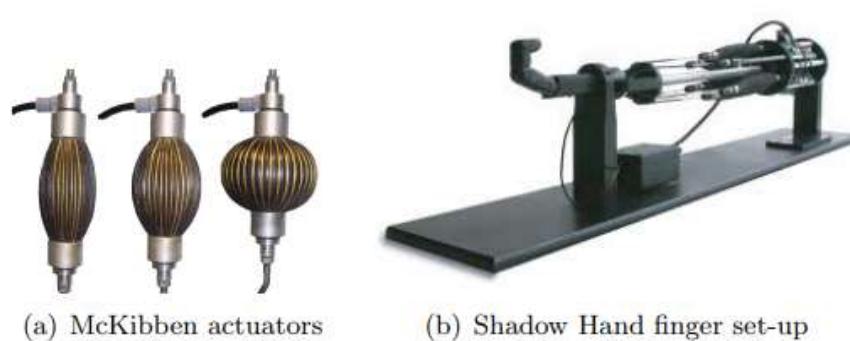
Proprieties class	Power density $\rho$ [W/Kg]	$\sigma_{max}$ [MPa]	$\epsilon_{max}$	E [GPa]	Efficiency
DC motors	100	0.1	0.4	*	0.6–0.8
Pneumatic	400	0.5–0.9	1	$5\text{--}9 \times 10^{-4}$	0.4–0.5
Hydraulic	2,000	20–70	1	2–3	0.9–0.98
SMA	1,000	100–700	0.07	30–90	0.01–0.02
Human muscle	500	0.1–0.4	0.3–0.7	0.005–0.09	0.2–0.25

FIGURE 2.11: Actuator Performance Indices: Power density  $\rho$  = Power per unit of weight,  $\sigma_{max}$  = Maximum force exerted by the actuators per area,  $\epsilon_{max}$  = Maximum run per length, E = Actuator stiffness. Maximum stress and strain are indexes specifically designed for linear actuators. Units are expressed as follow: W Watt, Kg kilogram, MPa Mega Pascal, GPa Giga Pascal.

\*Depending on the gearhead



# Actuator



(a) McKibben actuators

(b) Shadow Hand finger set-up

FIGURE 2.12: Pneumatic actuators for robotic hands

Video  
(5 mins)



# Actuator

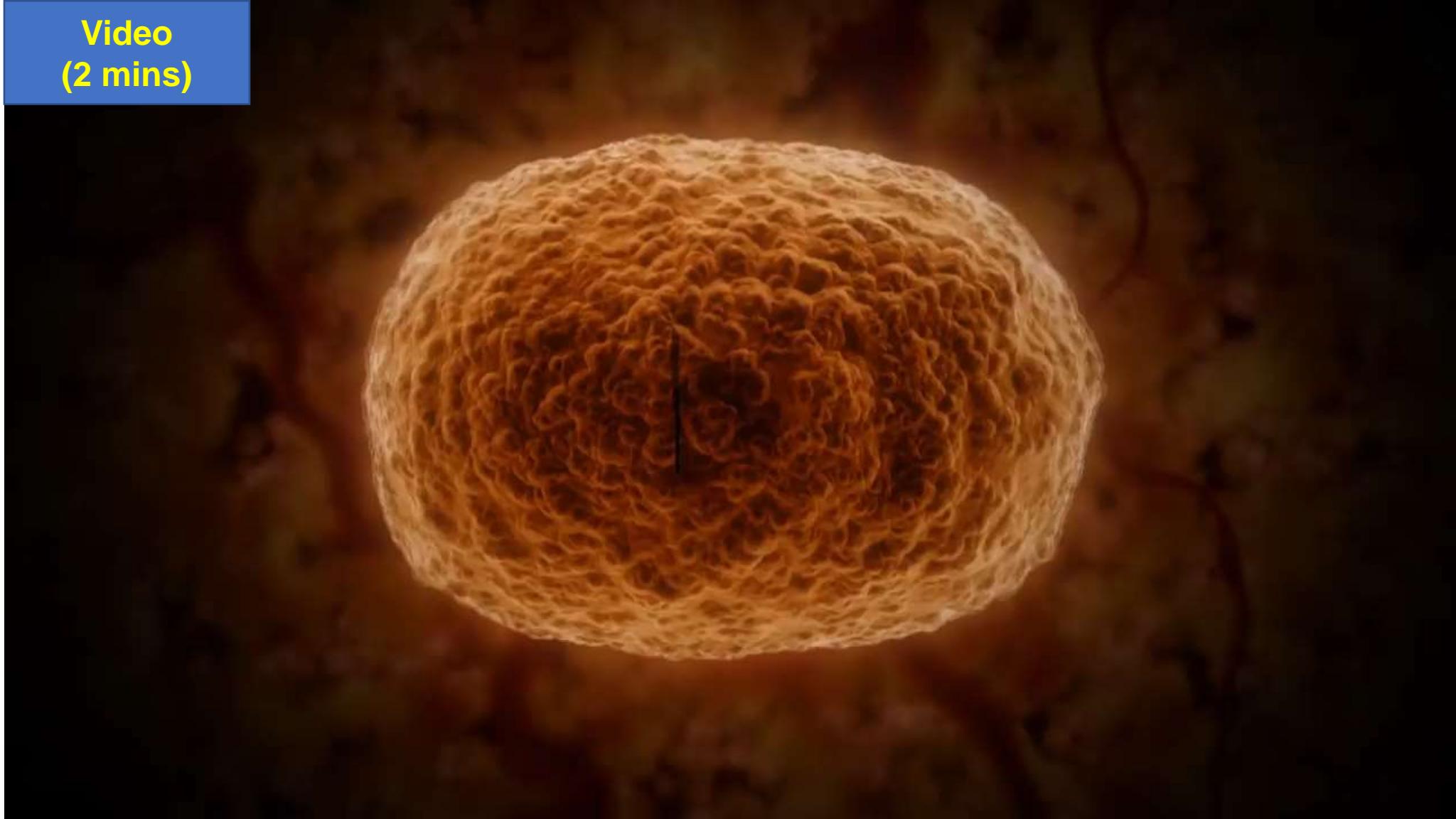
Video  
(3 mins)





# Actuator

Video  
(2 mins)



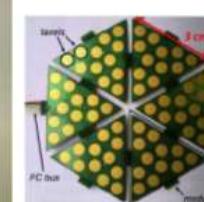
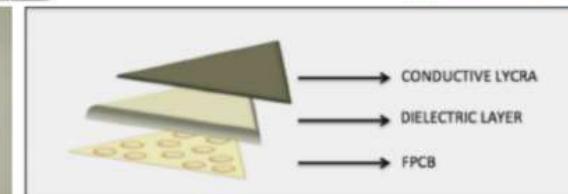
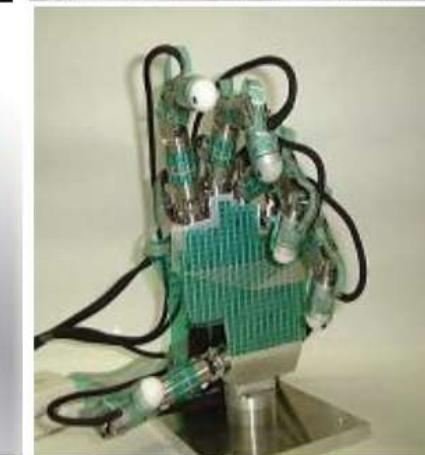
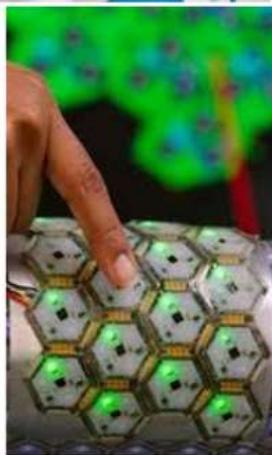
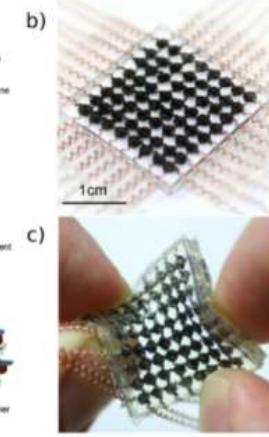
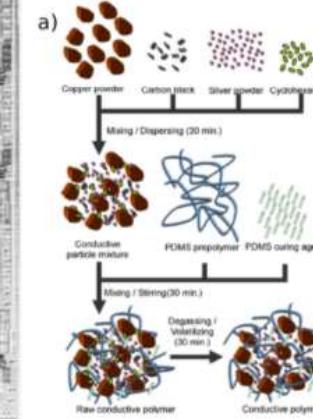
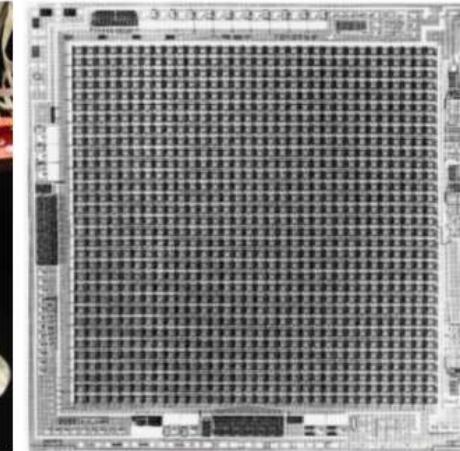
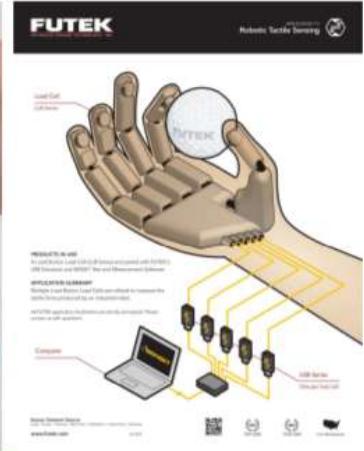


# Sensors

- motor position sensors; ✓
- finger joints position sensors; ✓
- ✓ • motor torque sensors;
- ✓ • joint torque sensors;
- tactile sensors;
- temperature sensors; ✘
- in hand camera.



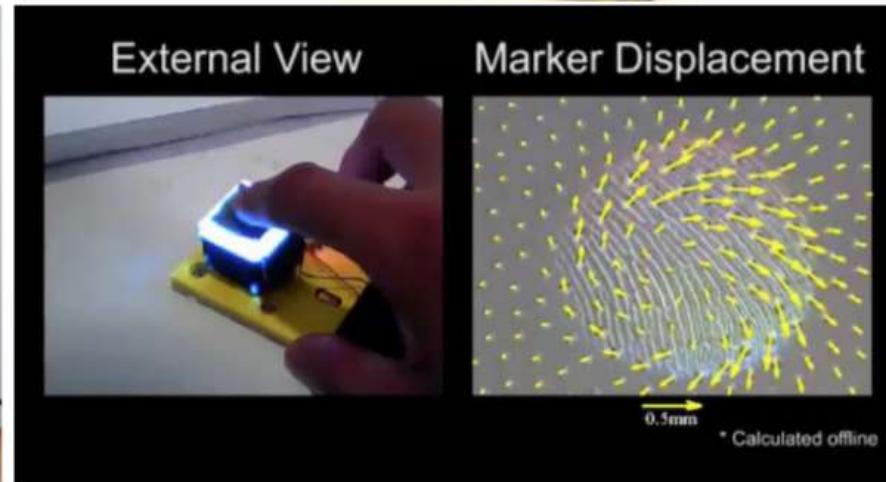
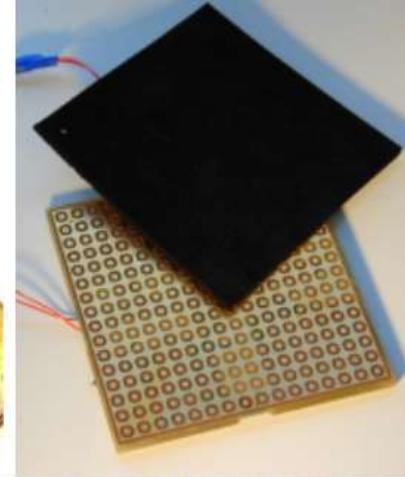
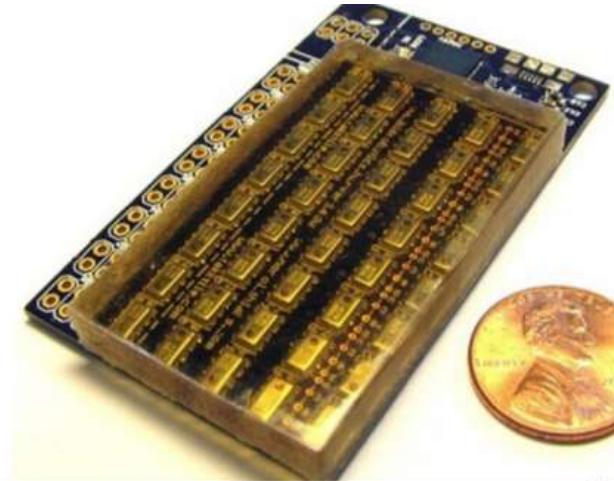
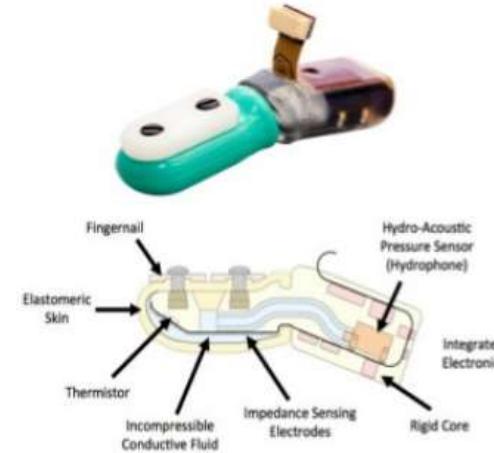
# Sensors



Still a hot topic

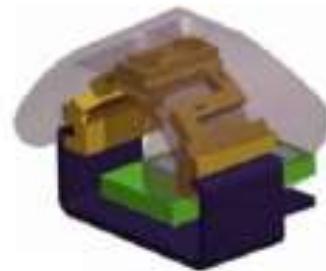


# Sensors





# Sensors



(a) Force/Torque  
sensor [35]



(b) Tendon tension sensor [35]



(c) Single axis  
joint sensor [36]

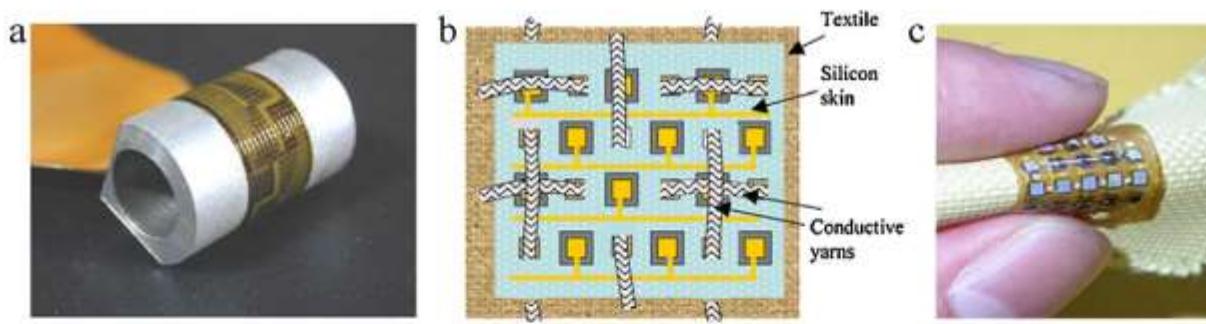


(d) Double axis  
joint sensor [36]

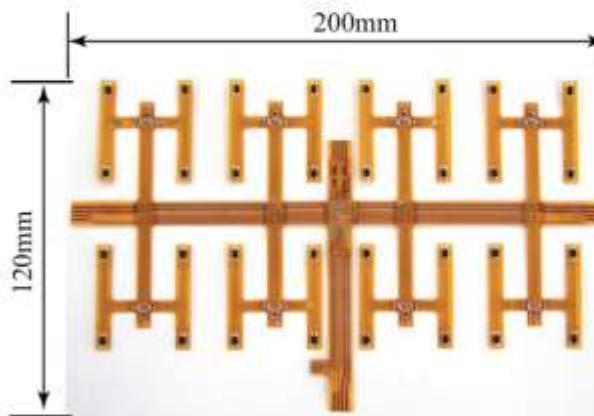
FIGURE 2.15: Force/Torque integrated sensors



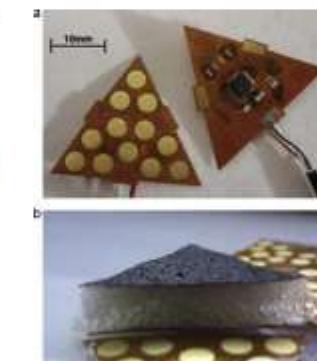
# Sensors



(a) Strain gauges tactile sensor [37]



(b) Led based tactile sensor [38]



(c) Capacitive tactile sensor [39]

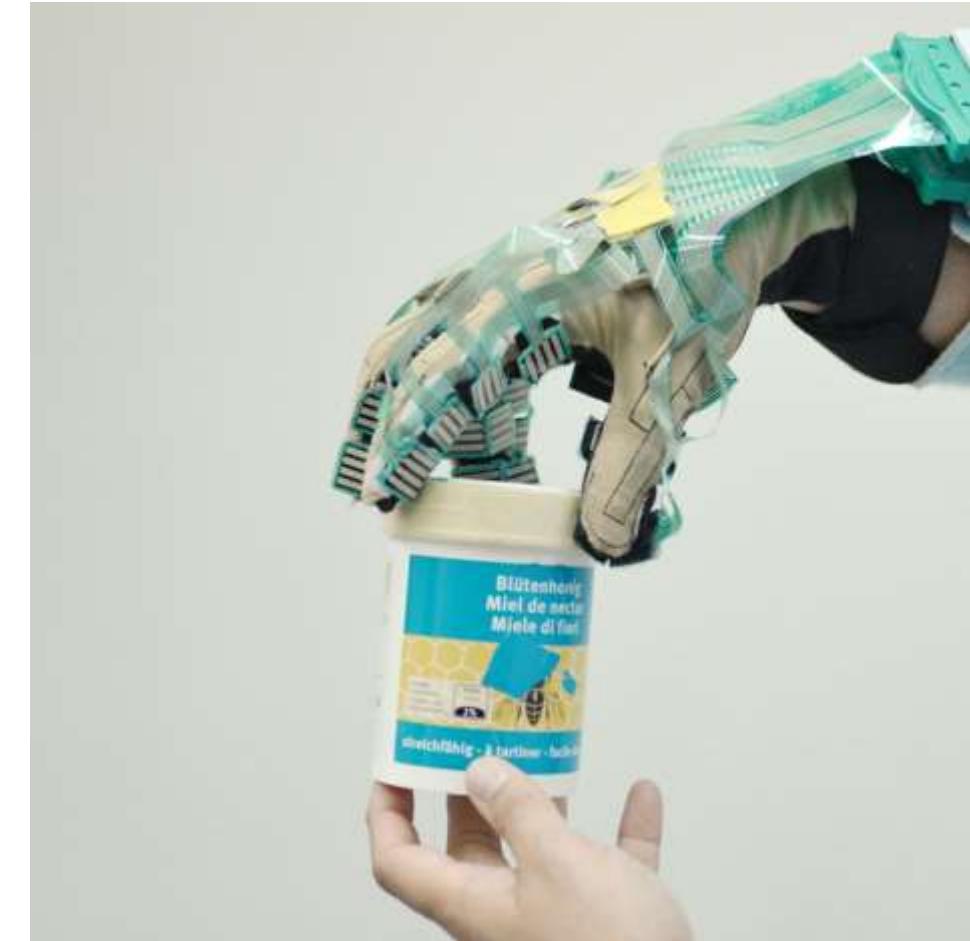
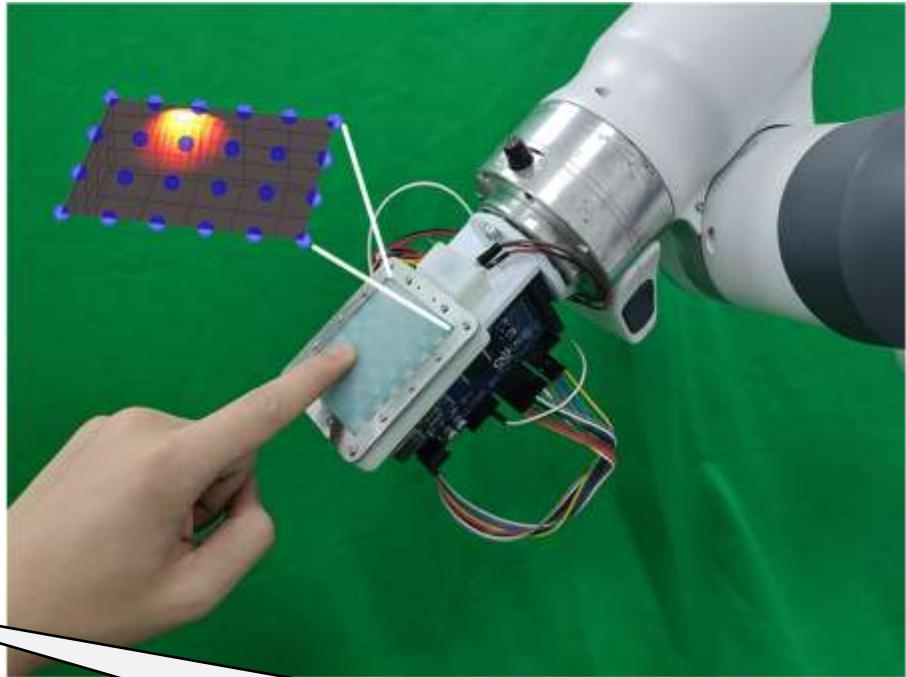


FIGURE 2.16: Tactile sensors

# 柔性触觉传感器



In case you need some tactile  
sensor for your design

A biomimetic tactile palm for robotic object  
manipulation

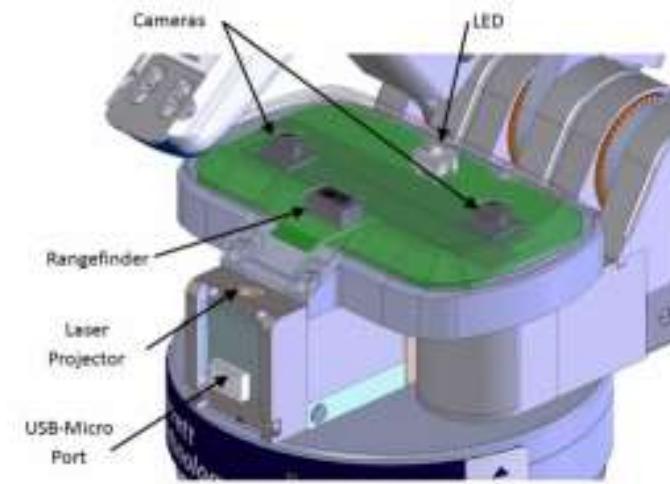
Ziwei Lei<sup>1,3</sup>, Xutian Deng<sup>1</sup>, Yi Wang<sup>1</sup>, Xiaohui Xiao<sup>2</sup>, Dong Han<sup>3</sup>, Fei Chen<sup>4,\*</sup>, Miao Li<sup>1,2,\*</sup>



# Sensors



(a) Barrett Hand



(b) In Hand Cam Integration

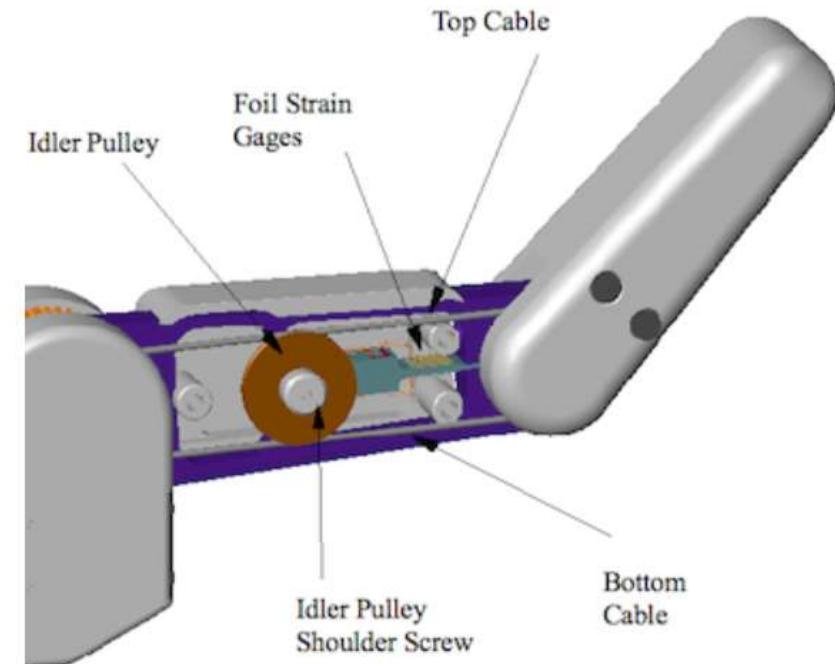
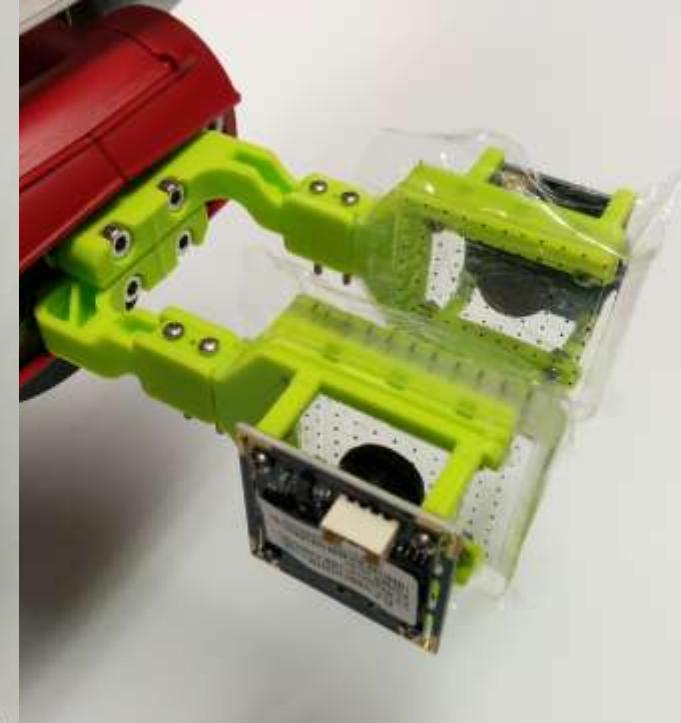
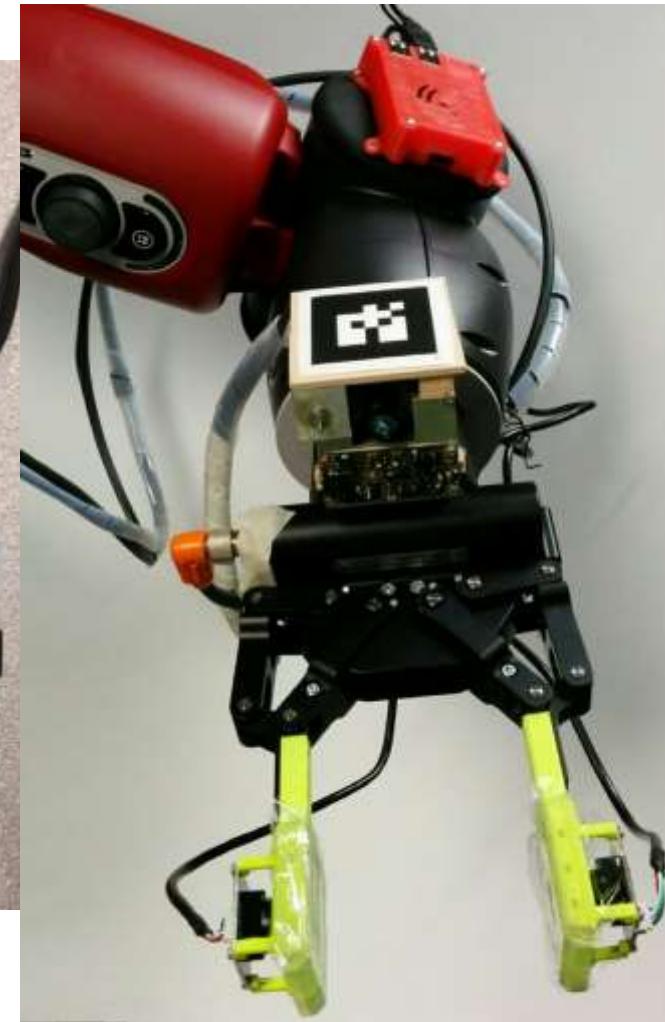


FIGURE 2.17: Patented Hand-Eye integration [32]



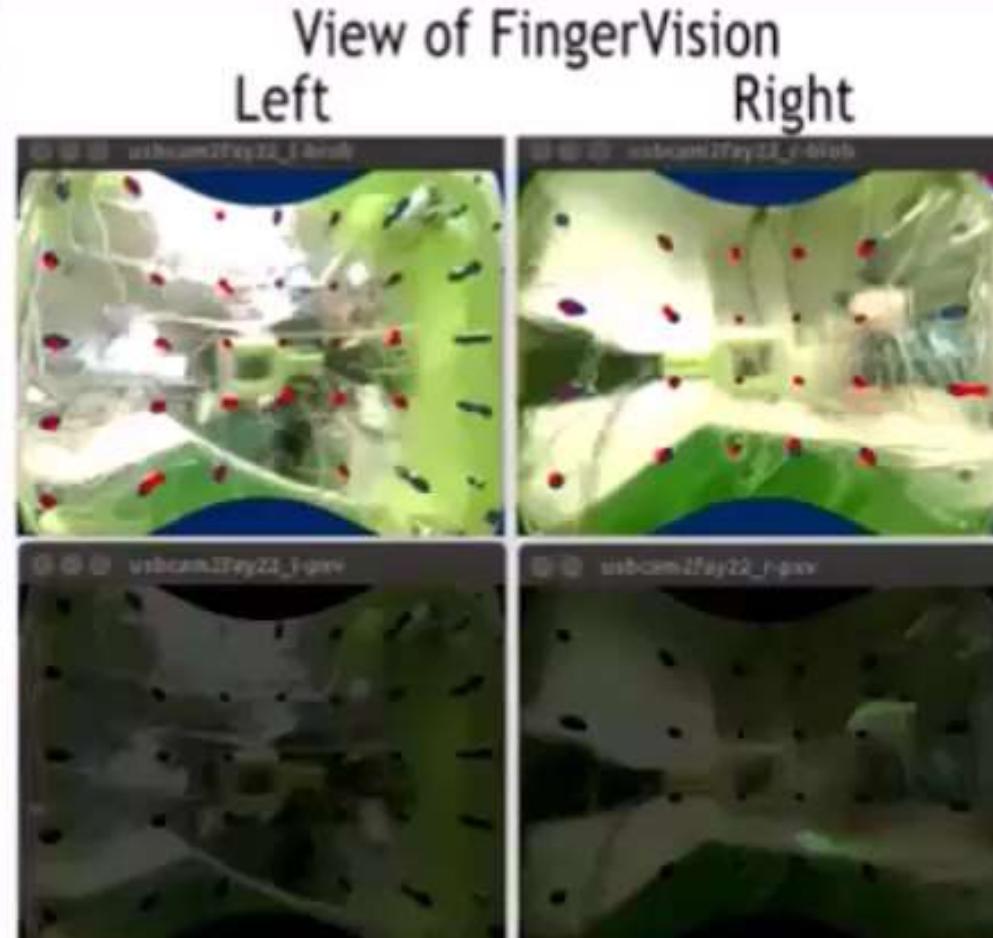
# Sensors





# Sensors

Finger Vision: Tactile Sensing  
Feeling With Your Eyes



✳:Force

✳:Slip

✳:Object



# Sensors

Figure 2.18: Fluid-filled soft-pad concept and prototype.

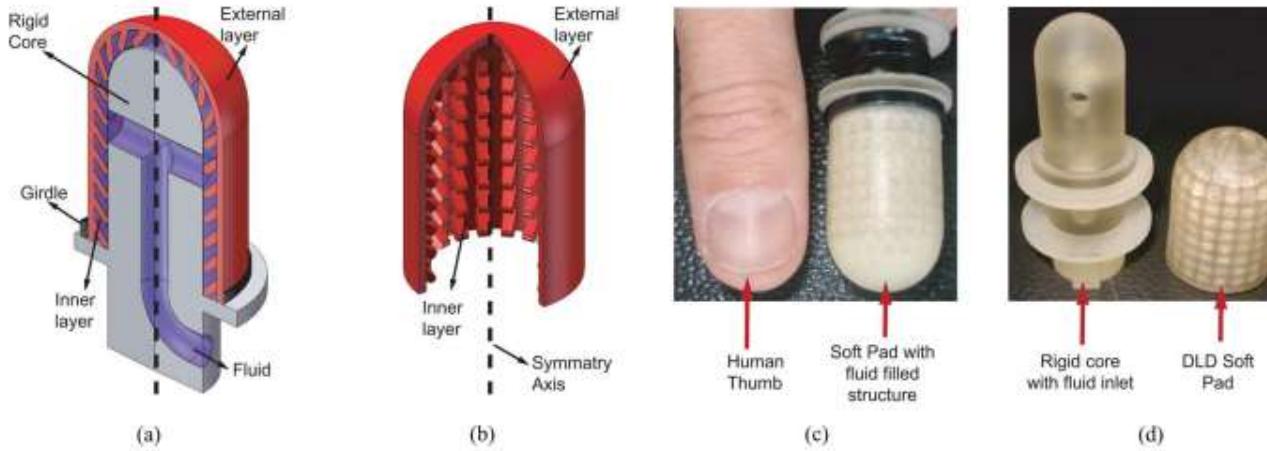
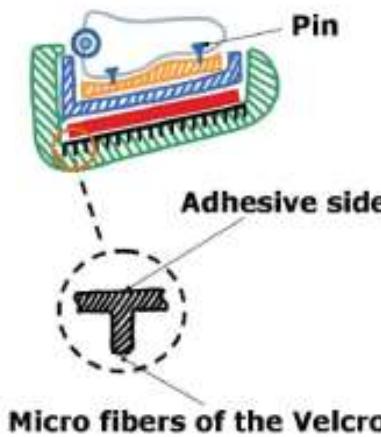


FIGURE 2.18: Fluid-filled soft-pad concept and prototype. (a) 3-D model. (b) Longitudinal cross section. (c) Prototype comparison with human-thumb dimensions. (d) Rigid core with fluid inlet and soft pad.



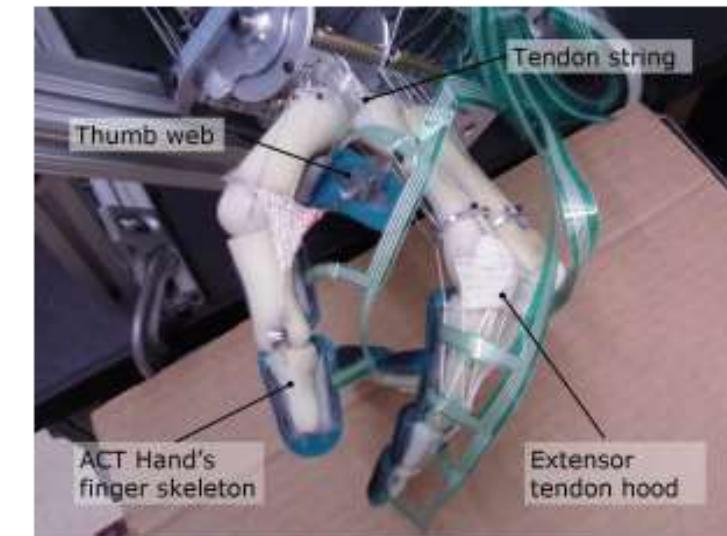


# Sensors



(a) Sensorized artificial skin concept

- ACT Hand finger skeleton
- ▨ Deformable thermoplastic
- ▨ 3D printed frame
- Tactile sensel
- ▨ Velcro embedded silicon rubber skin



(b) Integration of the skin within the robotic hand

FIGURE 2.19: Artificial skin with integrated tactile sensors



# Sensors



**Learning Object Exploration from  
Human Demonstration**

Dr. Sahar El Khoury  
Ravin Luis De Souza

Miao Li

Prof. Aude Billard  
Learning Algorithms and Systems Laboratory  
**EPFL**



# Sensors

Video  
(2 mins)

## Dexterous Bimanual Object Exploration with Whole-hand Tactile Sensing

Nicolas Sommer, Miao Li

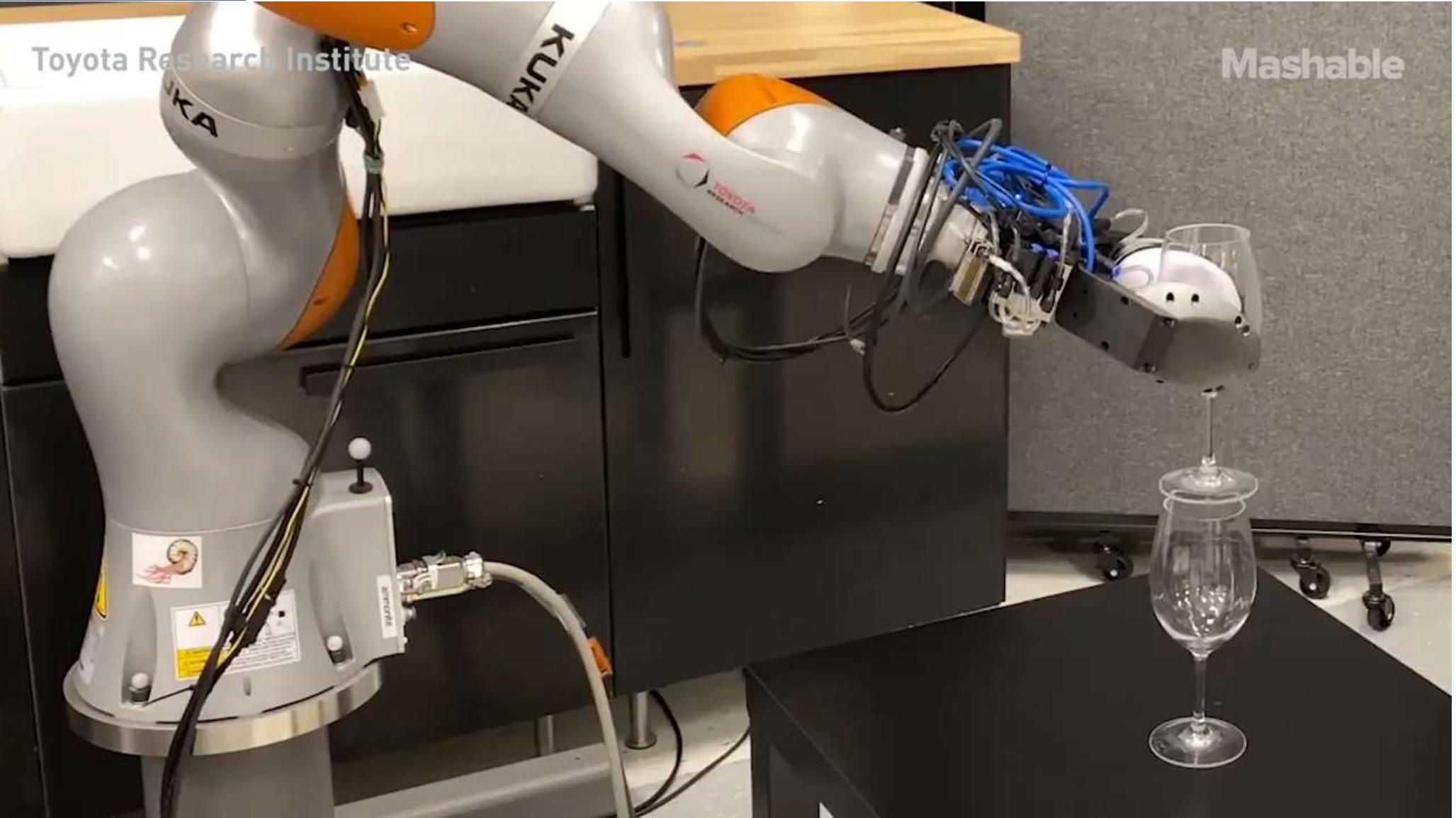
Aude Billard

Learning Algorithms and Systems Laboratory  
EPFL



Video  
(1 mins)

# Sensors



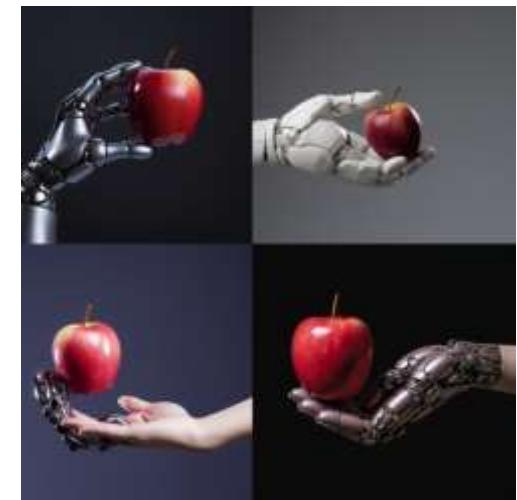
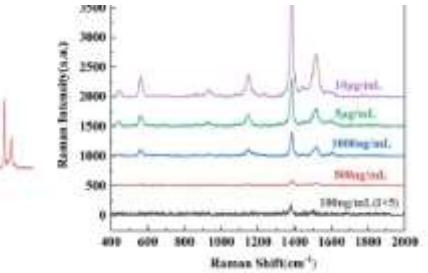
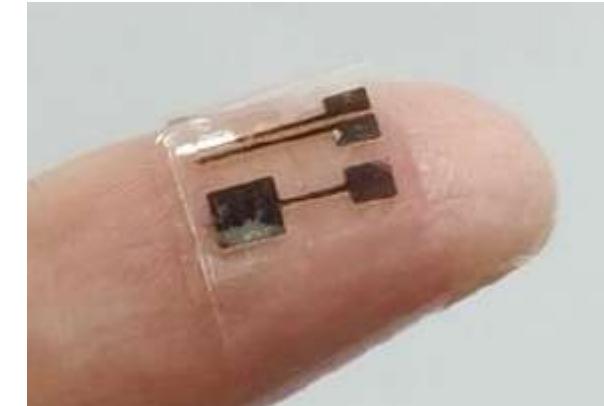


# Sensors

Attach the device to the palm of your hand



Can we attach this sensor  
to something else?

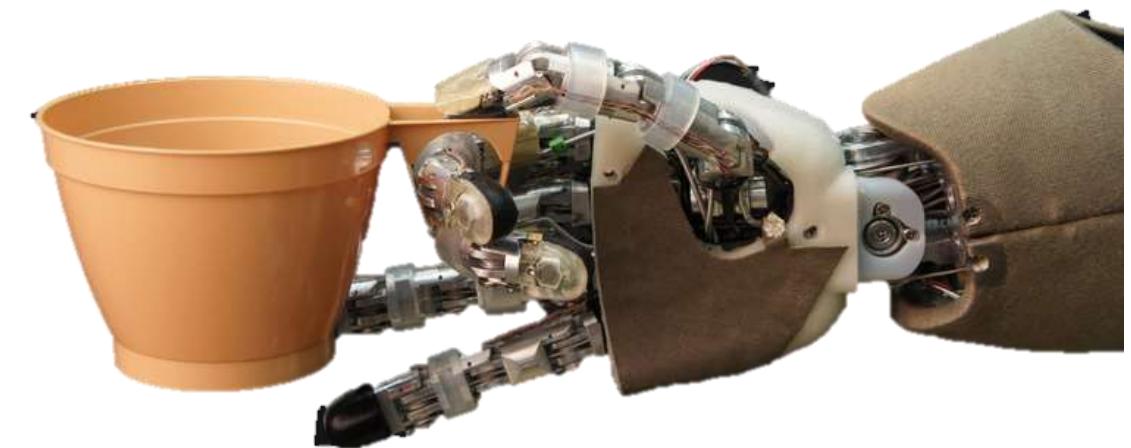


Please join us if you are interested in this project!



# Today

- Design and Modelling of typical robotic arm/hand
- DH parameters
- Kinematics, IK, Jacobian
- Soft hand
- Grasp planning and control
- Simulation tool introduction
- Group list



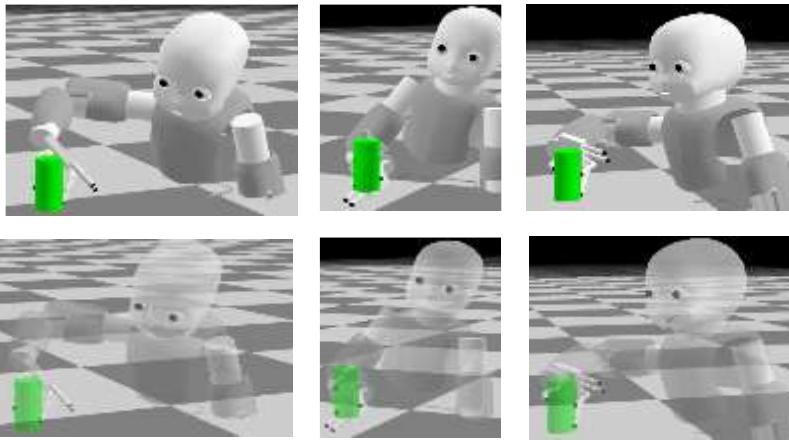


# Goal for this course

- Design: soft hand design **x1** ✓
- Perception: vision, point cloud, tactile, force/torque **x1**
- Planning: sampling-based, optimization-based, learning-based **x3**
- Control: feedback, multi-modal **x2**
- Learning: imitation learning, RL **x2** 
- Simulation tool (pybullet, matlab, OpenRAVE, Issac Nvidia, Gazebo)
- **How to get a robot moving!**



# Grasp planning



**Grasp Planning as Optimization**

$$\arg \min_{\theta, H, p, n} f(\theta, H, p, n)$$

subject to:

$$h_i(\theta_i, H) - p_i = 0$$
$$l_i(\theta_i, H) - n_i = 0$$
$$g(p_i) = 0$$
$$\nabla g(p_i) \times n_i = 0$$
$$\nabla g(p_i) \cdot n_i < 0$$
$$Q_{\text{task}}(\theta, H, p, n) \in \mathcal{G}_{\text{task}}$$

objective function

hand constraints

object constraints

task constraints

where  $\theta = (\theta^{1T}, \dots, \theta^{NT})^T$  is the vector of the generalized joint positions for  $N$  fingers.  $H \in SE(3)$  represents the hand position and orientation.  $p = (p^{1T}, \dots, p^{NT})^T$  and  $n = (n^{1T}, \dots, n^{NT})^T$  is the vector of fingertip positions and normal directions.  $h_i$  and  $l_i$  are functions derived from hand forward kinematics, to compute fingertip positions and normal direction.  $g$  is the implicit representation of the object surface and  $\nabla g(p^i)$  is the outward normal direction of object surface at  $p^i$ .  $Q_{\text{task}}$  represents the task constraints and  $\mathcal{G}_{\text{task}}$  contains all the grasp that suitable for the task.





# Grasp control

**Robotic Hands**

**STABILITY OF VARIABLE GRASP STIFFNESS CONTROL**

We want to address the control stability of grasping stiffness in robotic grasping using a two-degree-of-freedom system, as shown in the figure. We derived a detailed formula for the dynamics of stiffness and the effect of perturbations on the grasp, giving the object center and force from the point of contact.

**Complicated with many assumptions**

**B.1. DYNAMICS**

This part, we first consider the contact model of the fingertip and the constraints under the hand contact system. Then the overall dynamics of the grasping system. The dynamics of the system are represented in Fig. B.1 to simplify the understanding of the grasping dynamics.

**B.1.1 CONTACT MODEL OF FINGERTIPS**

$$F = \alpha_1(\theta)^T + \alpha_2(\theta) \frac{d\theta}{dt} \quad (B.1)$$

**B.1.2. RELATING COMPLEXITY**

While  $\alpha_1$  and  $\alpha_2$  are positive constant matrices which depend on the position of the fingertip and  $d\theta/dt$  is the derivative of the fingertip. The fingertip should be in contact with the object surface, as shown in Fig. B.1(b), which can be expressed as follows:

$$\alpha_1 \cdot \alpha_1^T - \alpha_2 \cdot \alpha_2^T = I \quad (B.2)$$

$$\alpha_1 \cdot \alpha_1^T - \alpha_2 \cdot \alpha_2^T = I \quad (B.3)$$

From the condition in equation B.2, the contact of surfaces can be simplified as

$$I = \sum_{i=1}^n (\frac{\partial \alpha_1}{\partial \theta_i})^2 - \sum_{i=1}^n (\frac{\partial \alpha_2}{\partial \theta_i})^2 = 0 \quad (B.4)$$

$$I = \sum_{i=1}^n (\frac{\partial \alpha_1}{\partial \theta_i})^2 - \sum_{i=1}^n (\frac{\partial \alpha_2}{\partial \theta_i})^2 = 0 \quad (B.5)$$

$$I = \sum_{i=1}^n (\frac{\partial \alpha_1}{\partial \theta_i})^2 - \sum_{i=1}^n (\frac{\partial \alpha_2}{\partial \theta_i})^2 = 0 \quad (B.6)$$

From the condition in equation B.3, the contact of surfaces can be simplified as

$$I = (\alpha_1 \cdot \alpha_1^T - \alpha_2 \cdot \alpha_2^T) \cdot I = (\alpha_1 \cdot \alpha_1^T - \alpha_2 \cdot \alpha_2^T) \cdot I = 0 \quad (B.7)$$

$$I = (\alpha_1 \cdot \alpha_1^T - \alpha_2 \cdot \alpha_2^T) \cdot I = (\alpha_1 \cdot \alpha_1^T - \alpha_2 \cdot \alpha_2^T) \cdot I = 0 \quad (B.8)$$

$$I = (\alpha_1 \cdot \alpha_1^T - \alpha_2 \cdot \alpha_2^T) \cdot I = (\alpha_1 \cdot \alpha_1^T - \alpha_2 \cdot \alpha_2^T) \cdot I = 0 \quad (B.9)$$

**B.1.3. OVERALL STATEMENT**

The constraint energy for the overall system can be described as follows:

$$U = \sum_{i=1}^n \frac{1}{2} \alpha_i^T P \alpha_i + \frac{1}{2} \theta^T Q \theta + \frac{1}{2} \dot{\theta}^T R \dot{\theta} \quad (B.10)$$

where  $\alpha_i = [\alpha_1, \alpha_2]^T$  is the vector of finger force and  $\theta = \theta^{opt}$  is the deformation for each finger.  $P$  and  $Q$  are the mass and inertia matrix of the object respectively. The total potential energy when deformation can be given as

$$U = \sum_{i=1}^n \int_{\theta_i}^{\theta_i^*} \int_{\theta_i^*}^{\theta_i} \alpha_i^T P \alpha_i \quad (B.11)$$

Then from the Hamilton's principle, we have

$$\int_{\theta_i}^{\theta_i^*} \int_{\theta_i^*}^{\theta_i} \alpha_i^T P \alpha_i d\theta_i + \sum_{i=1}^n \dot{\theta}_i \frac{\partial U}{\partial \dot{\theta}_i} = \sum_{i=1}^n \dot{\theta}_i \frac{\partial U}{\partial \dot{\theta}_i} + \sum_{i=1}^n \alpha_i^T \dot{\theta}_i \alpha_i = 0 \quad (B.12)$$

Since  $X = [\alpha_1^T, \alpha_2^T]^T = \alpha^T$ . Therefore, we have overall dynamics for the object-hand system as follows:

$$\dot{X} = \alpha^T \dot{\theta} = P \dot{\theta} = \frac{d\alpha}{d\theta} \cdot \dot{\theta} = \frac{d\alpha}{d\theta} \cdot \left( \frac{d\theta}{d\dot{\theta}} \cdot \dot{\theta} \right) = \frac{d\alpha}{d\theta} \cdot \theta = 0 \quad (B.13)$$

**TU Berlin** **RBO**

**Surprisingly Robust In-Hand Manipulation: An Empirical Study**

Aditya Bhatt\* Adrian Sieler\* Steffen Puhmann Oliver Brock

Presented at RSS 2021

\* Both authors contributed equally to this work.

# Model-based → Learning-based

**ICRA**

May 30 to June 5, 2021

Xi'an China



# Soft Robotics for Delicate and Dexterous Manipulation

**Robert Wood**  
Harvard University

**ICRA 2021 Plenary Talk**  
June 4, 2021



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Automation  
Society

IEEE 2021

**ICRA**

May 30 to June 5, 2021

Xi'an China



# Soft Robotics for Delicate and Dexterous Manipulation

**Robert Wood**  
Harvard University



**ICRA 2021 Plenary Talk**  
June 1, 2021

