Robotics

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Fall 2023, Wuhan University

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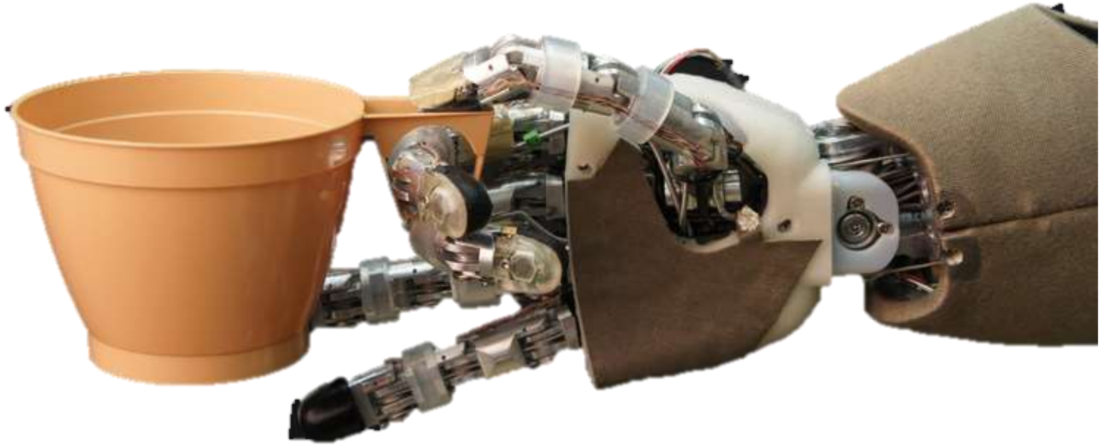
Today

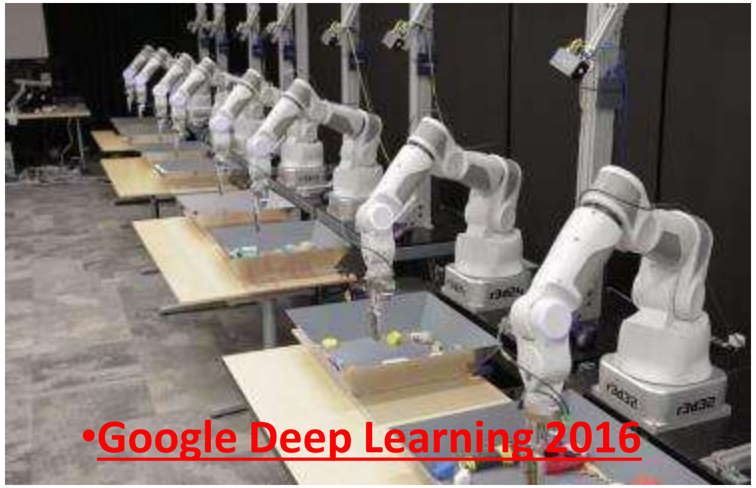
- **Design and Modelling of typical robotic arm/hand**
- **DH parameters**
- **Kinematics, IK, Jacobian**
- **Soft hand**
- **Grasp planning**
- **Simulation tool introduction**
- **Group list**



Why robotic hand and grasping?

Grasping and manipulation is an essential skill for humans

Why robotic hand and grasping?



•Google Deep Learning 2016

•10 Breakthrough Technologies 2015

•18 Months Baby

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…… "

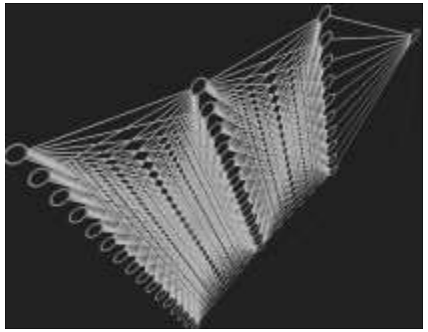
----- Russ Tedrake

Why robotic hand and grasping?

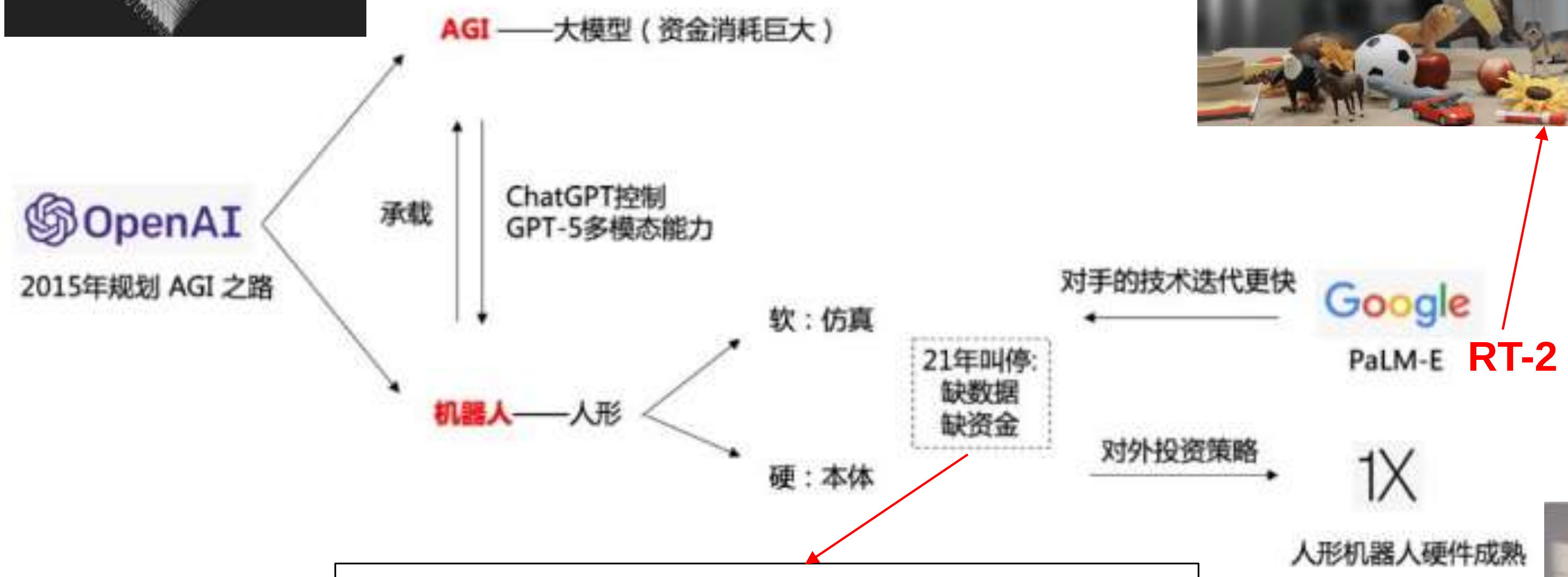




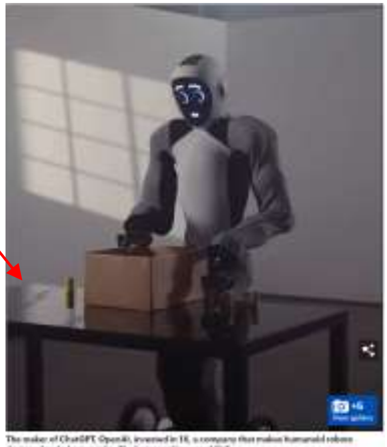




Why hand?

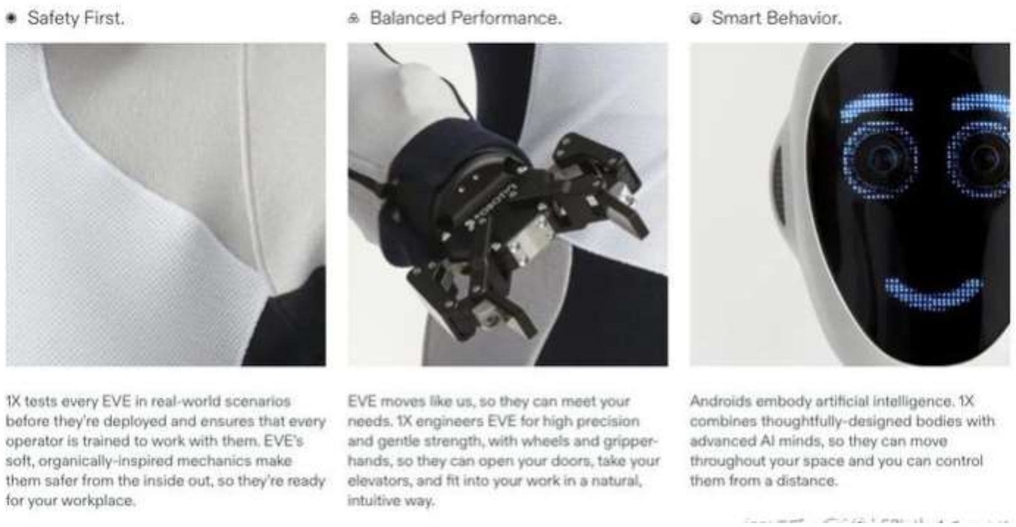


"So it turns out that we can make a gigantic progress whenever we have access to data. And I kept all of our machinery unsupervised, [using] reinforcement learning — [it] work[s] extremely well. There [are] actually plenty of domains that are very, very rich with data. And ultimately that was holding us back in terms of robotics," Zaremba said. "The decision [to disband the robotics team] was quite hard for me. But I got the realization some time ago that actually, that's for the best from the perspective of the company."



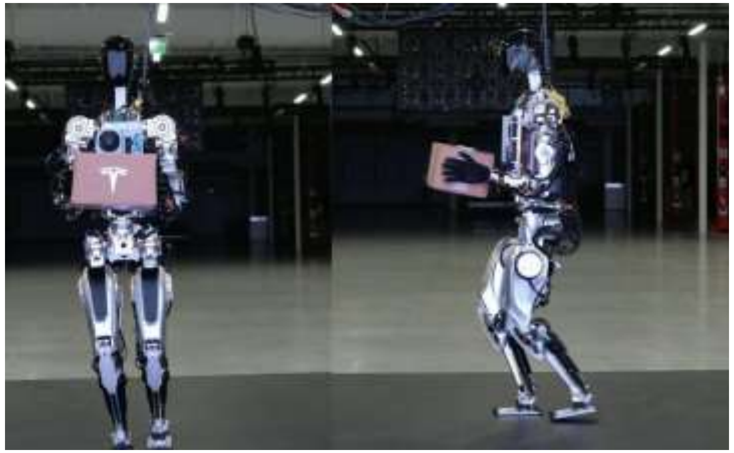
https://venturebeat.com/business/openai-disbands-its-robotics-research-team/

Why hand?



1X

Boston Dynamics



Tesla Bot

Sanctuary

https://www.youtube.com/watch?v=YHk7Czt
k6Lg&ab_channel=SanctuaryAI

Why hand?

RODNEY BROOKS *Robots, AI, and other stuff* BLOG MIT ROBUST.AI

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POST: RESEARCH NEEDED ON ROBOT HANDS

JANUARY 30, 2017 — QUICK TAKES

Research Needed on Robot Hands

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.

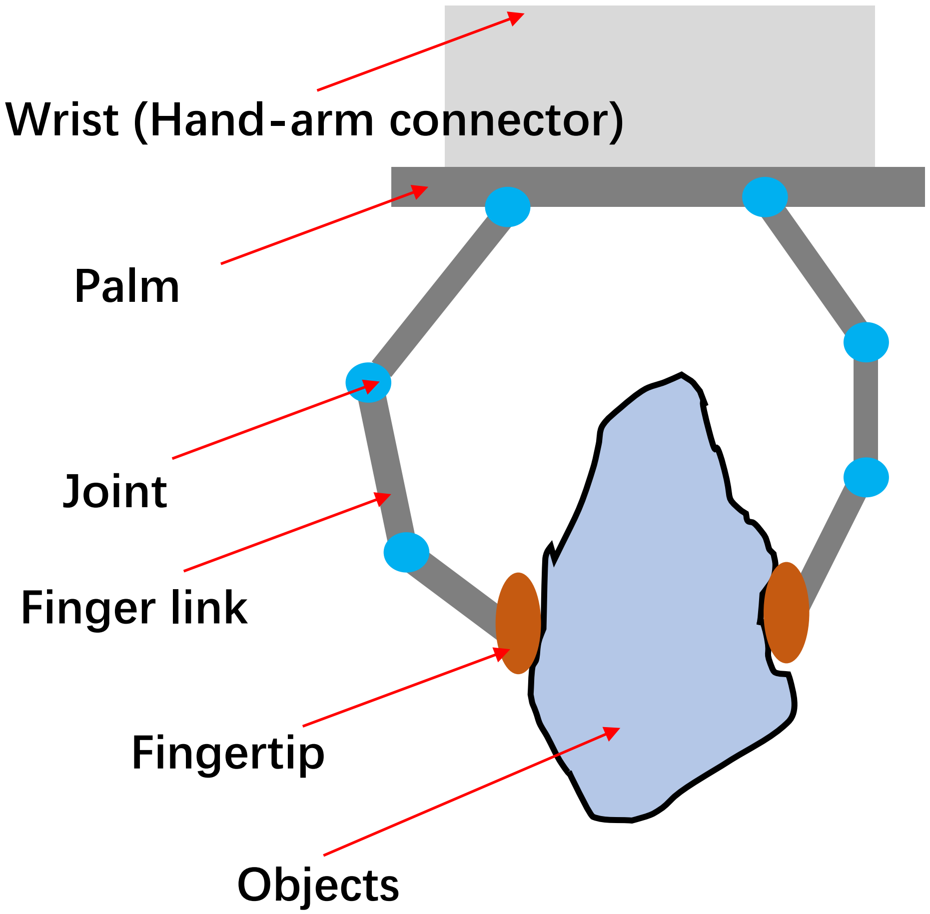
Human hands just work. Give them an object from a very wide class of objects and they grip that object, usually with a wide variety of possible grips. They sense when the grip is failing and adjust. They work reliably and quickly.

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

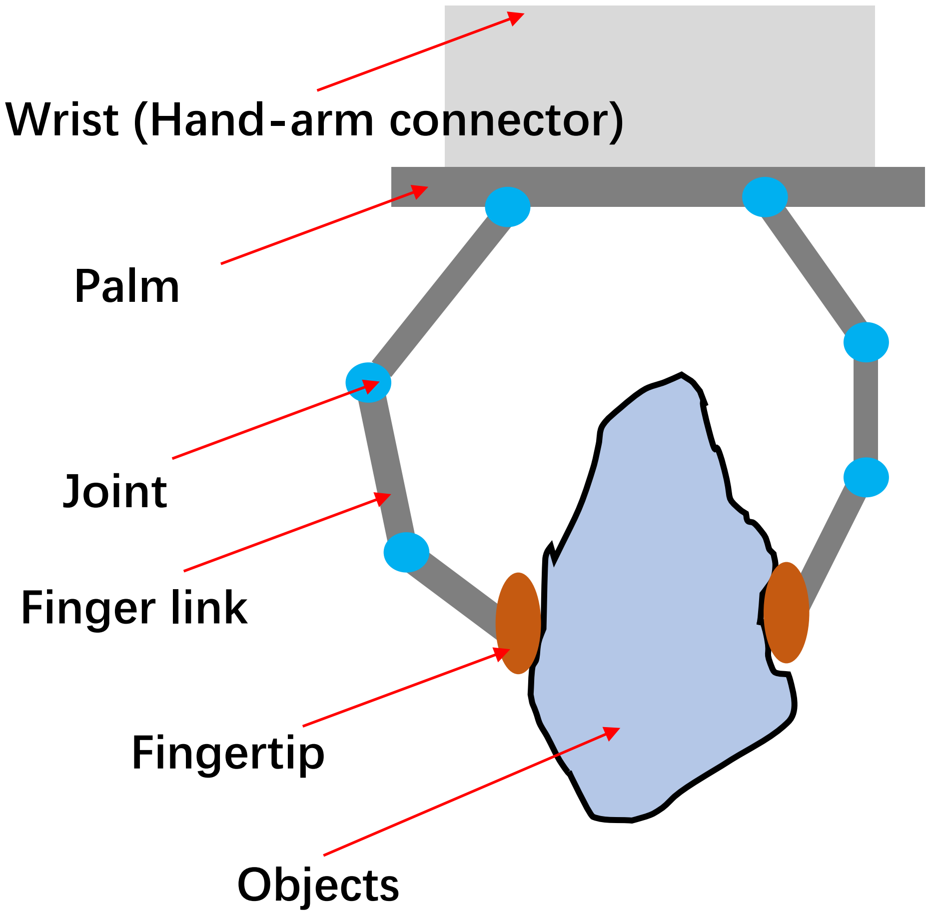
https://rodneybrooks.com/research-needed-on-robot-hands/

A robotic grasping system



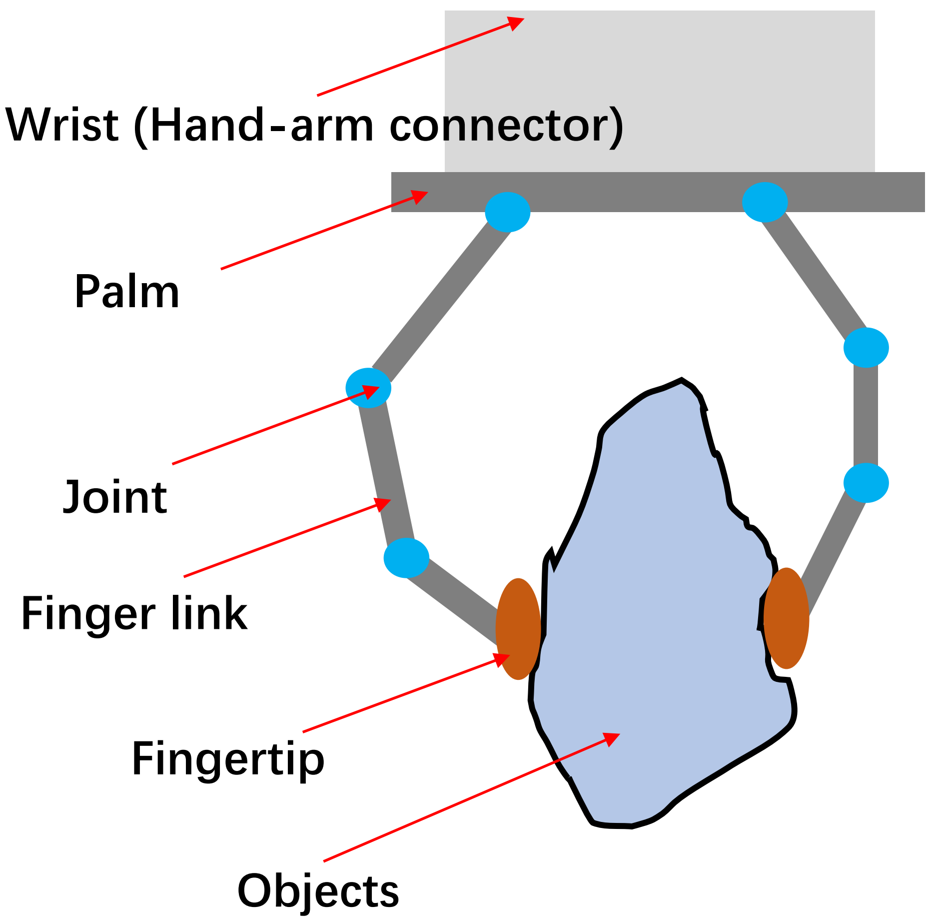
How to design, model, and control a robotic hand?

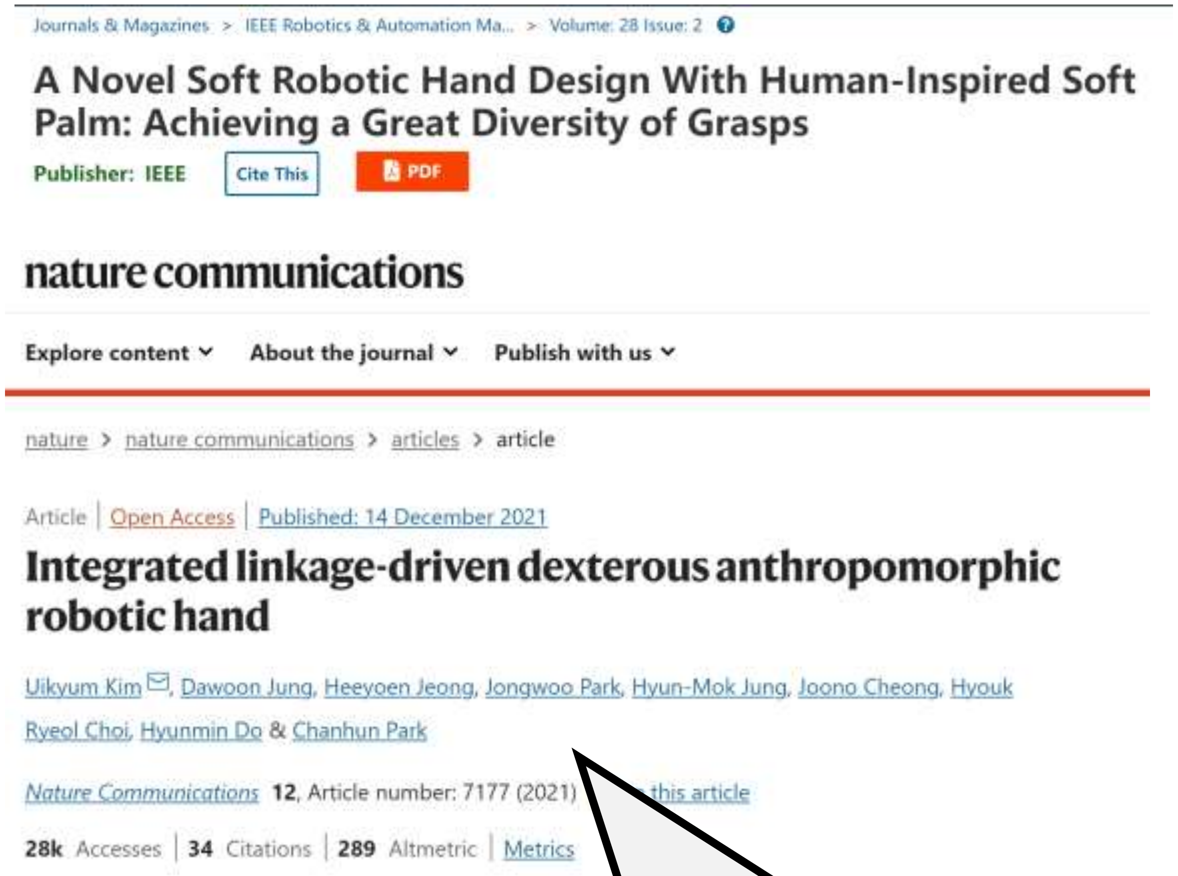
A robotic grasping system



- 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

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Article | Open Access | Published: 14 December 2021

Integrated linkage-driven dexterous anthropomorphic robotic hand

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

Nature Communications **12**, Article number: 7177 (2021) ... this article

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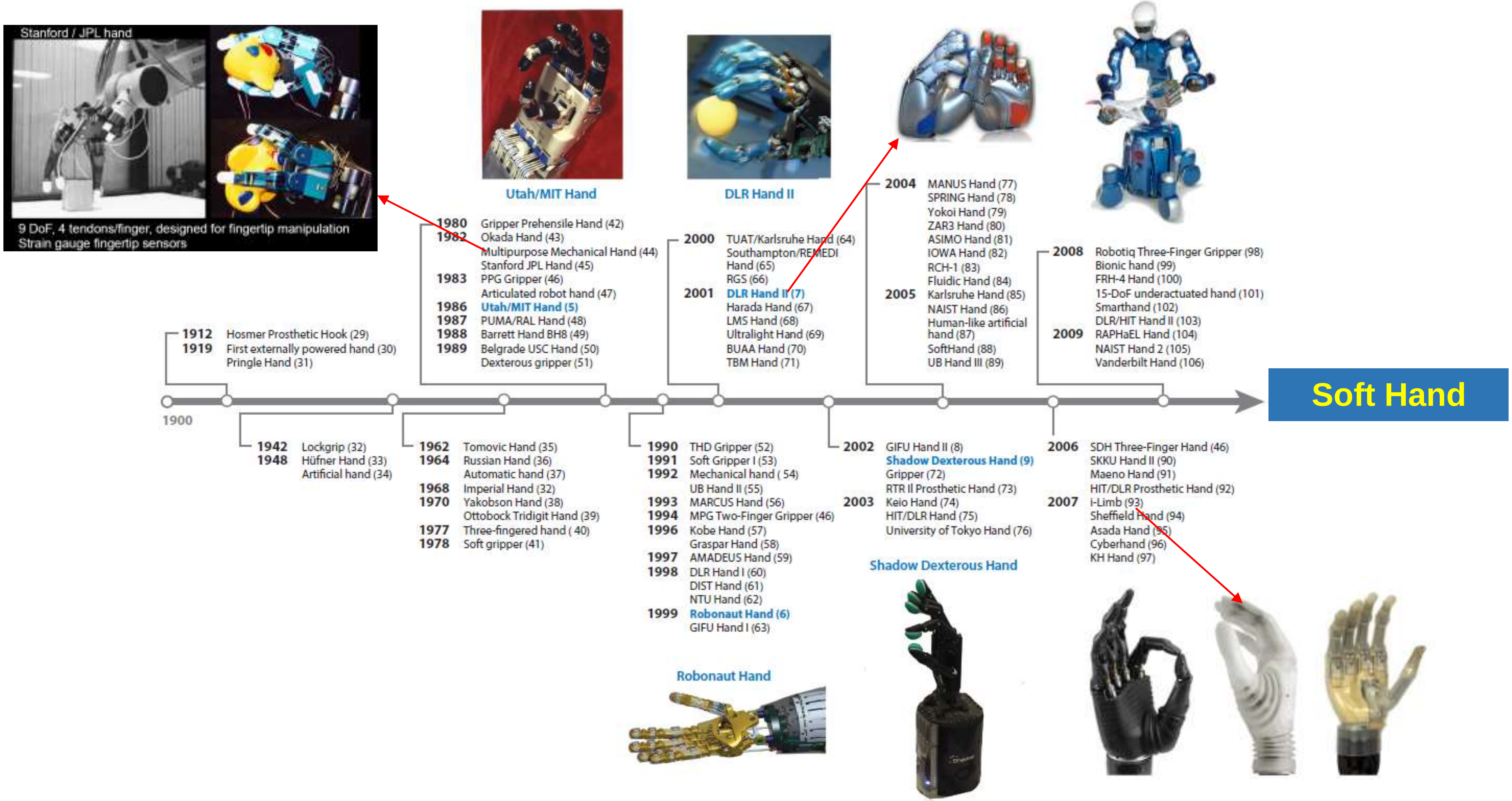
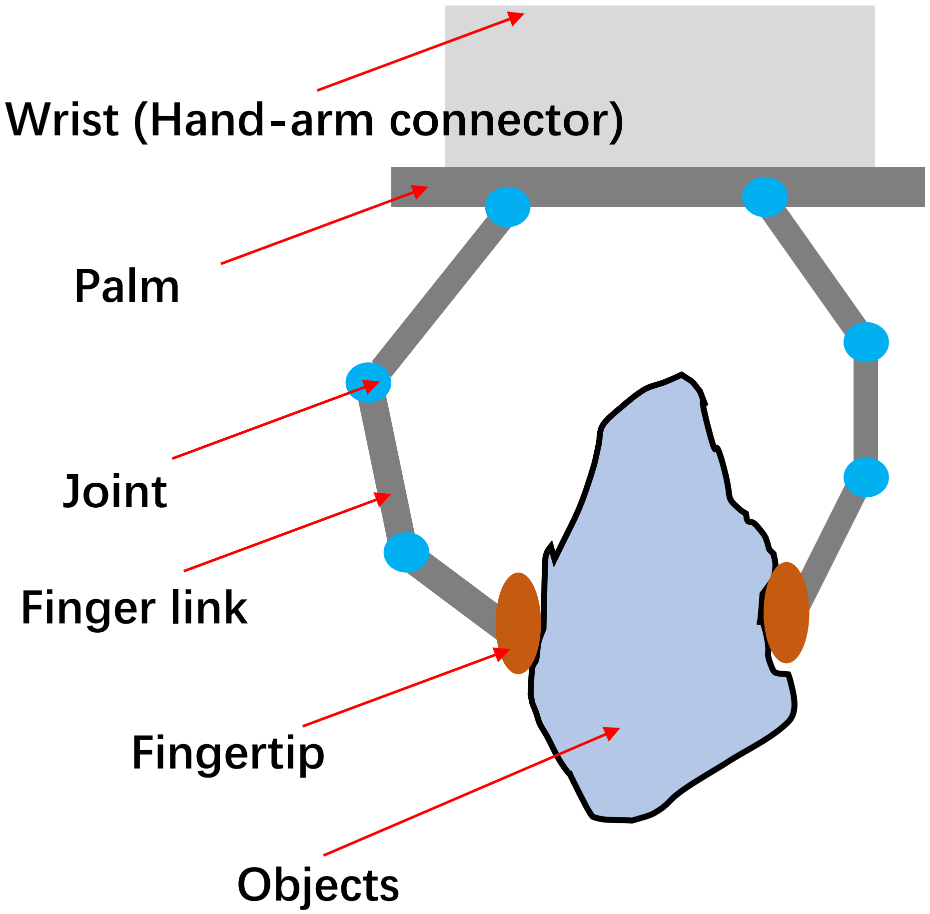
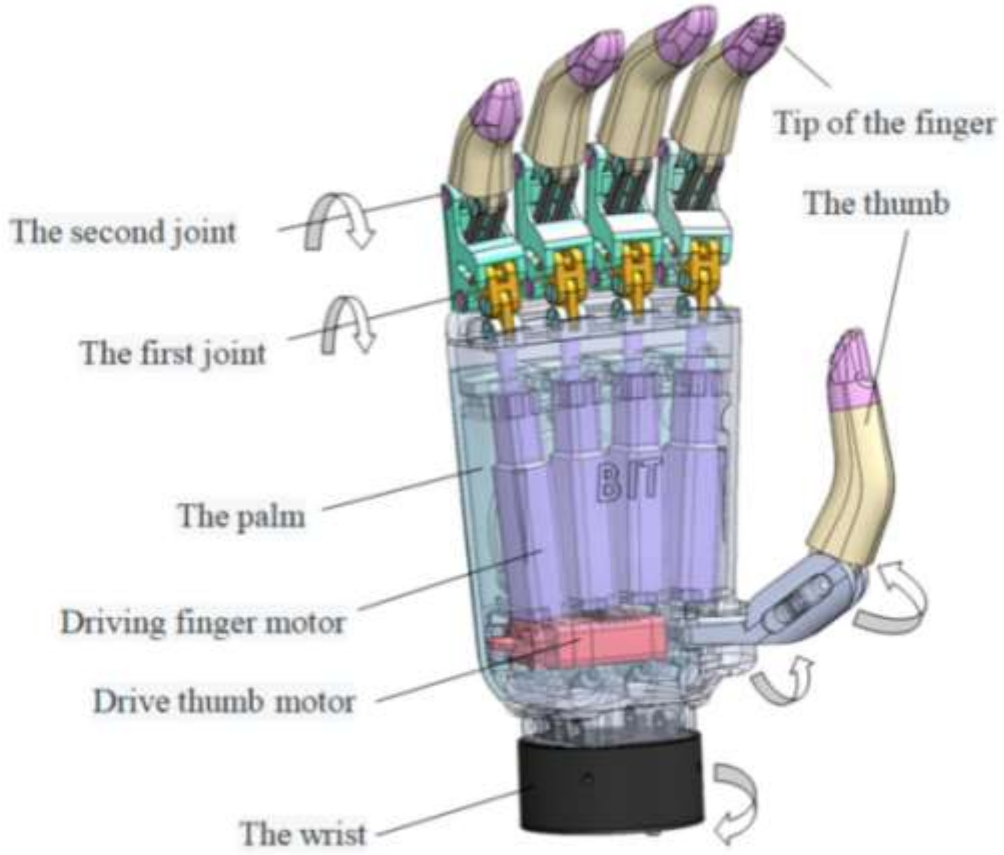
Still a hot topic in robotics

A robotic grasping system

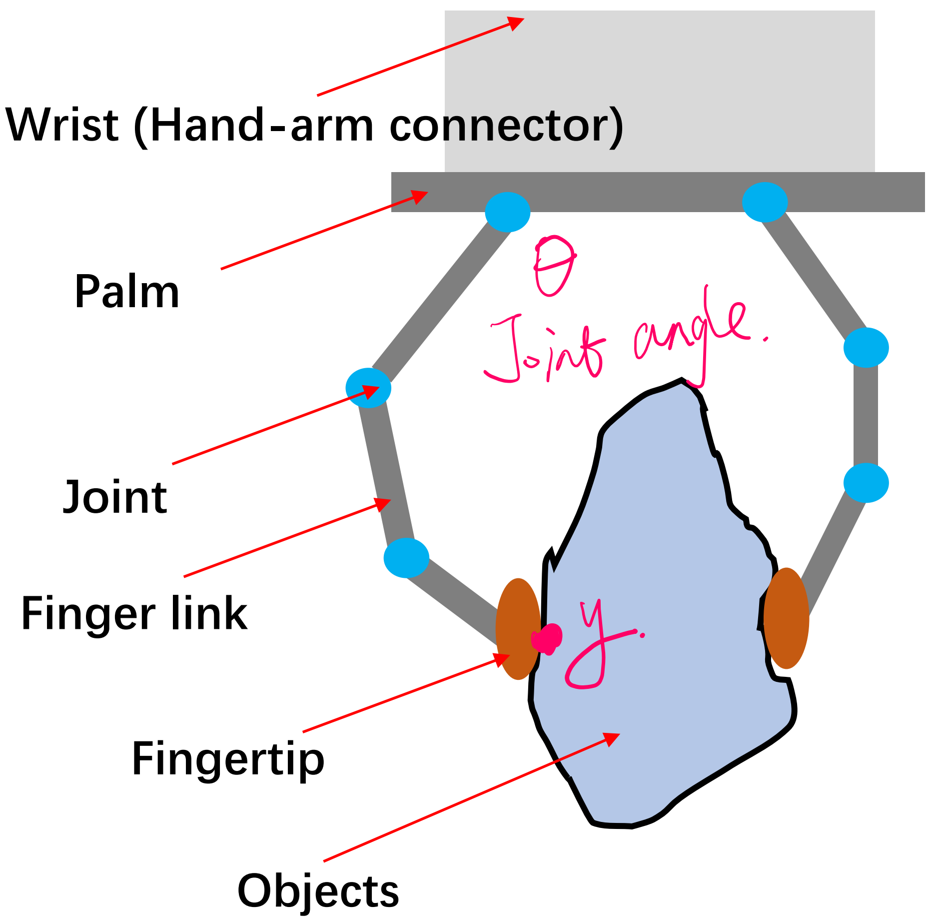


A robotic grasping system





Hand Kinematics

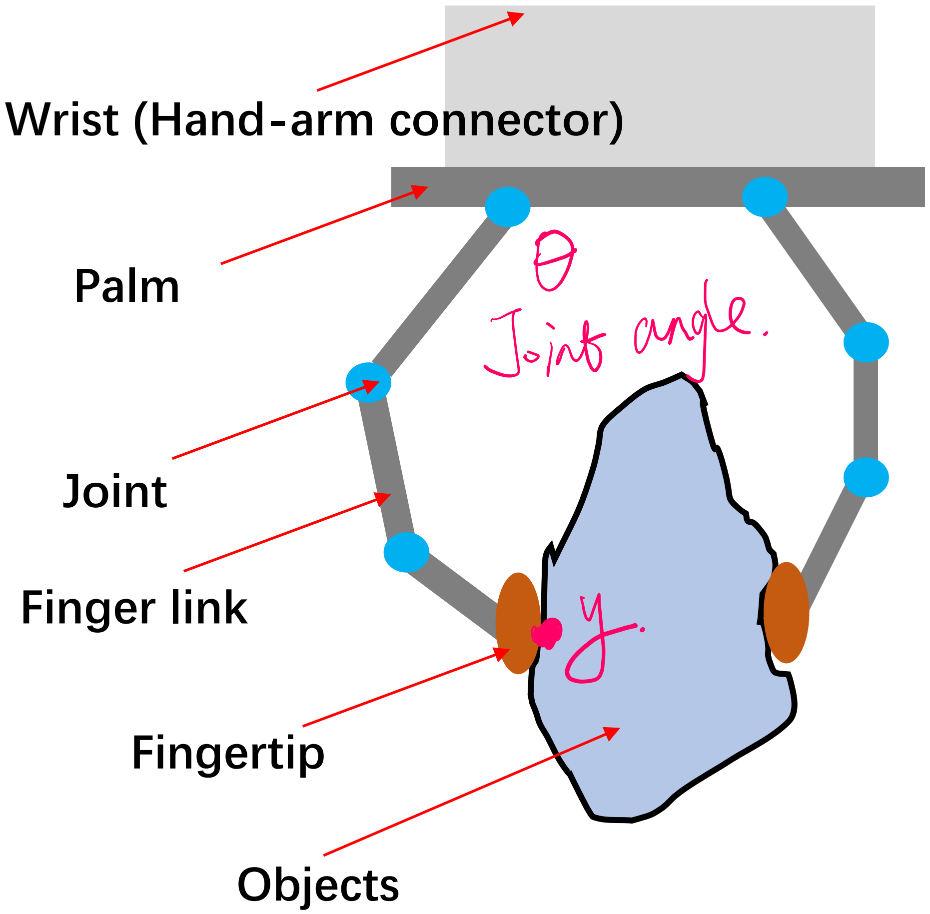


$$y = f(\theta)$$

↓ pos of fingertip

↓ Joint Angle.

Hand Kinematics



$$y = f(\theta)$$

y → pos of fingertip

θ → 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

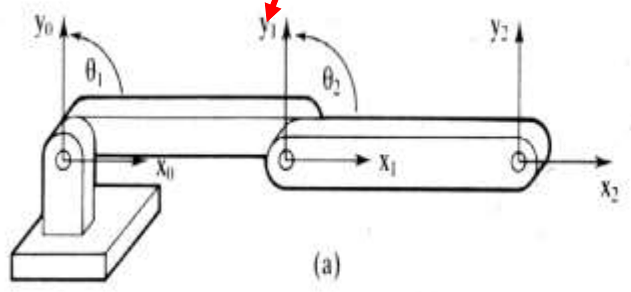
Inverse Kinematics (position to angles)

What you are given: The length of each link
The position of some point on the robot

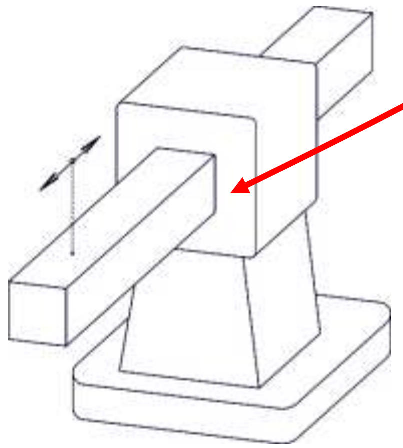
What you can find: The angles of each joint needed to obtain that position

Hand Kinematics- Joints

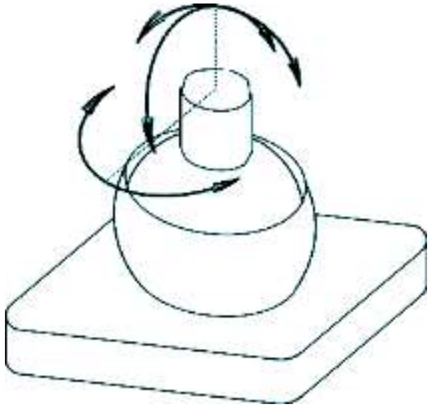
$$q_i = \begin{cases} \theta_i & : \text{joint i revolute} \\ d_i & : \text{joint i prismatic} \end{cases}$$



Revolute Joint
1 DOF

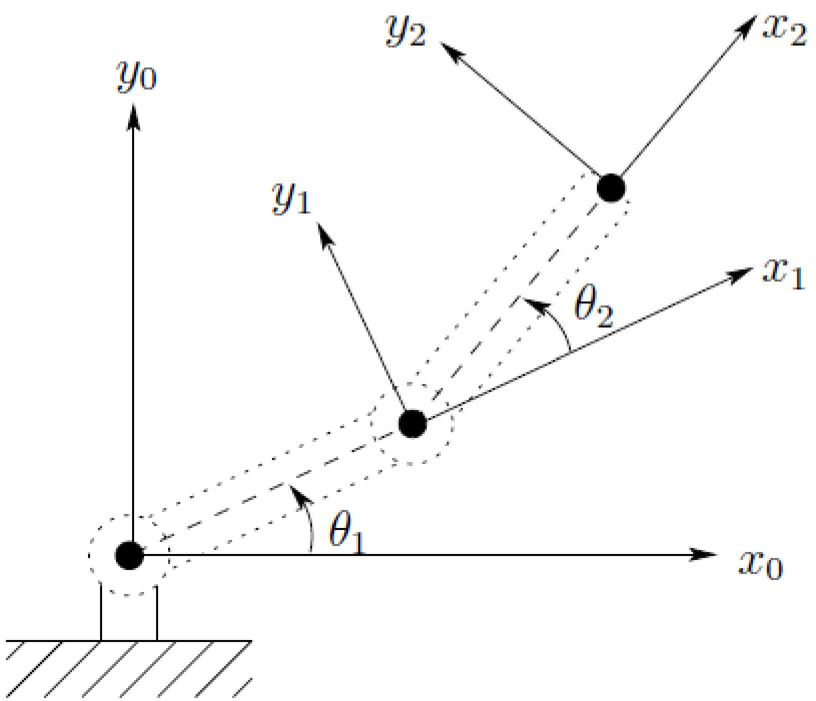


Prismatic Joint
1 DOF (linear)



Spherical Joint
3 DOF

Hand Kinematics- An 2D example



Position

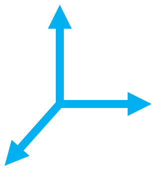
$$
\begin{aligned}
x &= x_2 = \alpha_1 \cos\theta_1 + \alpha_2 \cos(\theta_1 + \theta_2) \\
y &= y_2 = \alpha_1 \sin\theta_1 + \alpha_2 \sin(\theta_1 + \theta_2),
\end{aligned}
$$

Orientation Matrix

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

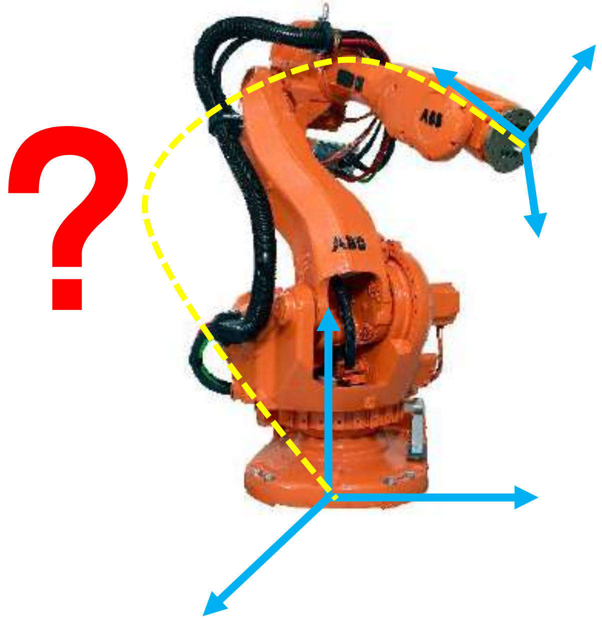
$$
\begin{bmatrix} x_2 \cdot x_0 & y_2 \cdot x_0 \\ x_2 \cdot y_0 & y_2 \cdot y_0 \end{bmatrix} = \begin{bmatrix} \cos(\theta_1 + \theta_2) & -\sin(\theta_1 + \theta_2) \\ \sin(\theta_1 + \theta_2) & \cos(\theta_1 + \theta_2) \end{bmatrix}
$$

Hand Kinematics- FK



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

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



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

$$T_j^i = A_{i+1} A_{i+2} \ldots A_{j-1} A_j \text{ if } i < j$$
$$T_j^i = I \text{ if } i = j$$
$$T_j^i = (T_i^j)^{-1} \text{ if } j > i.$$

$o_j x_j y_j z_j$ with respect to $o_i x_i y_i z_i$

$$H = \begin{bmatrix} R_n^0 & o_n^0 \\ 0 & 1 \end{bmatrix} \qquad H = T_n^0 = A_1(q_1) \cdots A_n(q_n)$$

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

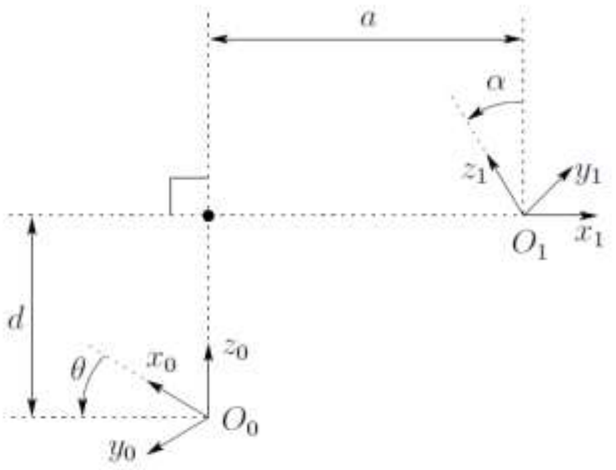
All about FK ?

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.*

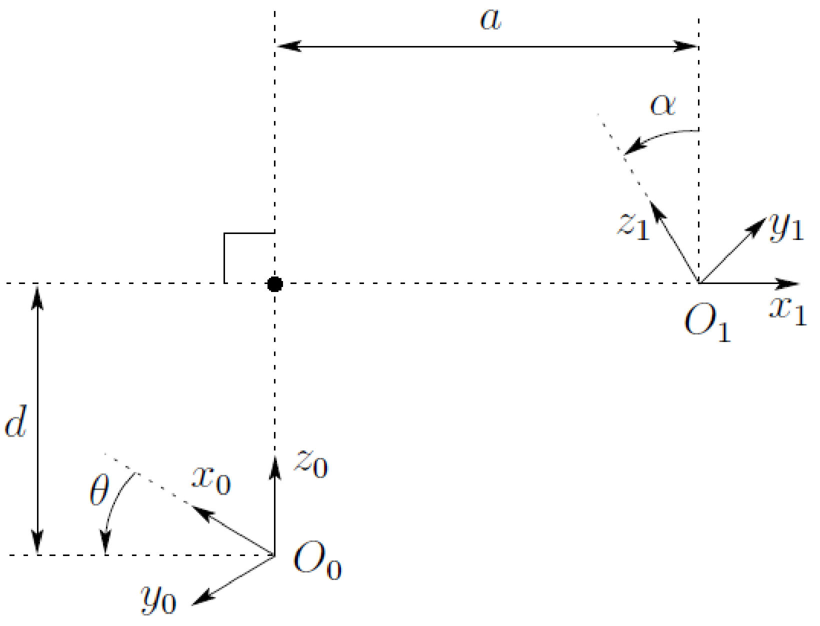
Hand Kinematics- FK

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

$$A = Rot_{z,\theta} \text{Trans}_{z,d} \text{Trans}_{x,a} Rot_{x,\alpha}$$

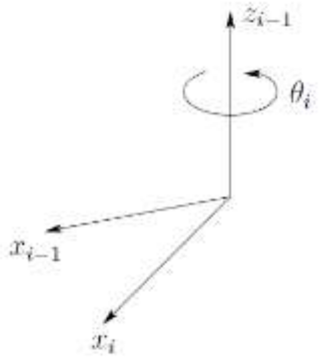


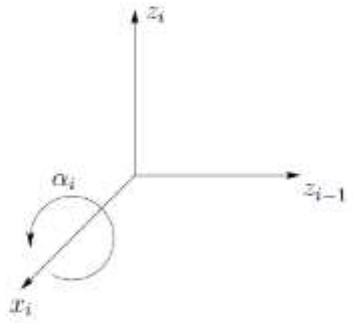
$\theta_i =$ the angle between x_{i-1} and x_i measured about z_{i-1}

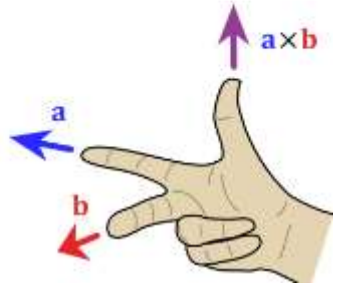
$d_i =$ distance along z_{i-1} from o_{i-1} to the intersection of the x_i and z_{i-1} axes. d_i is variable if joint i is prismatic.

$a_i =$ 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







right-hand rule

1. Spong, Mark W.; Vidyasagar, M. (1989). *Robot Dynamics and Control*. New York: John Wiley & Sons.

Hand Kinematics- FK

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

?

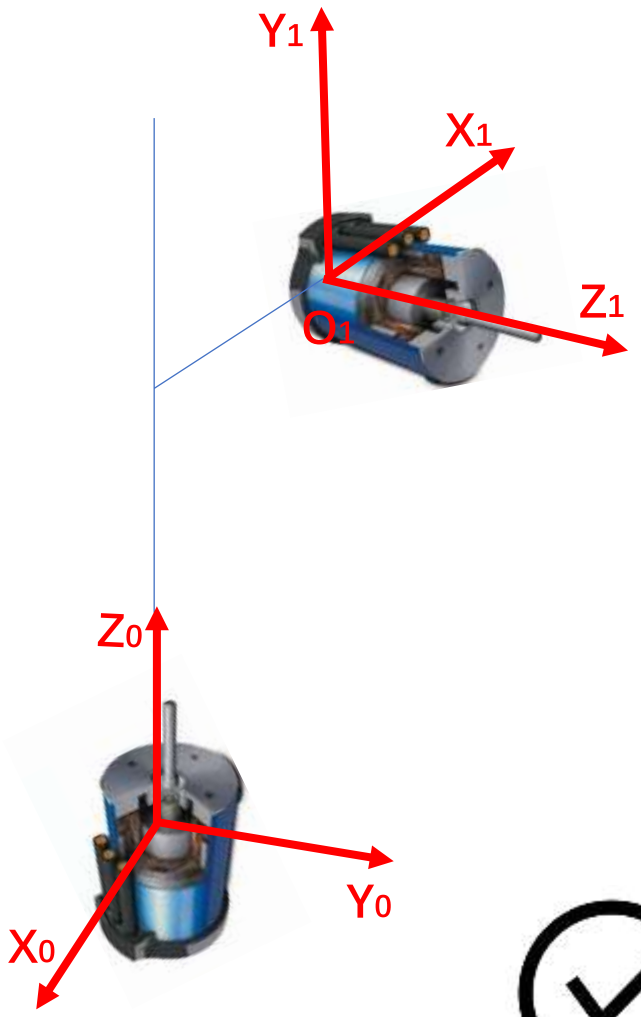
$$A = Rot_{z,\theta}\text{Trans}_{z,d}\text{Trans}_{x,a}Rot_{x,\alpha}$$

$$A_i = Rot_{z,\theta_i}\text{Trans}_{z,d_i}\text{Trans}_{x,a_i}Rot_{x,\alpha_i}$$

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

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

Hand Kinematics- DH param procedure



1 **Step 1:** Locate and label the joint axes $z_0, \ldots, z_{n-1}$.

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 $i = 1, \ldots, n-1$, 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.

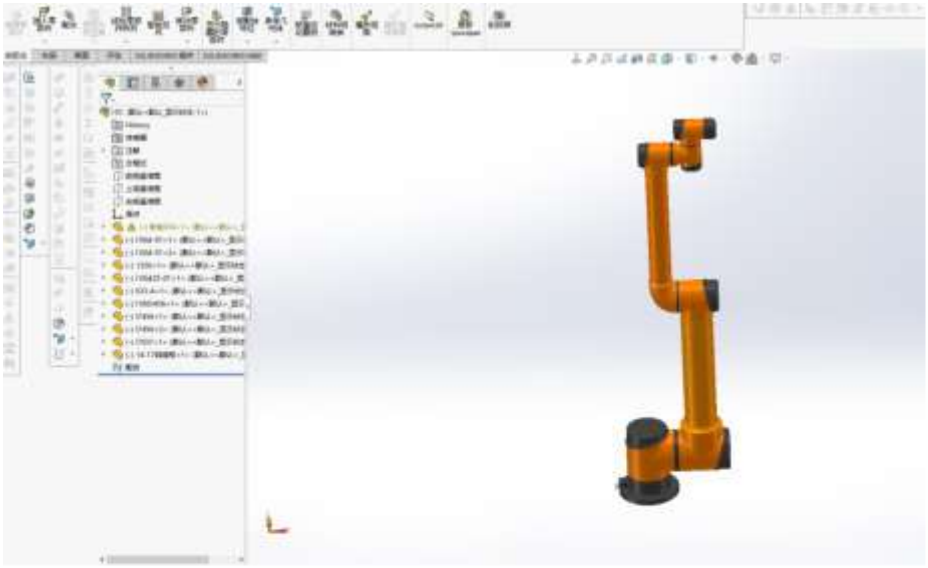
4 **Step 4:** Establish x_i along the common normal between z_{i-1} and z_i through o_i, or in the direction normal to the $z_{i-1} - z_i$ plane if z_{i-1} and z_i intersect.

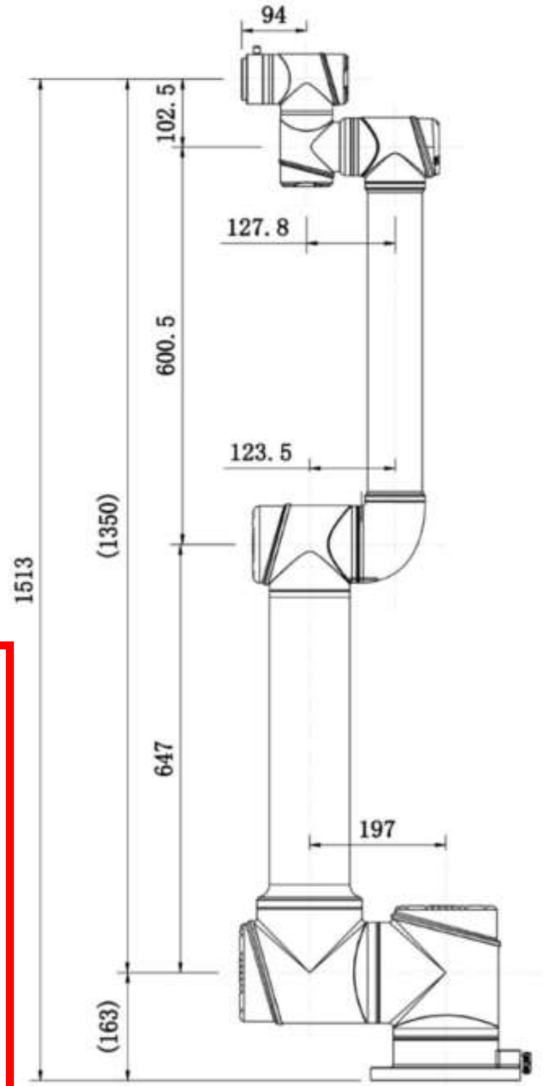
5 **Step 5:** Establish y_i to complete a right-hand frame.

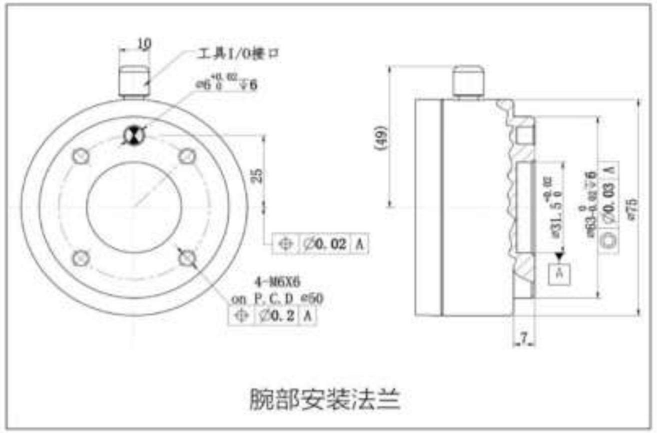
6 **Step 6:** Establish the end-effector frame $o_n x_n y_n z_n$. Assuming the n-th joint is revolute, set $z_n = a$ along the direction z_{n-1}. Establish the origin o_n conveniently along z_n, preferably at the center of the gripper or at the tip of any tool that the manipulator may be carrying. Set $y_n = s$ in the direction of the gripper closure and set $x_n = n$ as $s \times a$. If the tool is not a simple gripper set x_n and y_n conveniently to form a right-hand frame.

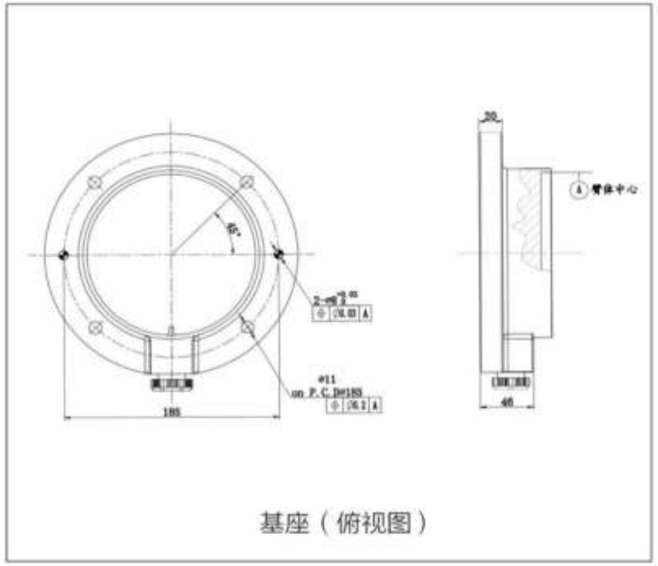
7 **Step 7:** Create a table of link parameters a_i, d_i, α_i, θ_i.

Hand Kinematics- DH in practice



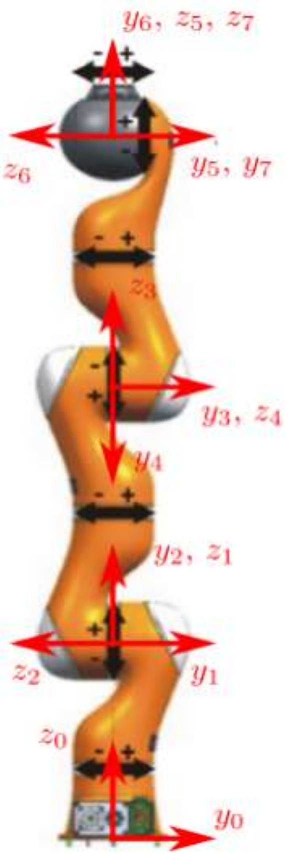


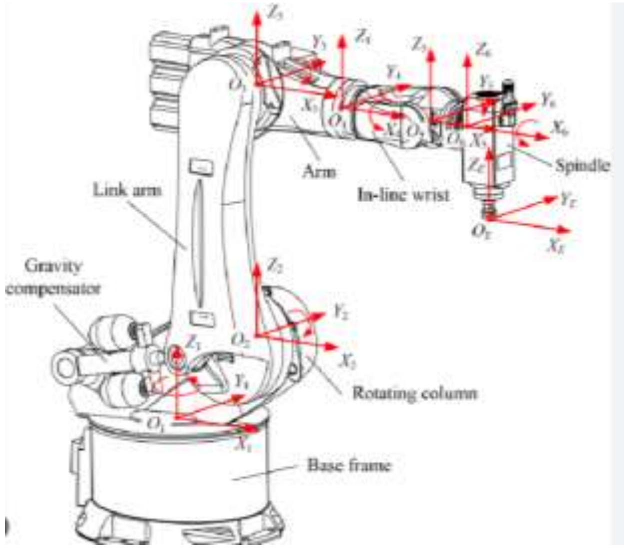


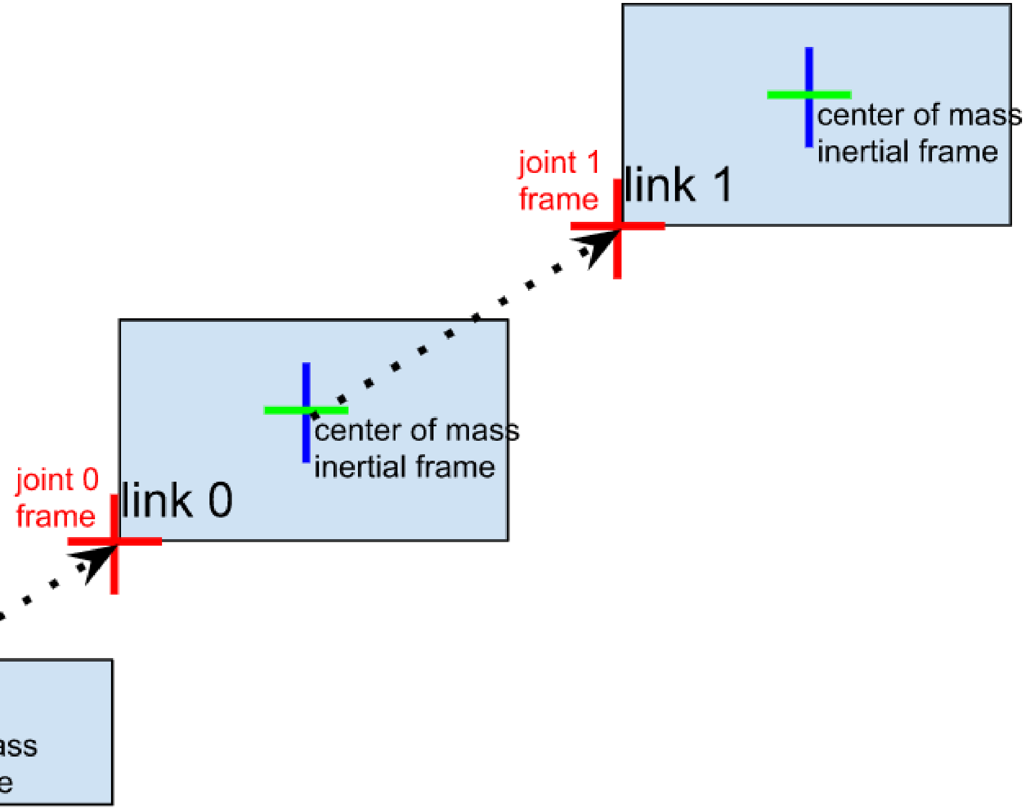


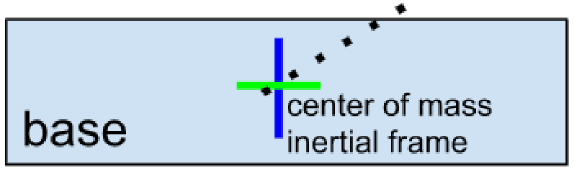
DH参数	d(m)	θ(°)	a(m)	α(°)
关节1	0	0	0	0
关节2	0.163	90	0	90
关节3	0	0	-0.647	0
关节4	0	0	-0.6005	0
关节5	0.2013	0	0	90
关节6	0.1025	0	0	-90

Hand Kinematics- FK in Practice



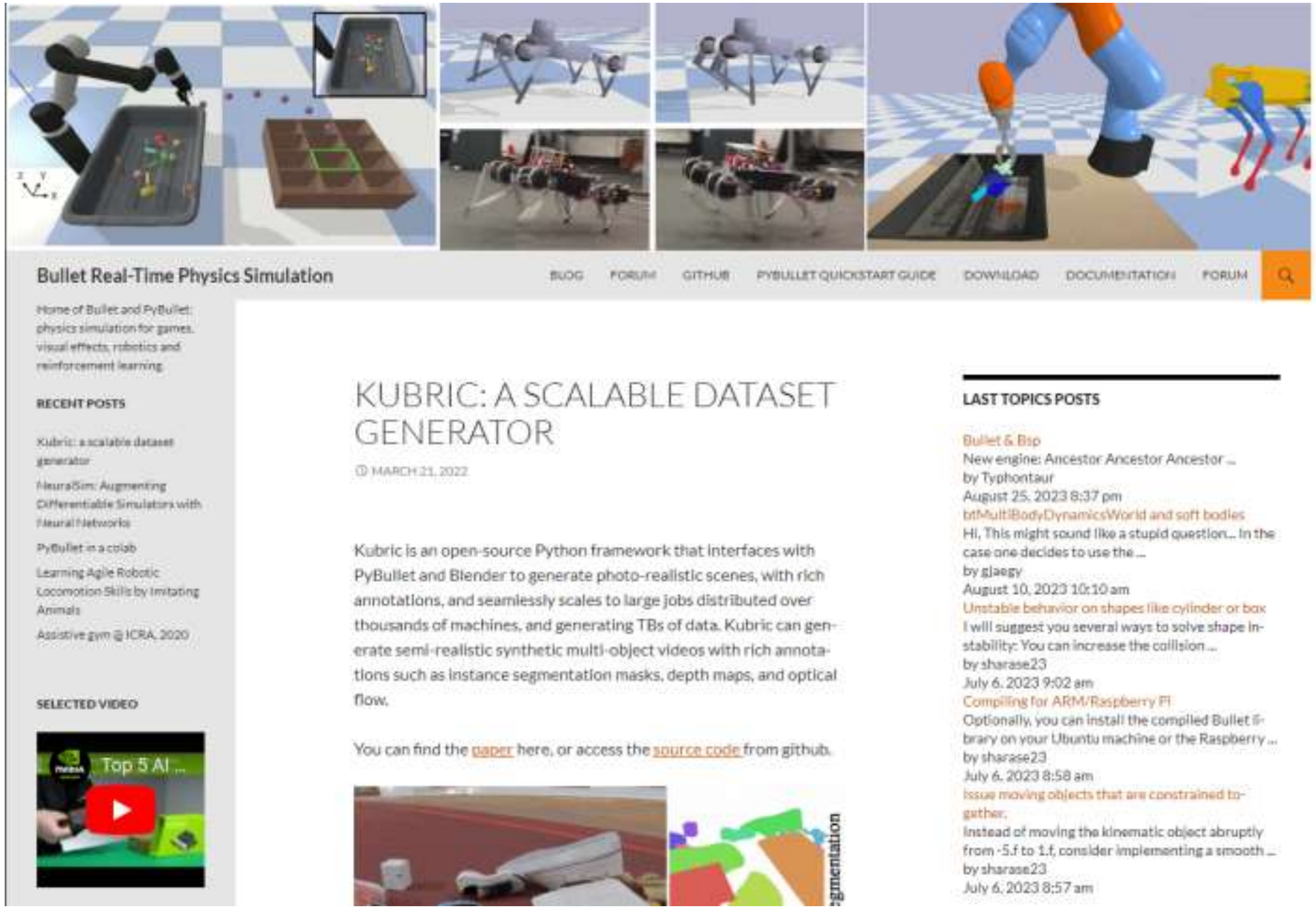






https://docs.google.com/document/d/10sXEhzFRSnvFcl3XxNGhnD4N2SedqwdAvK3dsihxVUA/edit

Hand Kinematics- FK in PyBullet

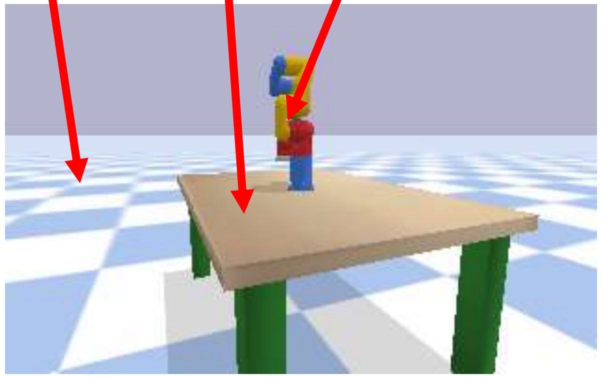


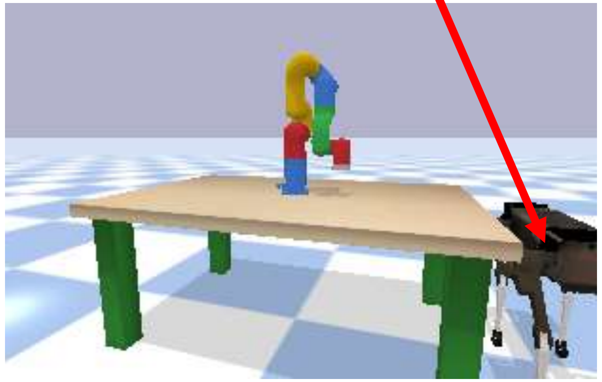
https://docs.google.com/document/d/10sXEhzFRSnvFcl3XxNGhnD4N2SedqwdAvK3dsihxVUA/edit

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/10sXEhzFRSnvFcl3XxNGhnD4N2SedqwdAvK3dsihxVUA/edit

Hand Kinematics- FK in Practice

getLinkState(s)

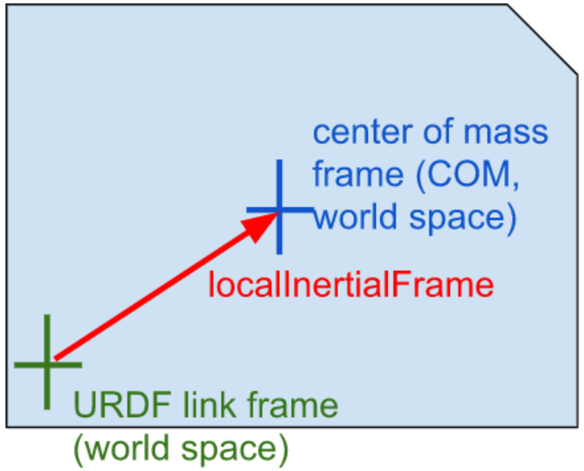
You can also query the Cartesian world position and orientation for the center of mass of each link using getLinkState. It will also report the local inertial frame of the center of mass to the URDF link frame, to make it easier to compute the graphics/visualization frame.

getLinkState input parameters

required	bodyUniqueId	int	body unique id as returned by loadURDF 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/10sXEhzFRSnvFcl3XxNGhnD4N2SedqwdAvK3dsihxVUA/edit

Hand Kinematics- FK in Practice



getLinkState return values

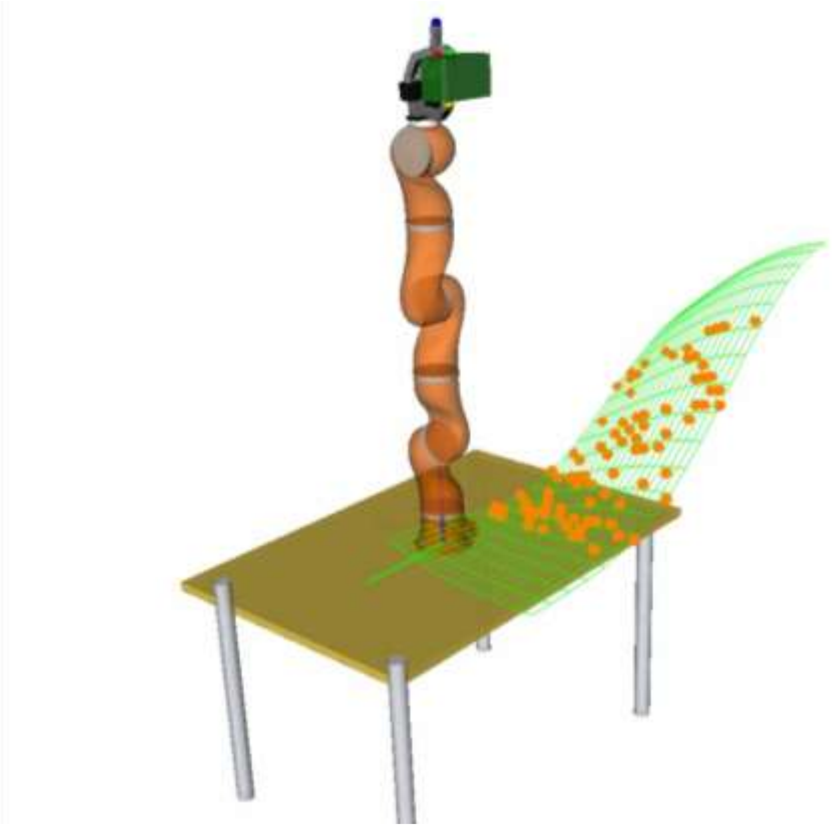
linkWorldPosition	vec3, list of 3 floats	Cartesian position of center of mass
linkWorldOrientation	vec4, list of 4 floats	Cartesian orientation of center of mass, in quaternion [x,y,z,w]
localInertialFramePosition	vec3, list of 3 floats	local position offset of inertial frame (center of mass) expressed 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/10sXEhzFRSnvFcl3XxNGhnD4N2SedqwdAvK3dsihxVUA/edit

Hand Kinematics- FK in Practice

PyBullet Quickstart Guide

Erwin Coumans, Yunfei Bai, 2016-2023
Visit desktop doc, forums, github discussions and star Bullet!

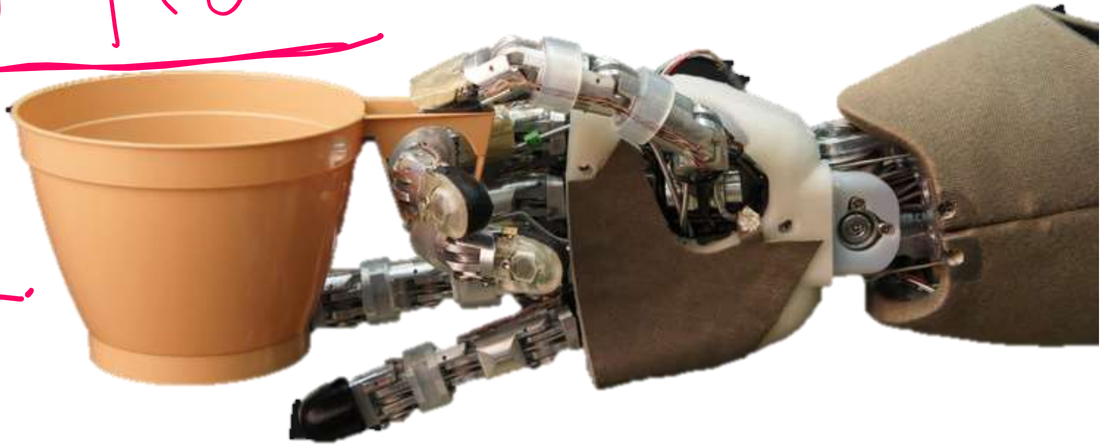


Today

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

$\dot{y} = f(\dot{\theta})$

$\theta = f^{-1}(y)$

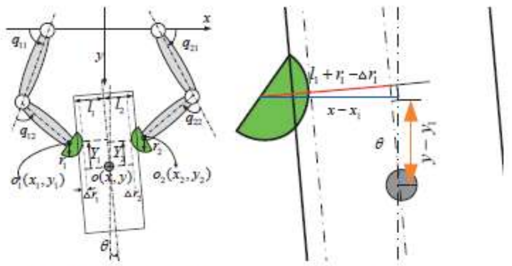


Robotic Hand Dynamics

STABILITY OF VARIABLE GRASP STIFFNESS CONTROL

In this part, we address the control stability of varying stiffness in robotic grasping using a two-fingered examples, as shown in Fig. B.1(a). To this end, a detailed formu-
lation for the dynamics o
constraints and the soft fi
formulation on the graspi
to grasp the object stably
rived from the proof of co

Complicated with many assumptions



(a) 2D hand-object grasping system (b) Constraints

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 Δr 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

$$Y_i = (x_i - x)\sin\theta + (y_i - y)\cos\theta \quad \text{(B.5)}$$

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

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

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 $\mathbf{q}_i = [q_{i1}, q_{i2}]^T$ 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

$$H_i(\mathbf{q}_i)\ddot{\mathbf{q}}_i + (\frac{1}{2}\dot{H}_i + S_i)\dot{\mathbf{q}}_i + f_i\frac{\partial\Delta r_i}{\partial\mathbf{q}_i^T} - \lambda_i[(r_i - \Delta r_i)\frac{\partial\phi_i}{\partial\mathbf{q}_i^T} + \frac{\partial Y_i}{\partial\mathbf{q}_i^T}] = \mathbf{u}_i \quad \text{(B.11)}$$

110

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

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

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

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

(B.15)

$$M\ddot{x} - (f_1 - f_2)\cos\theta + (\lambda_1 + \lambda_2)\sin\theta = 0 \quad \text{(B.16)}$$

$$M\ddot{y} + (f_1 - f_2)\sin\theta + (\lambda_1 + \lambda_2)\cos\theta = 0 \quad \text{(B.17)}$$

$$I\ddot{\theta} - f_1Y_1 + f_2Y_2 + l_1\lambda_1 - l_2\lambda_2 = 0 \quad \text{(B.18)}$$

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

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

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

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

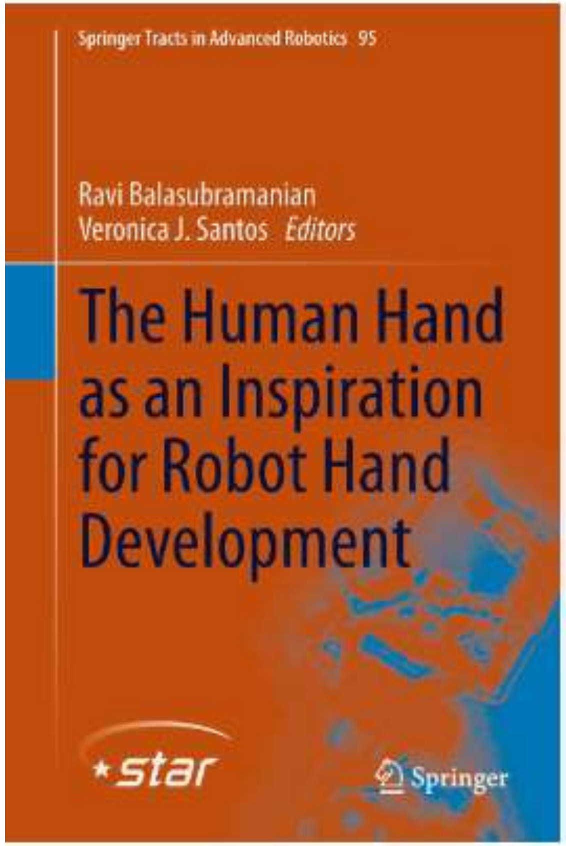
Taking the sum of inner product of Eq. (B.15) with $\dot{\mathbf{q}}_i, i = 1, 2$, Eq. (B.16) with $\dot{x}$, Eq. (B.17) with $\dot{y}$, Eq. (B.18) with $\dot{\theta}$, we have

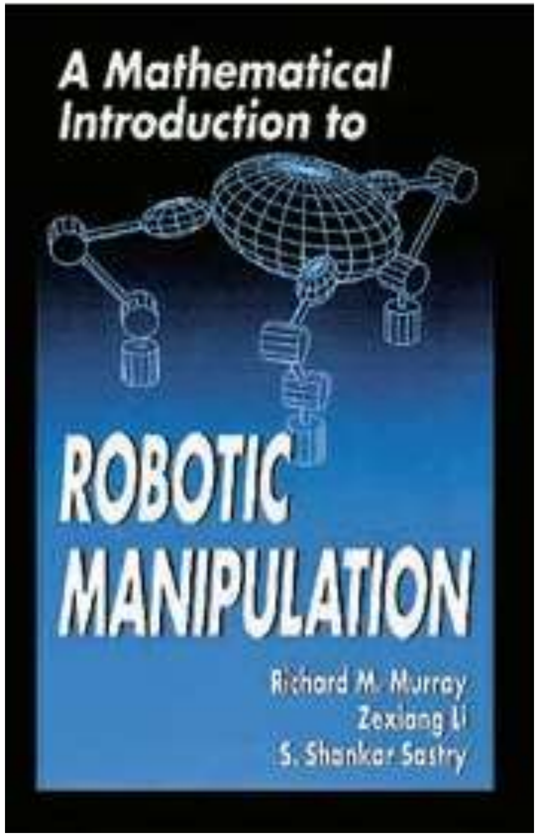
$$\frac{d}{dt}E = -\sum_{i=1,2}\{\dot{\mathbf{q}}_i^T D_i\dot{\mathbf{q}}_i + c_2\Delta\dot{r}_i^2\} + \frac{\dot{k}}{4}(\mathbf{x}_1 - \mathbf{x}_2)^T(\mathbf{x}_1 - \mathbf{x}_2) \quad \text{(B.21)}$$

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

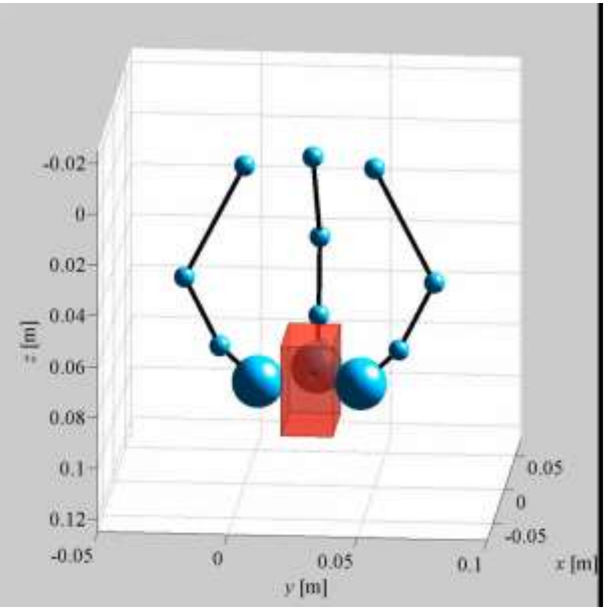
111

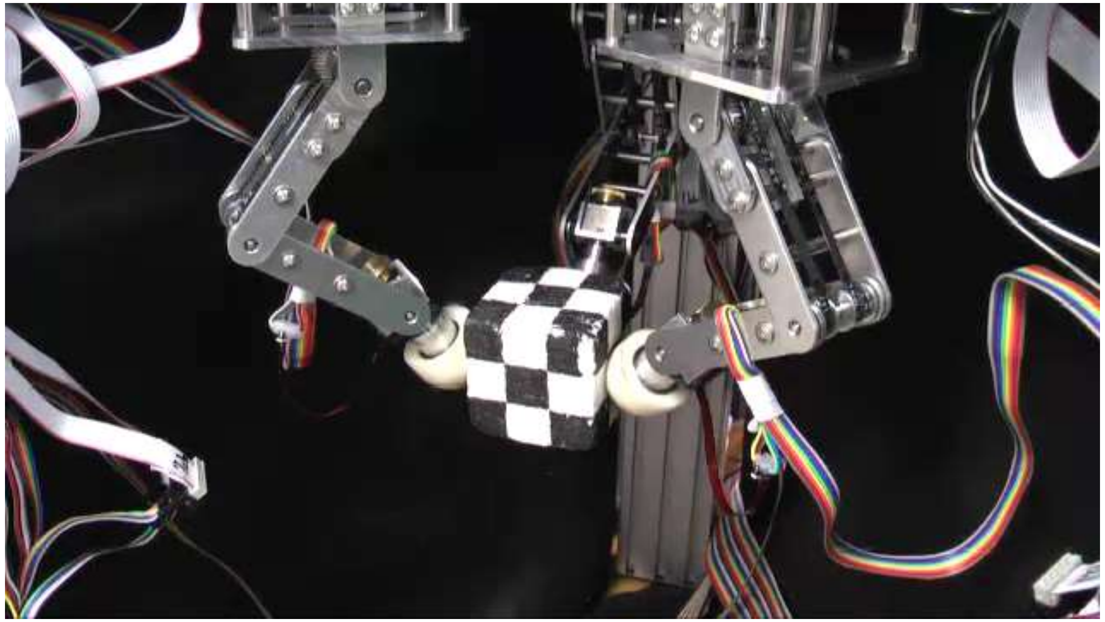
Robotic Hand Dynamics

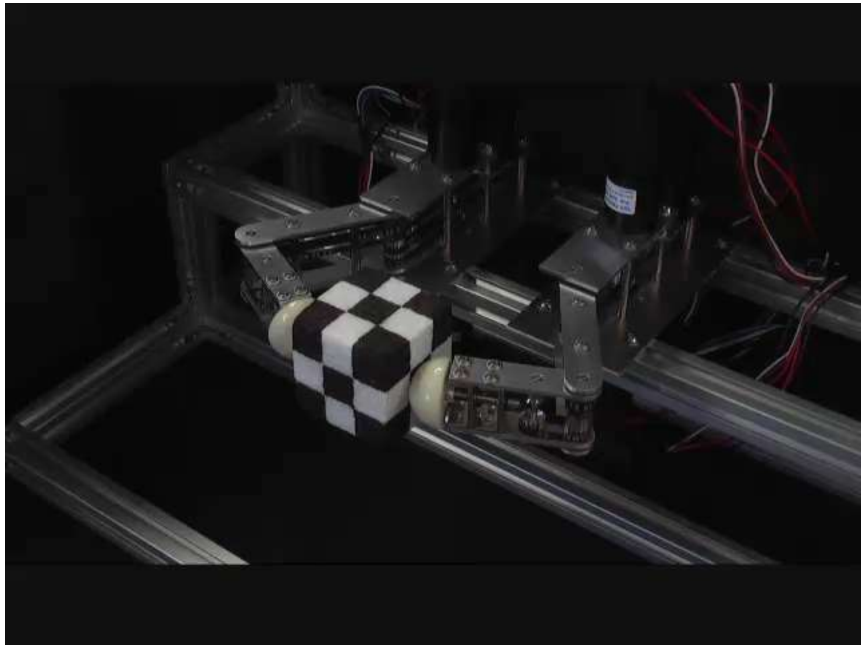


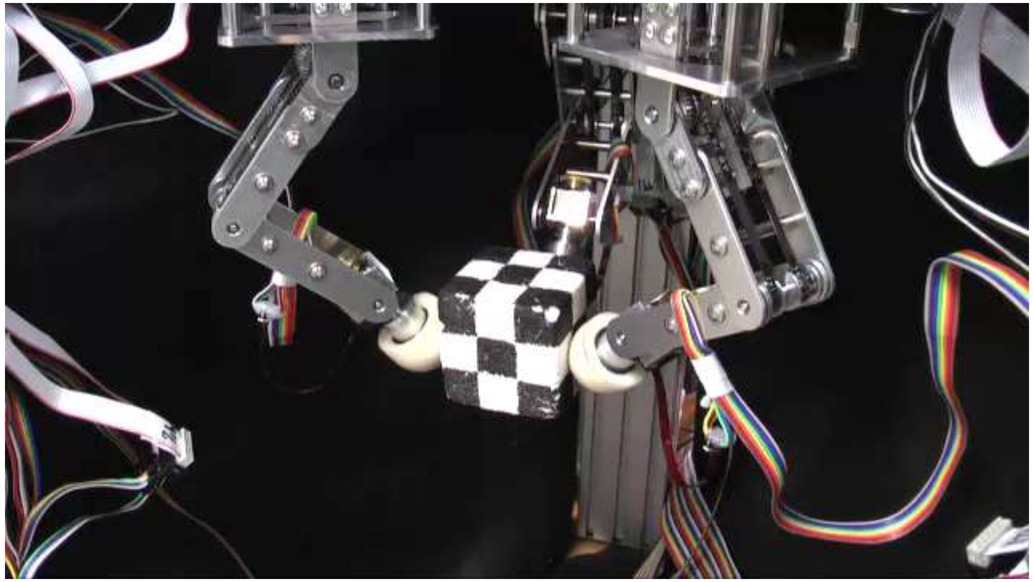


Robotic Hand Dynamics



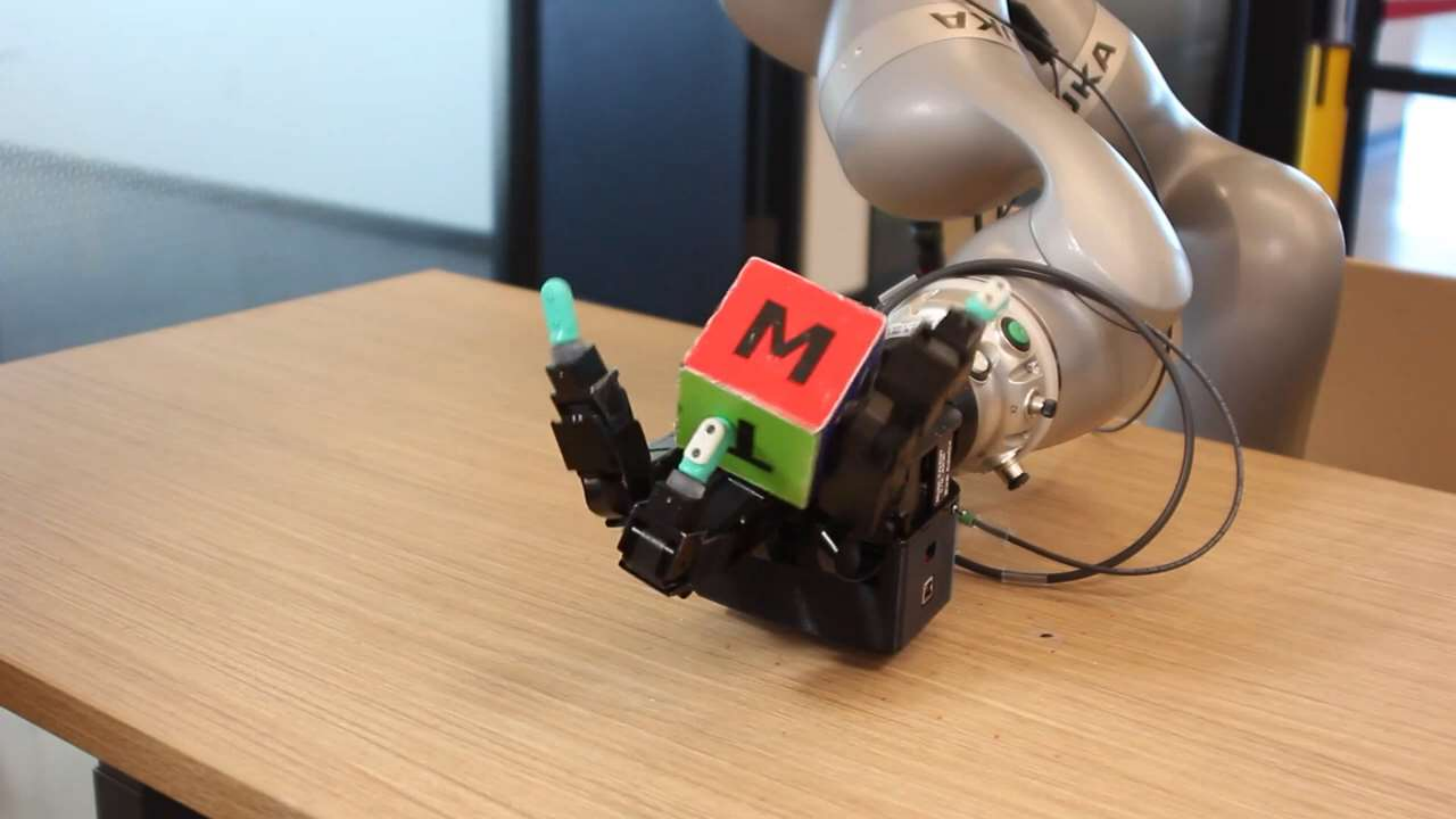






Opening thoughts on robot hands

- 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?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Today

- Design and Modelling of typical robotic arm/hand
- DH parameters
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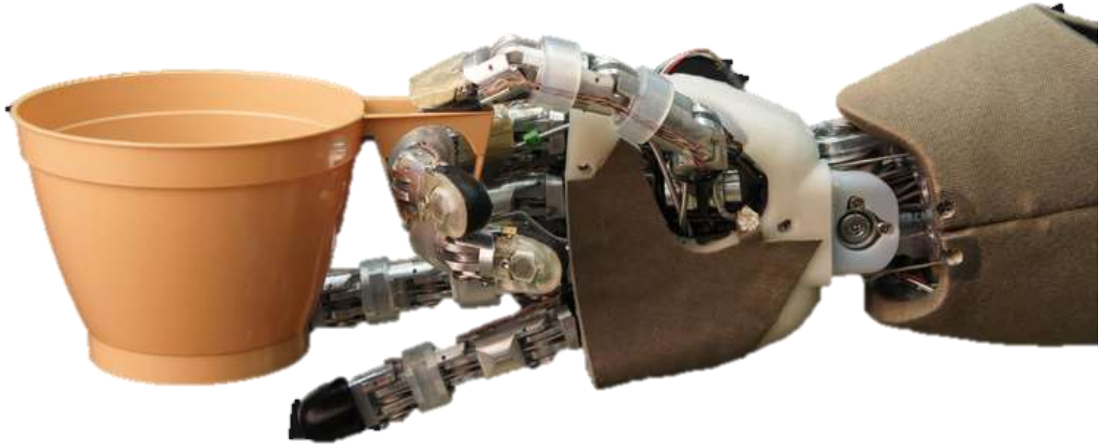
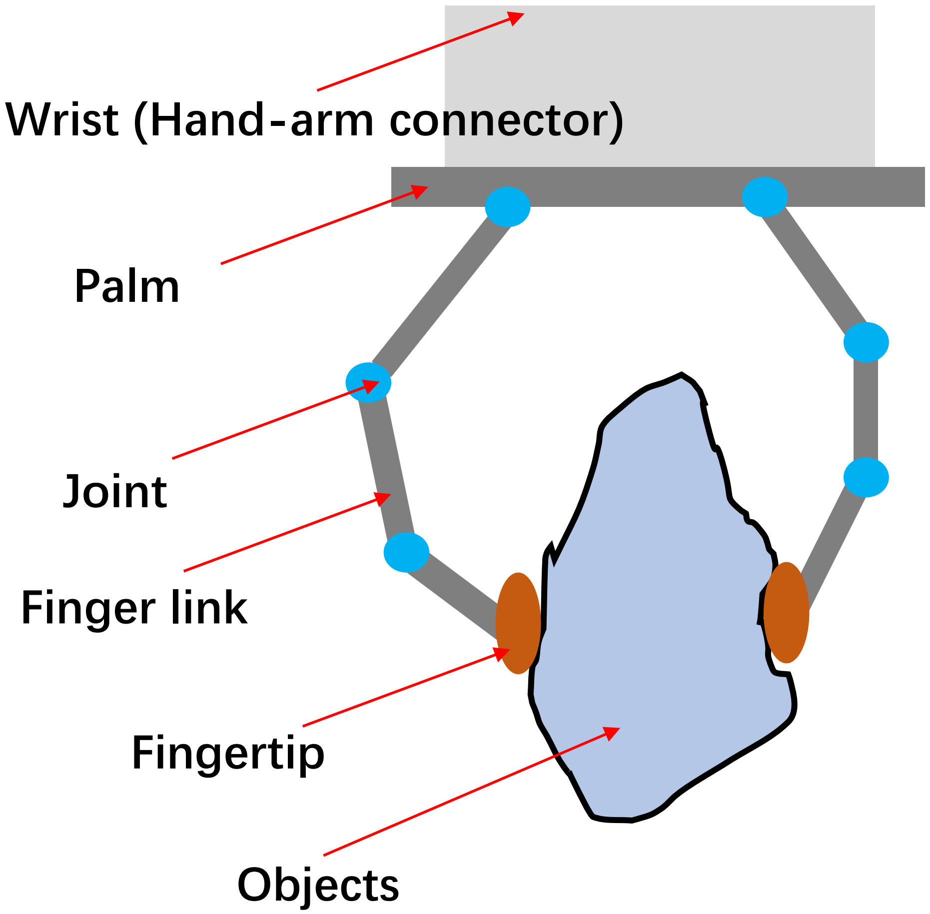
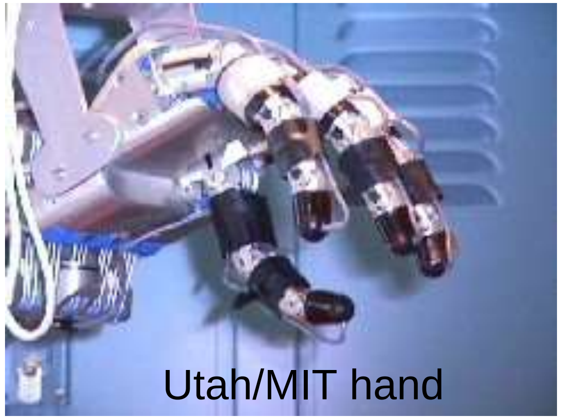
- Group list



A robotic grasping system



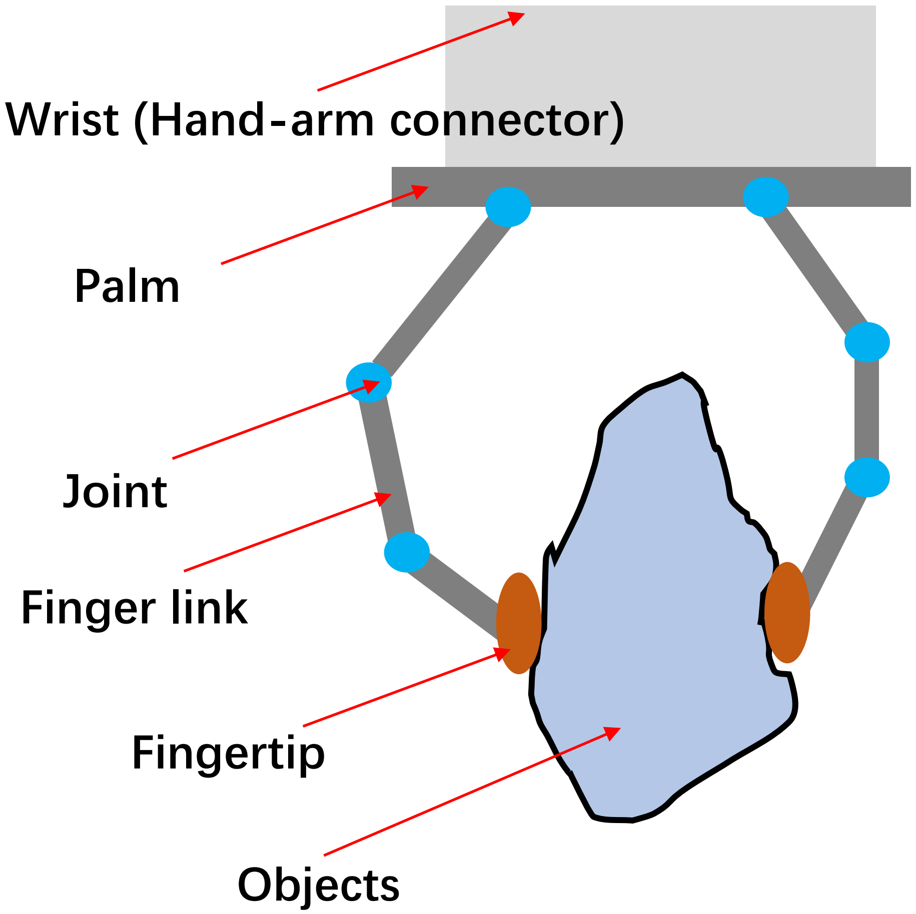
- **Complex hands = Complicated!**
  - **Difficult to control**
  - **Expensive**
  - **Fragile**

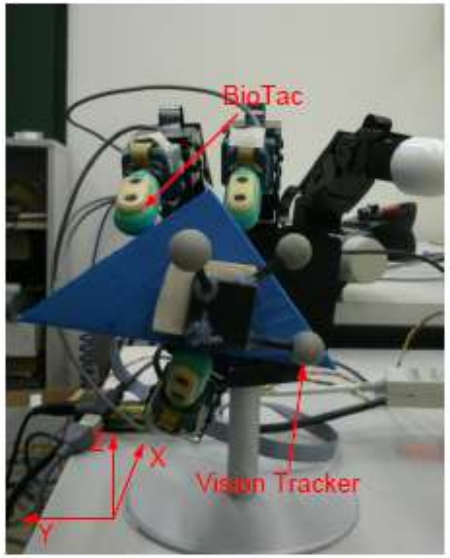


robonaut.jsc.nasa.gov

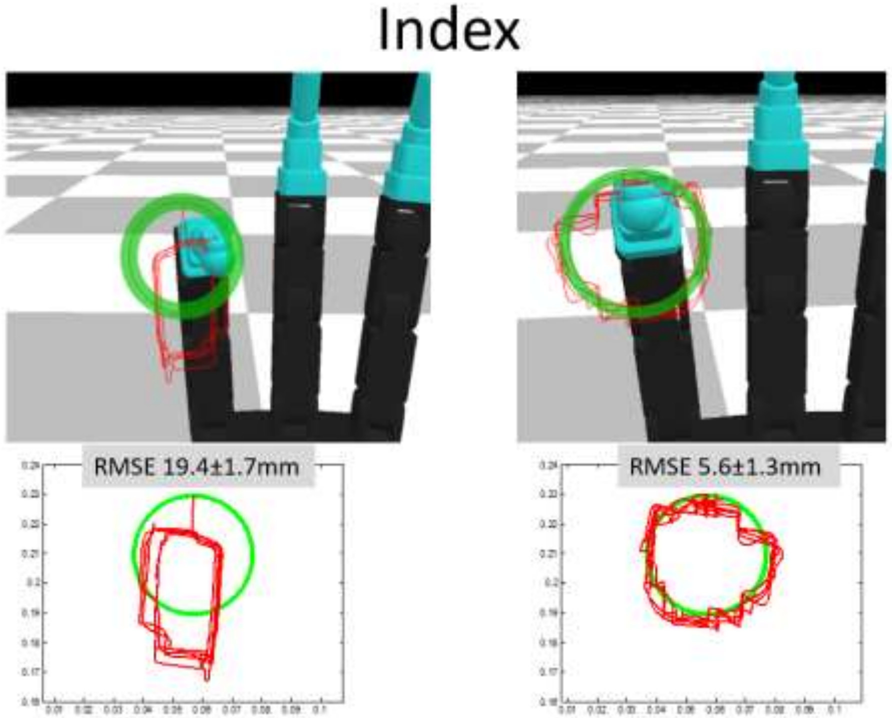
They don’t work reliably!

A robotic grasping system





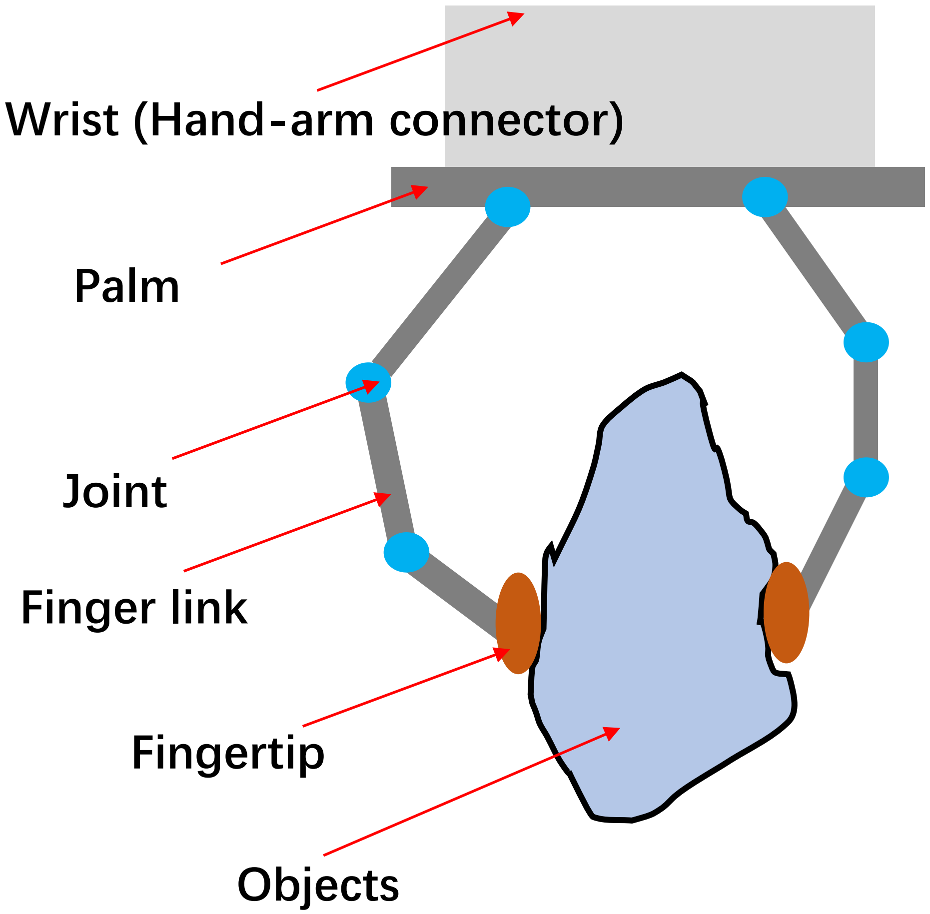
(a)

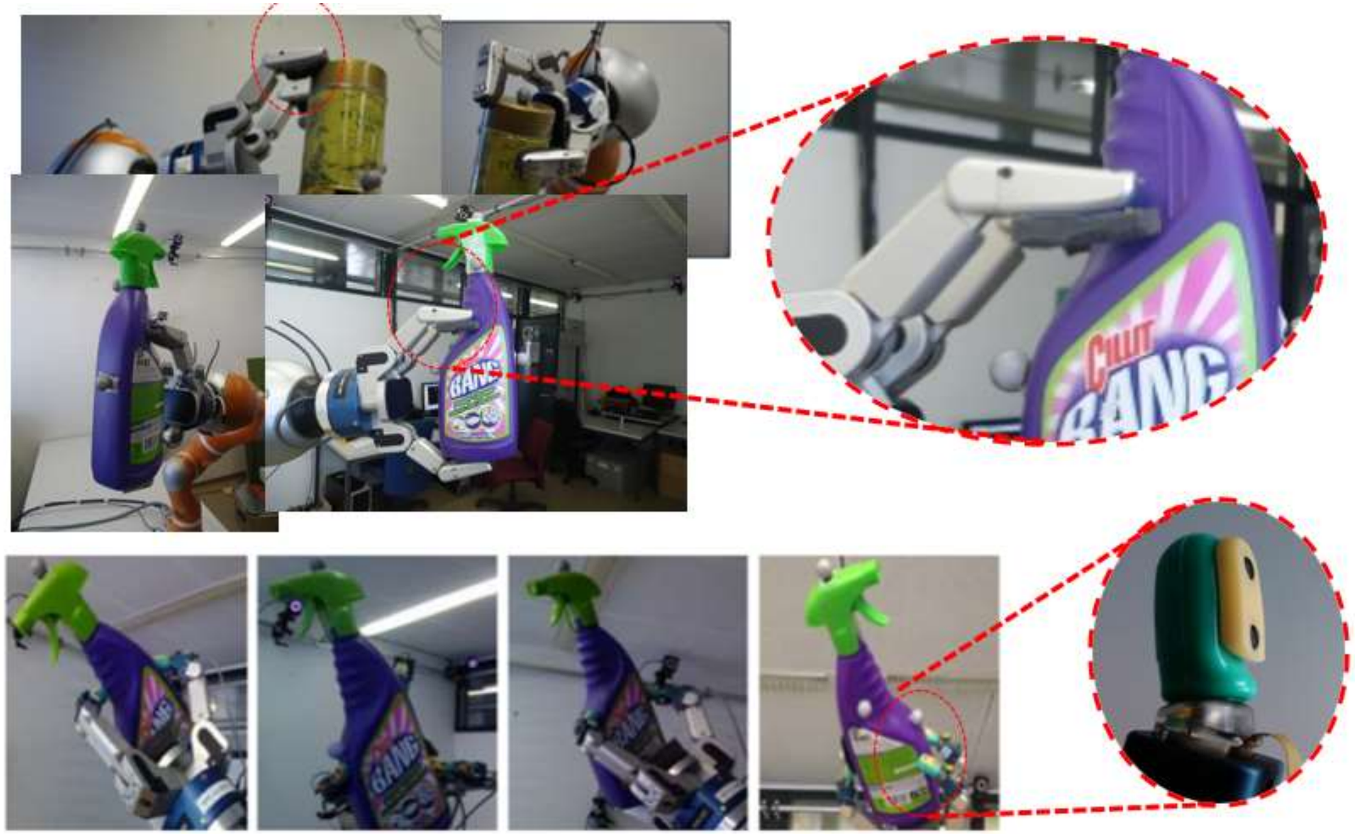


How to deal with "poor" sensing?

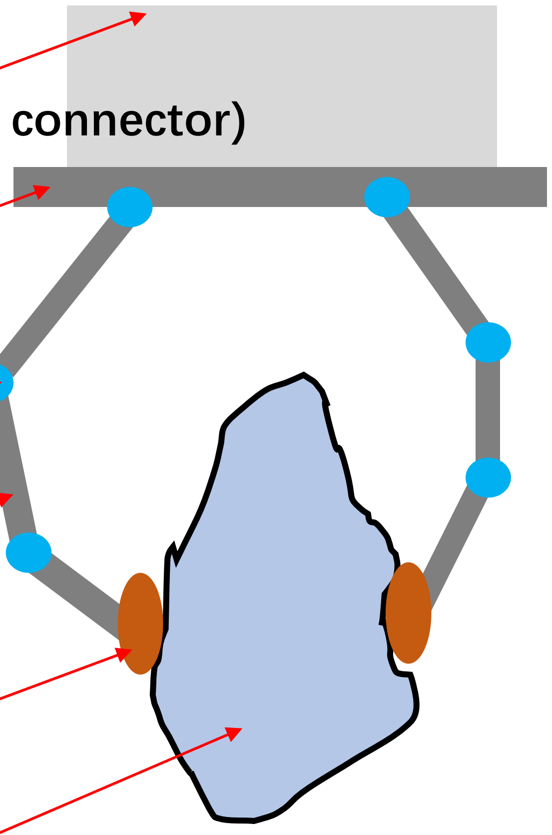
- **Errors in positioning, finger placement**
- **Can't control contact forces**

A robotic grasping system



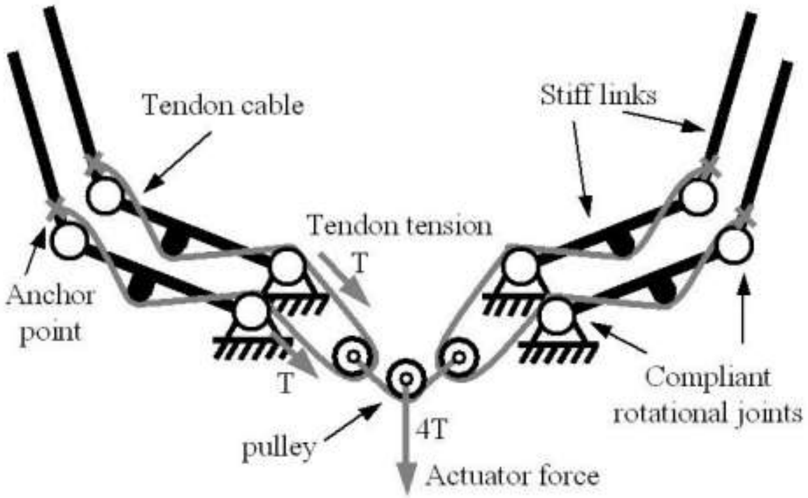


A new robotic grasping system



Compliant
+
Adaptive
+
Durable
||
Simple + Robust

- 3D printing
- Soft hand technology
- Anyone can make a hand?



Contact sensing and grasping performance of compliant hands

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.

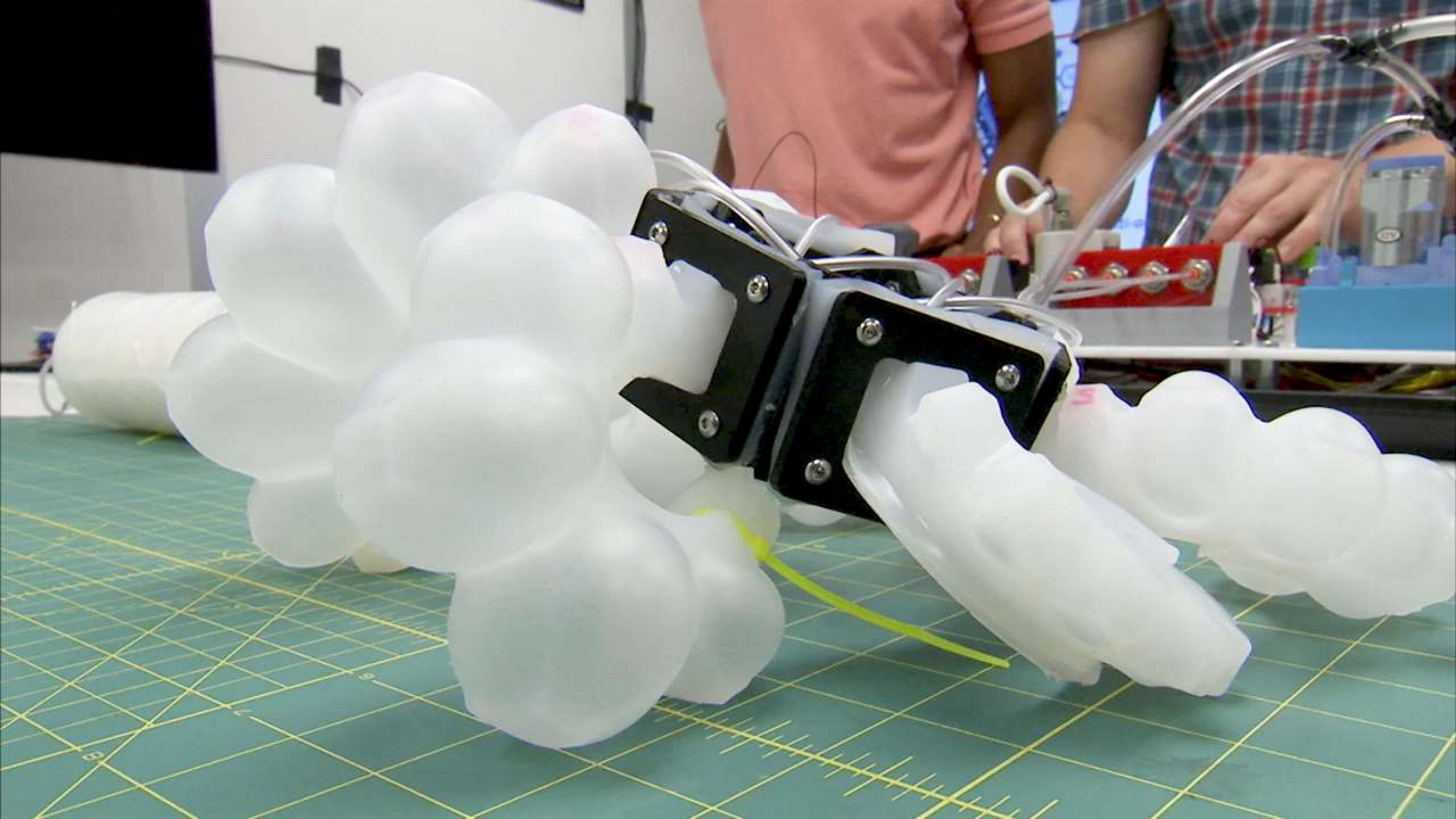
A toy example

Video
(2 mins)

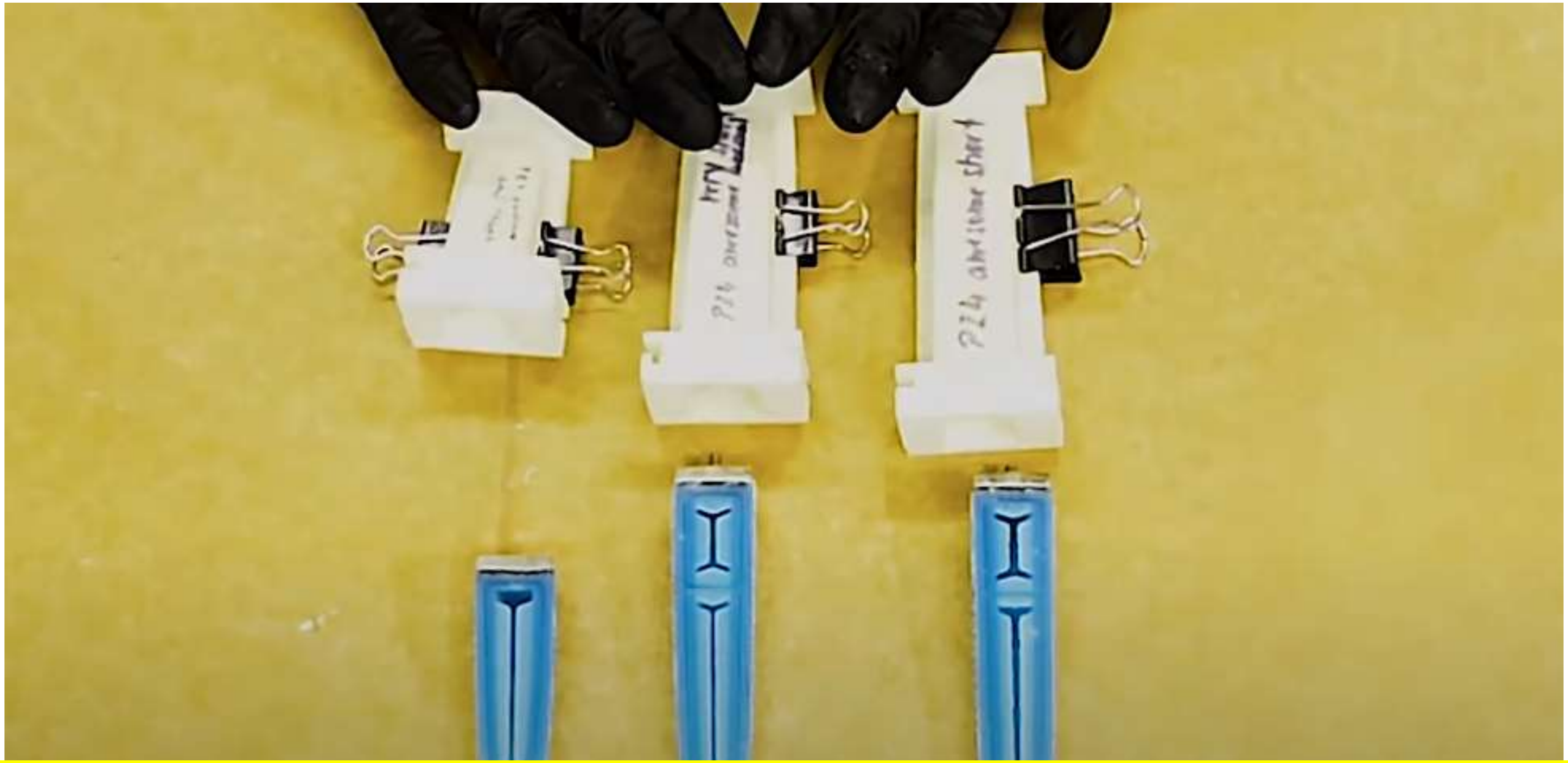
Video
(7 mins)

Soft Robotics


Soft robotic
gripper



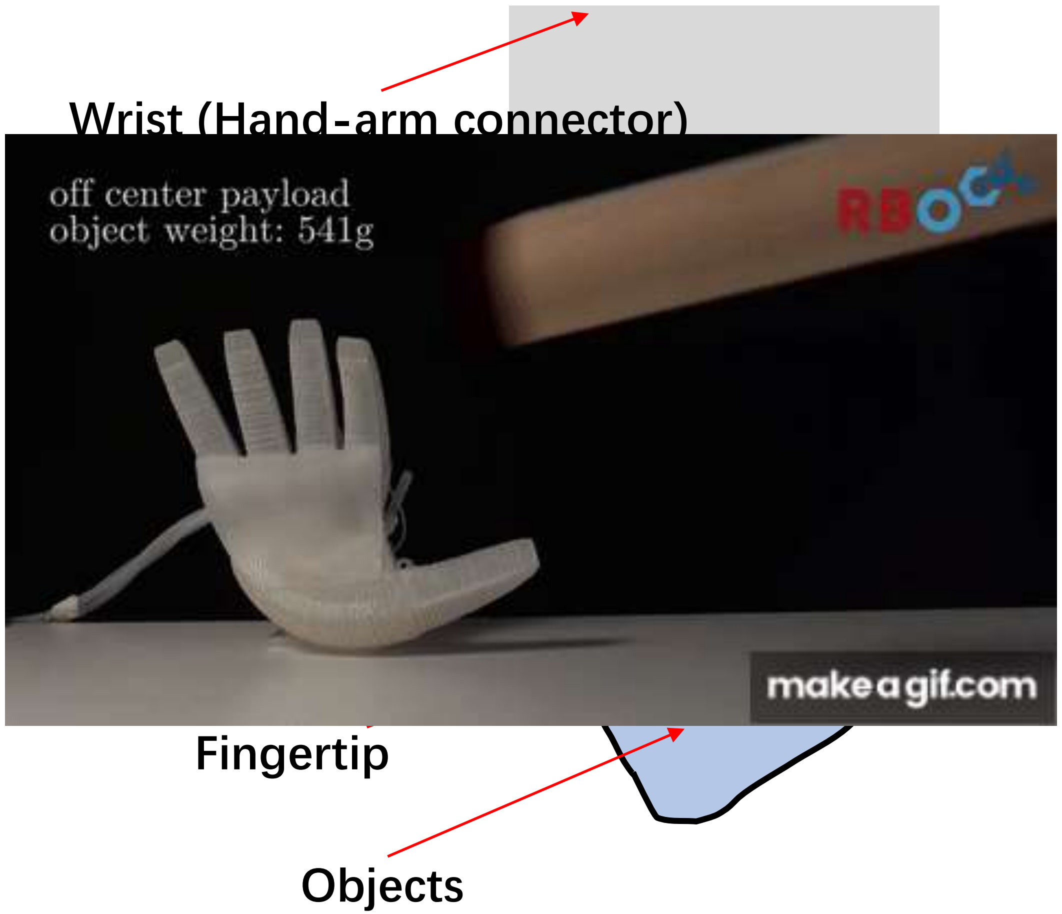
Soft Hands



How to build Soft Robotics Fingers, Pulps and Gloves

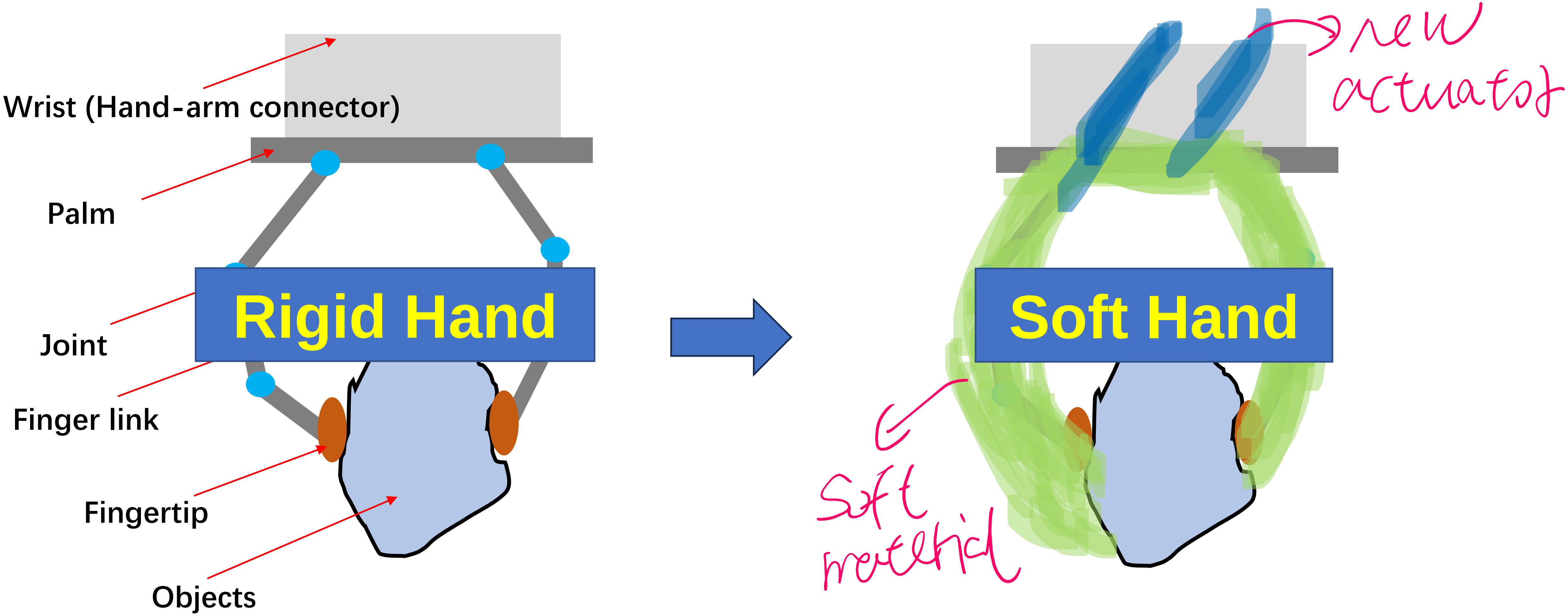
https://www.youtube.com/watch?v=HE4MGYLkXjk&ab_channel=RBOTUBerlin

A robotic grasping system



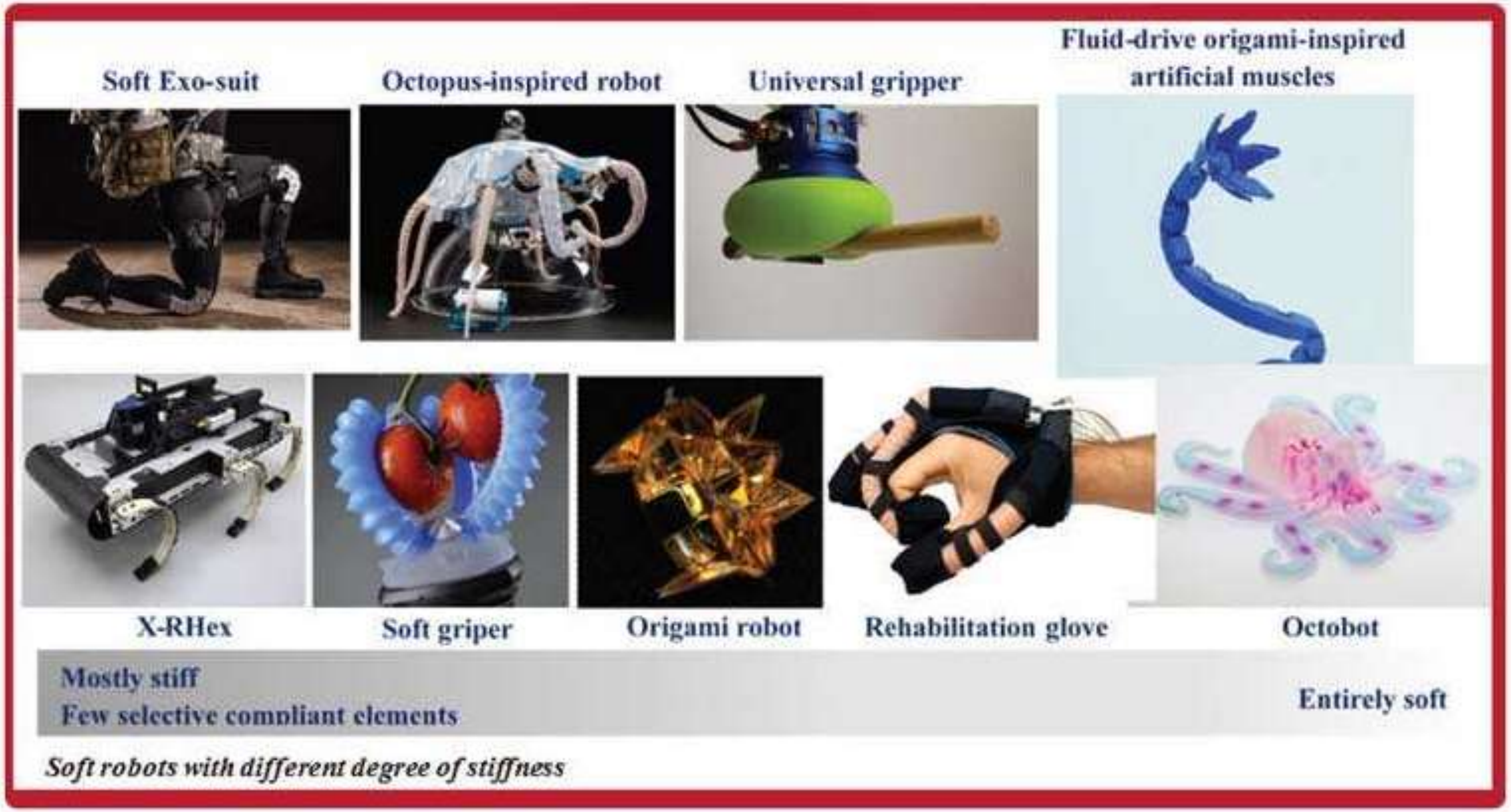
Deformation

A robotic grasping system



How to design and control the deformation?

Soft Hands



How to design and control the deformation?

Soft Hands

REVIEW

Soft Grippers

Soft Robotic Grippers

Jun Shintake, Vito Cacucciolo, Dario Floreano, and Herbert Shea*

Soft grippers using passive structure with external motors

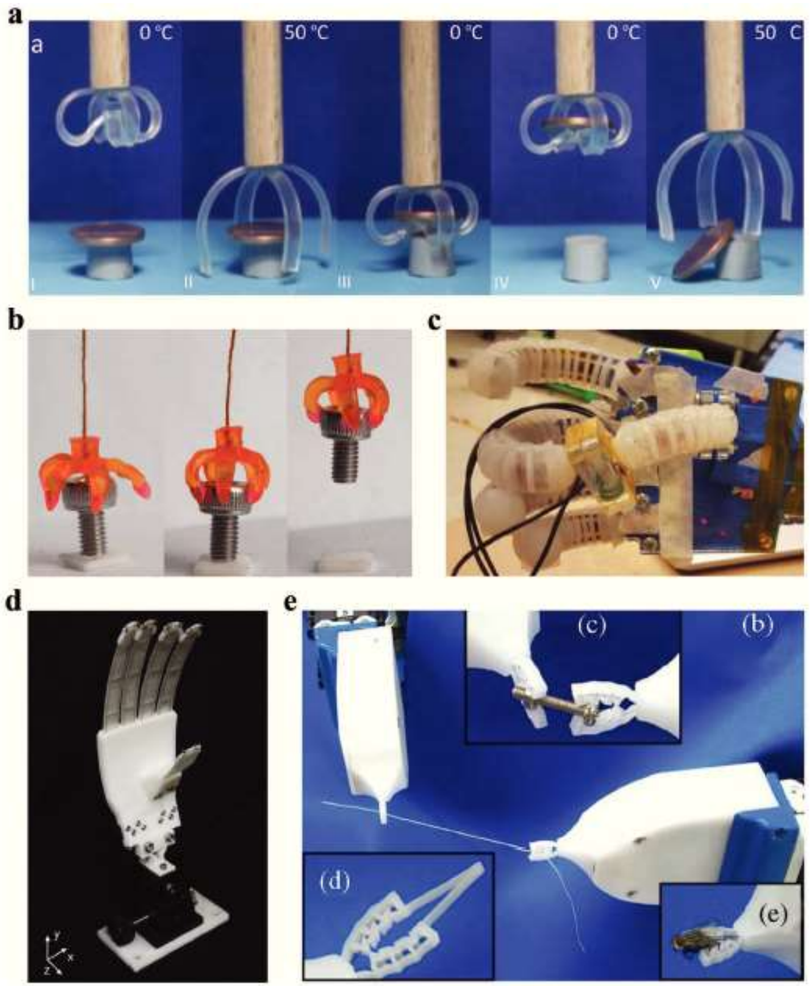
Soft grippers using fluidic elastomer actuators

Soft Hands

REVIEW
Soft Grippers
ADVANCED MATERIALS
www.advmat.de

Soft Robotic Grippers

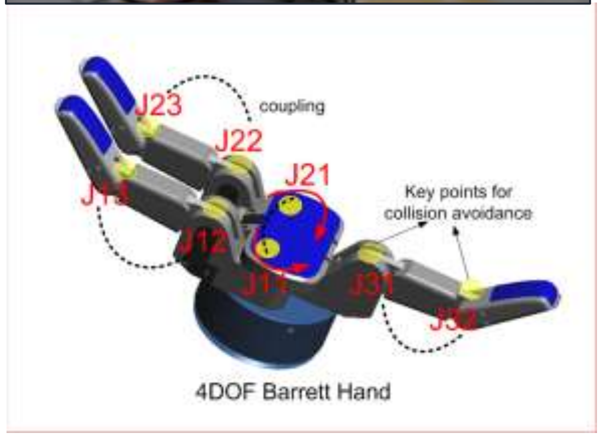
Jun Shintake, Vito Cacucciolo, Dario Floreano, and Herbert Shea*

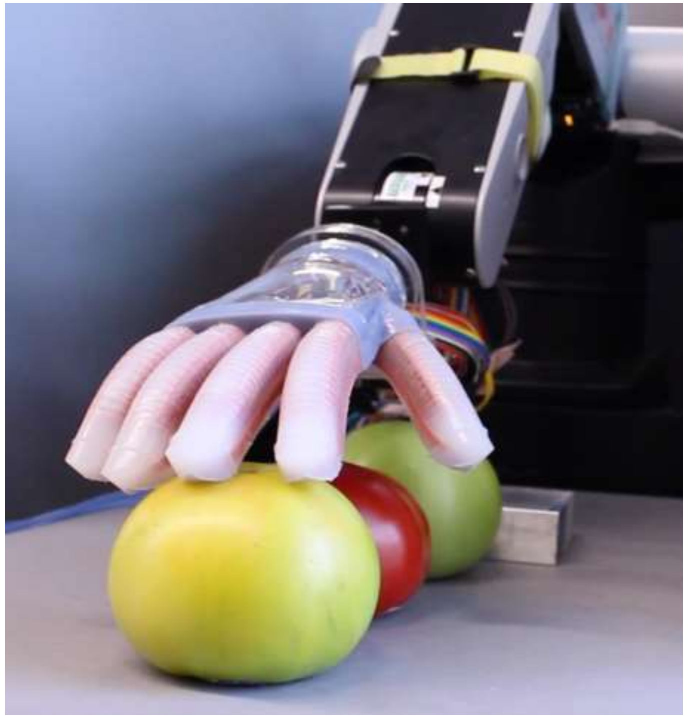


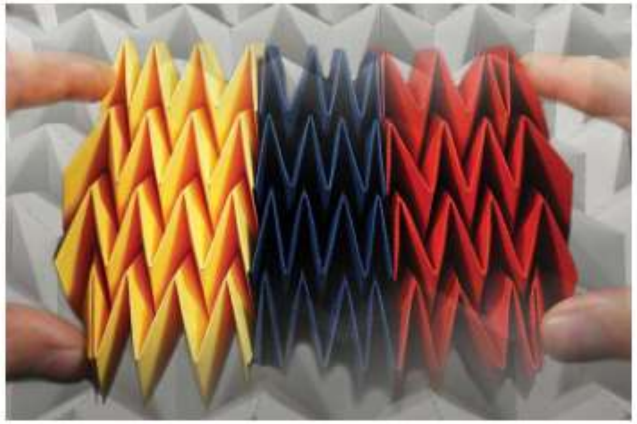
Soft grippers using dielectric elastomer actuators

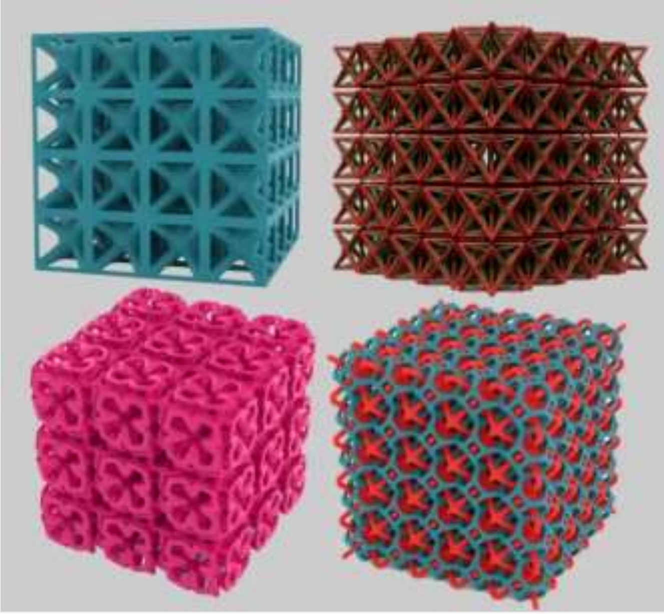
Soft grippers using shape memory materials

New Material









Steel → Rubber….→ Meta Material

Video
(3 mins)

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

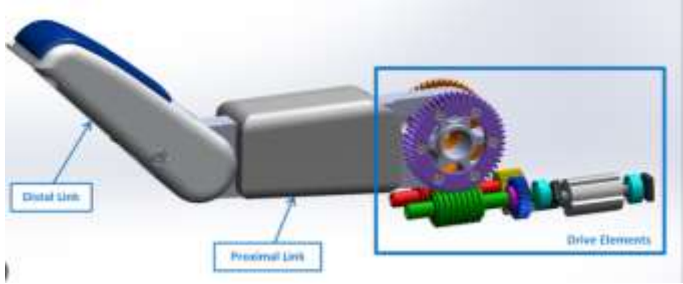
Biomimetic
Dexterous
Manipulation
Laboratory

Video
(1.5 mins)

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

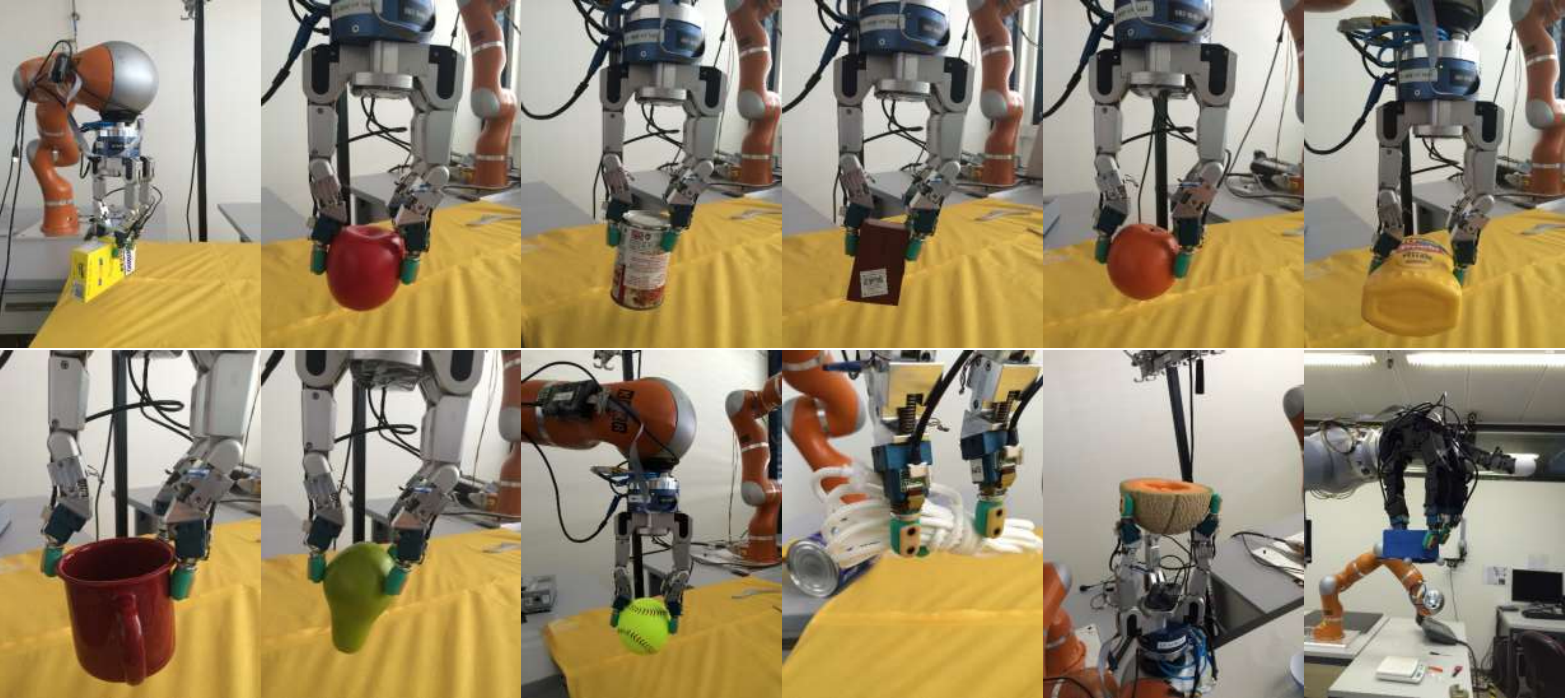
Jonathan P. King, Dominik Bauer, Cornelia Schlagenhauf,
Kai-Hung Chang, Daniele Moro, Nancy Pollard, and Stelian Coros

Motion Transmission

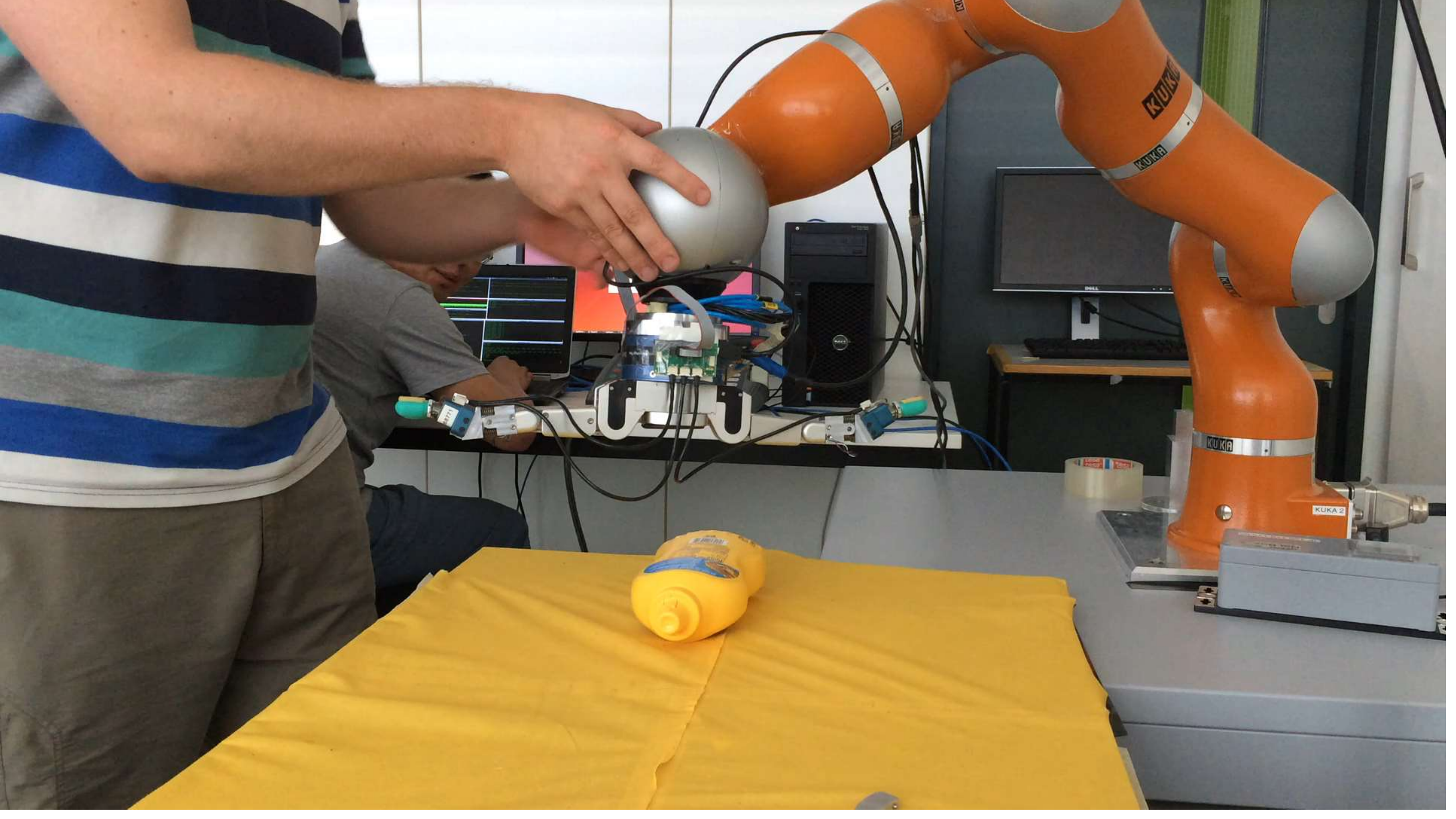


No(few) Deformation!

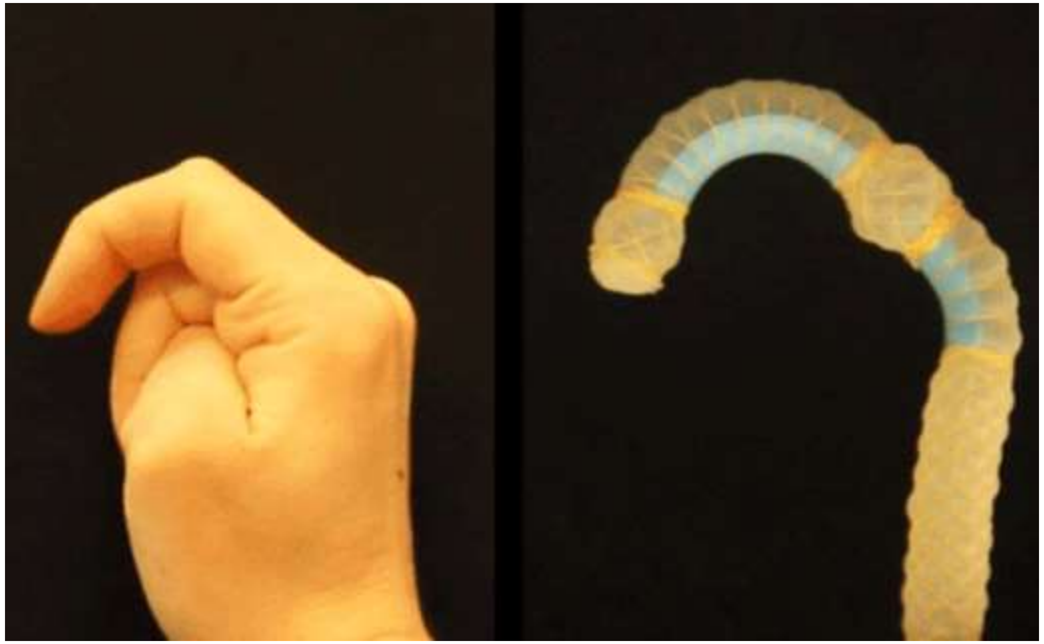
Back-drivable is already good enough for rigid hand!



Add some deformation to right hand!


KUKA
KUKA
KUKA
KUKA 2

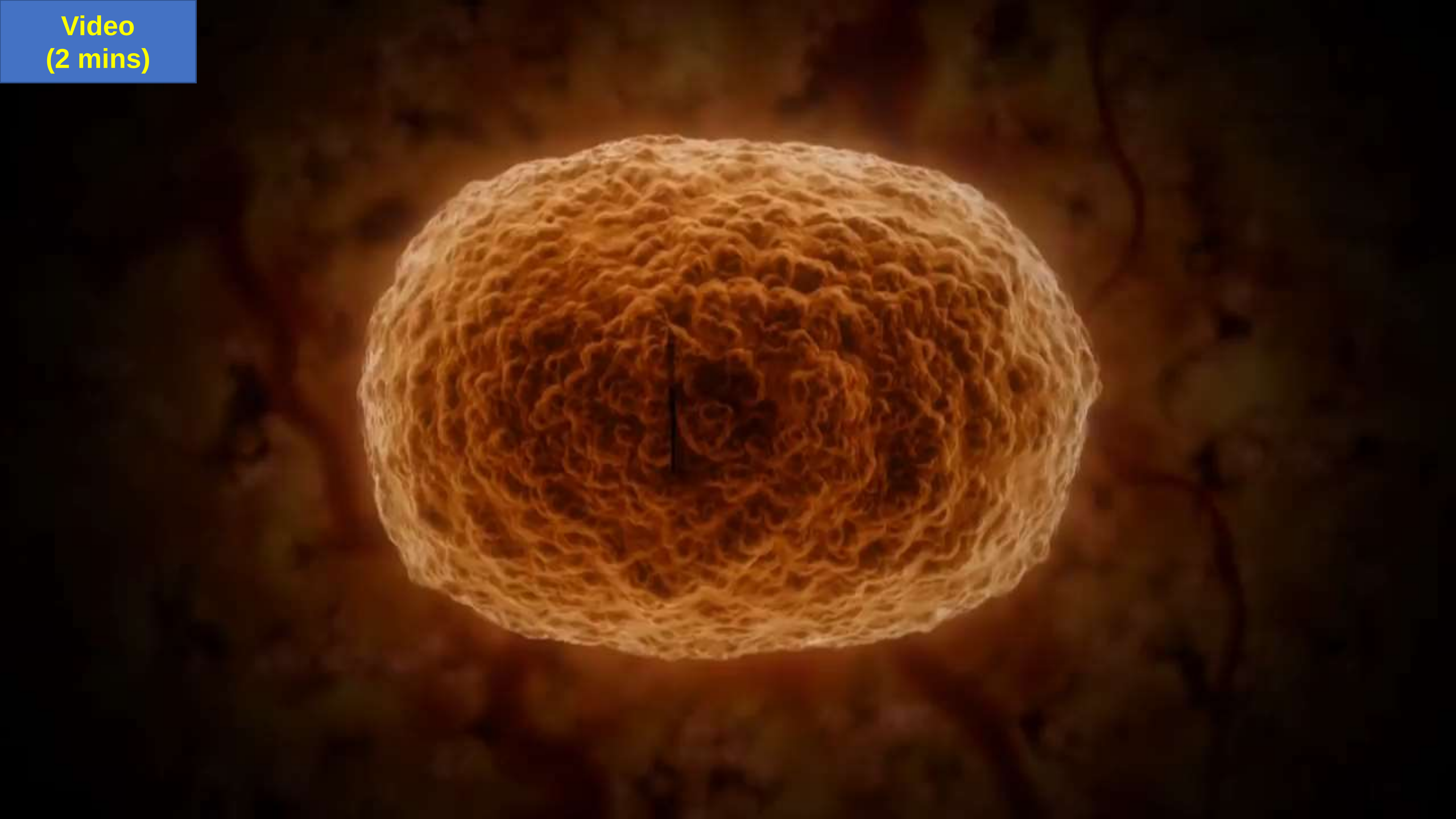
Motion Transmission



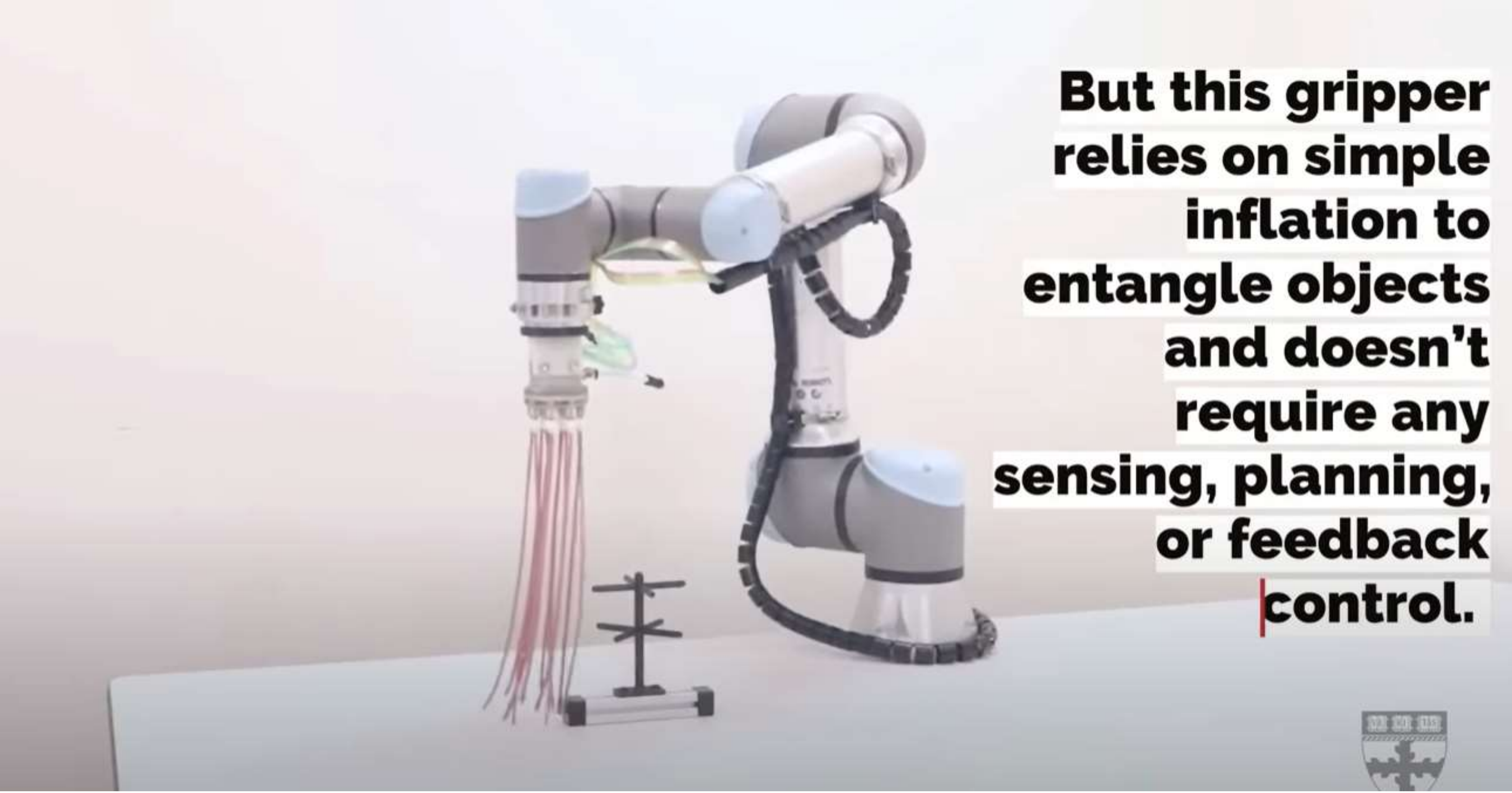
Deformation is motion!
Shape is function!

Video
(1 mins)

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 ρ[W/Kg]	σ_{max} [MPa]	ε_{max}	E [GPa]	Efficiency
DC motors	100	0.1	0.4	*	0.6–0.8
Pneumatic	400	0.5–0.9	1	$5–9 \times 10^{-4}$	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 ρ = Power per unit of weight, σ_{max}= Maximum force exerted by the actuators per area, ϵ_{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

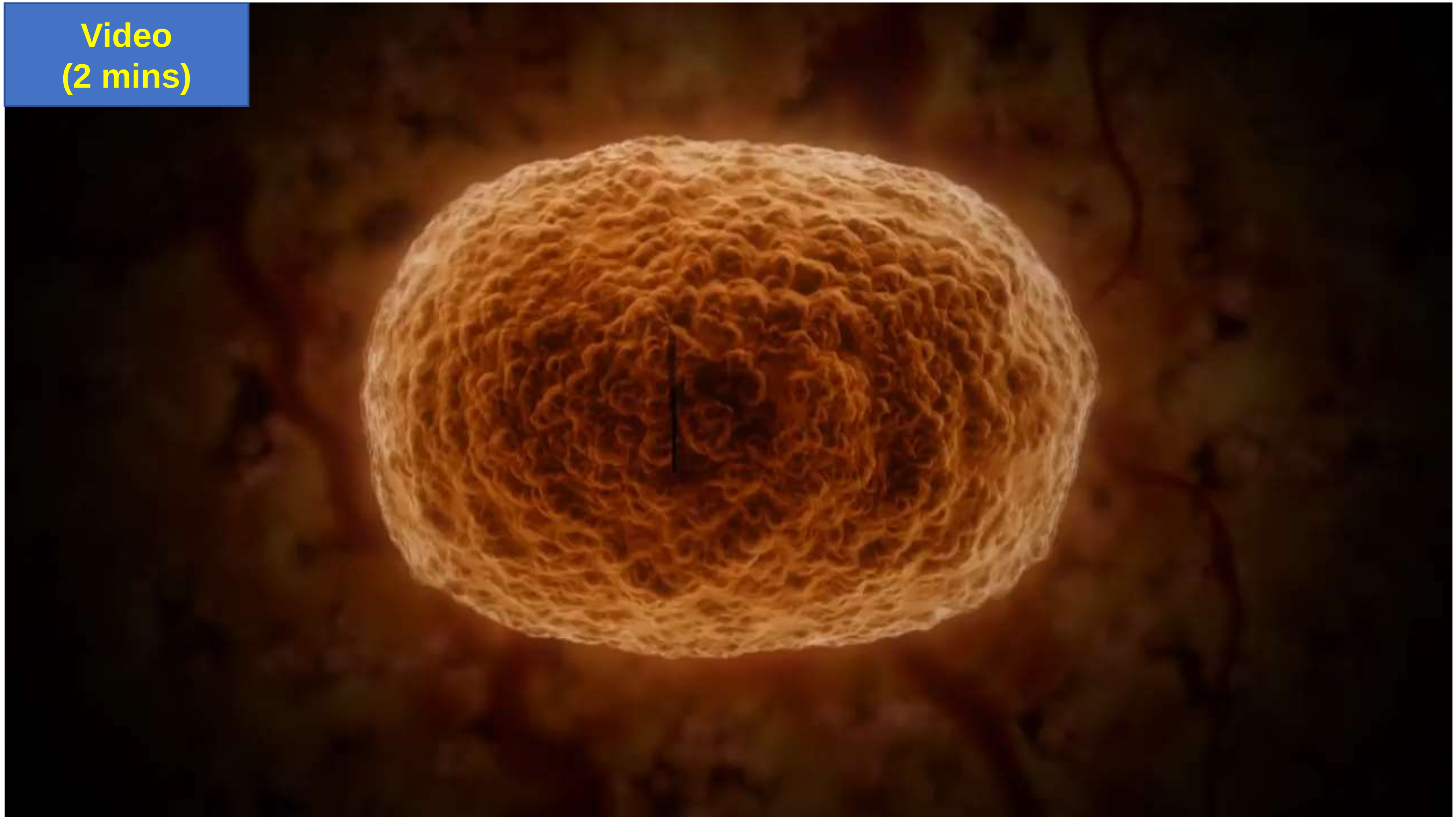
FIGURE 2.12: Pneumatic actuators for robotic hands

Video
(5 mins)

Actuator

Video
(3 mins)

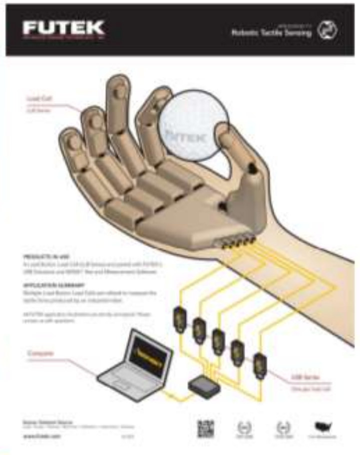
Actuator

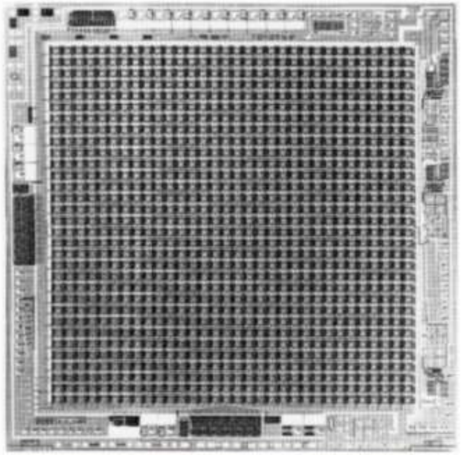


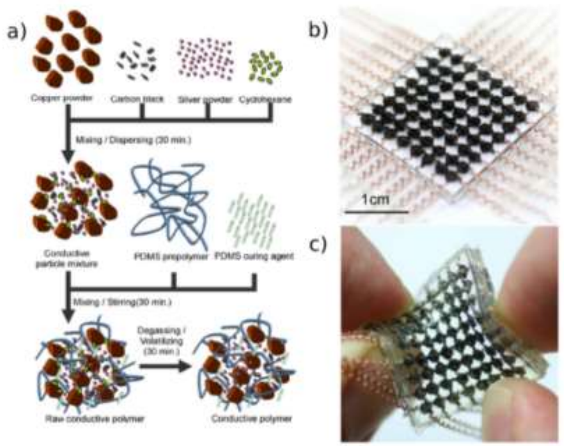
Sensors

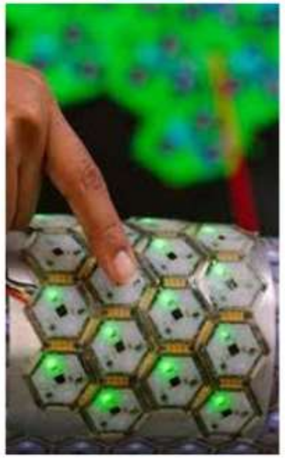
- motor position sensors;
- finger joints position sensors;
- motor torque sensors;
- joint torque sensors;
- tactile sensors;
- temperature sensors;
- in hand camera.

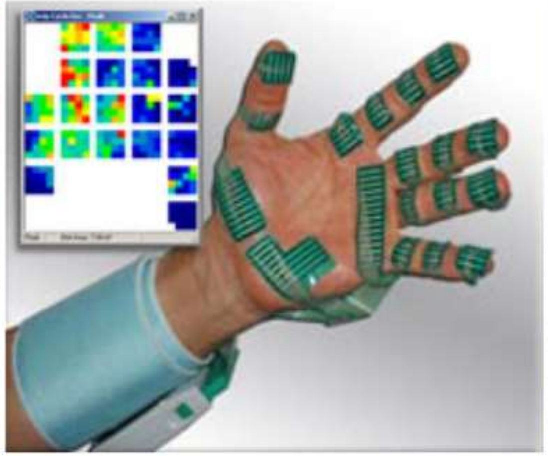
Sensors

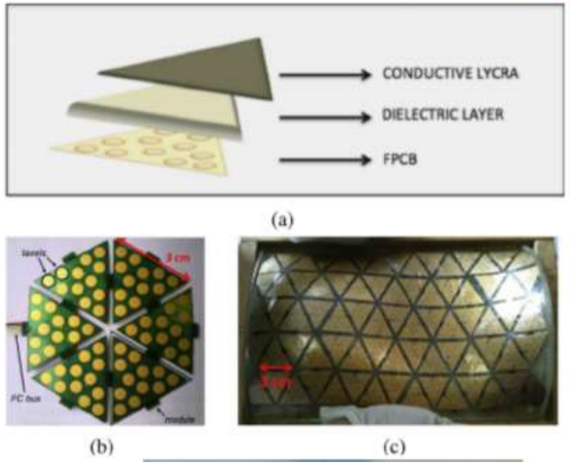






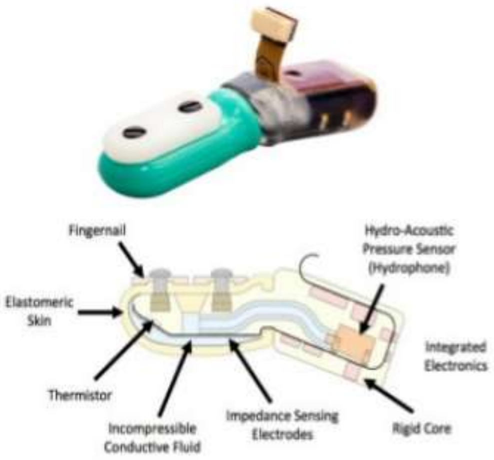


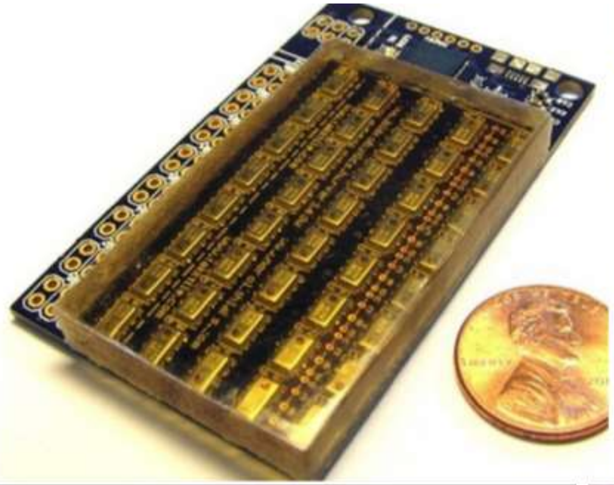


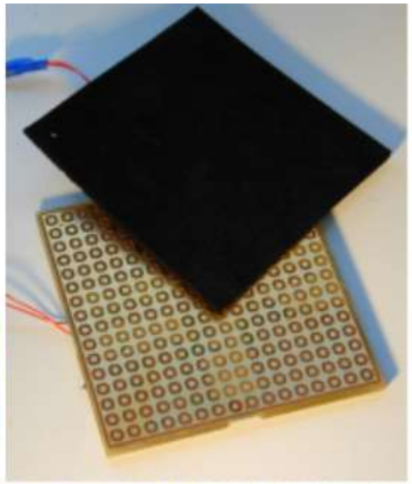


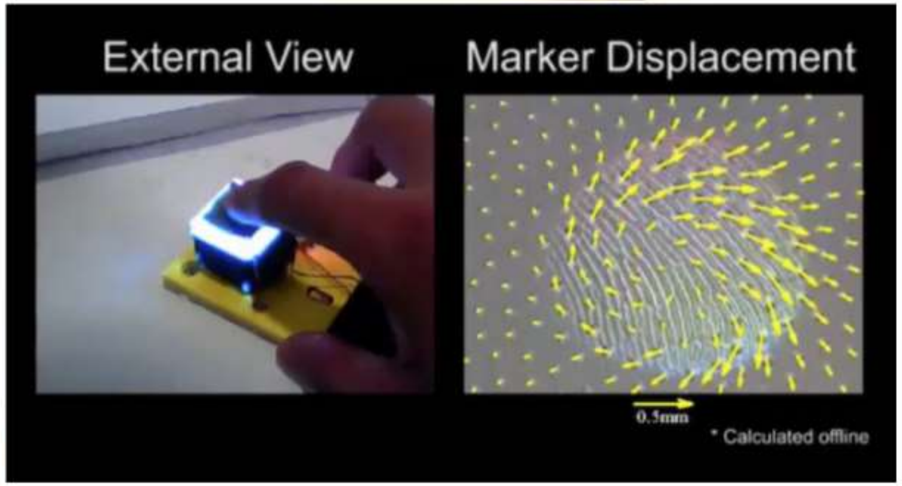
Still a hot topic

Sensors


Fingernail
Hydro-Acoustic Pressure Sensor (Hydrophone)
Elastomeric Skin
Integrated Electronics
Thermistor
Incompressible Conductive Fluid
Impedance Sensing Electrodes
Rigid Core






External View
Marker Displacement
0.5mm
* Calculated offline

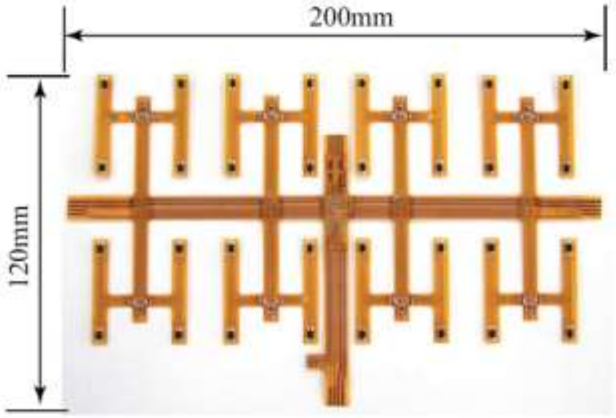
Sensors

(a) Force/Torque sensor [35] (b) Tendon tension sensor [35] (c) Single axis joint sensor [36] (d) Double axis joint sensor [36]

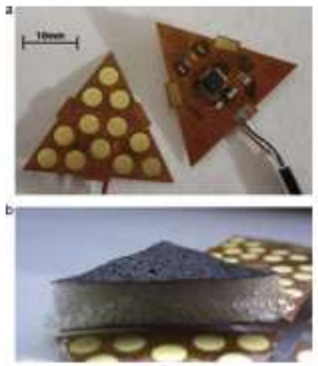
FIGURE 2.15: Force/Torque integrated sensors

Sensors

(a) Strain gauges tactile sensor [37]

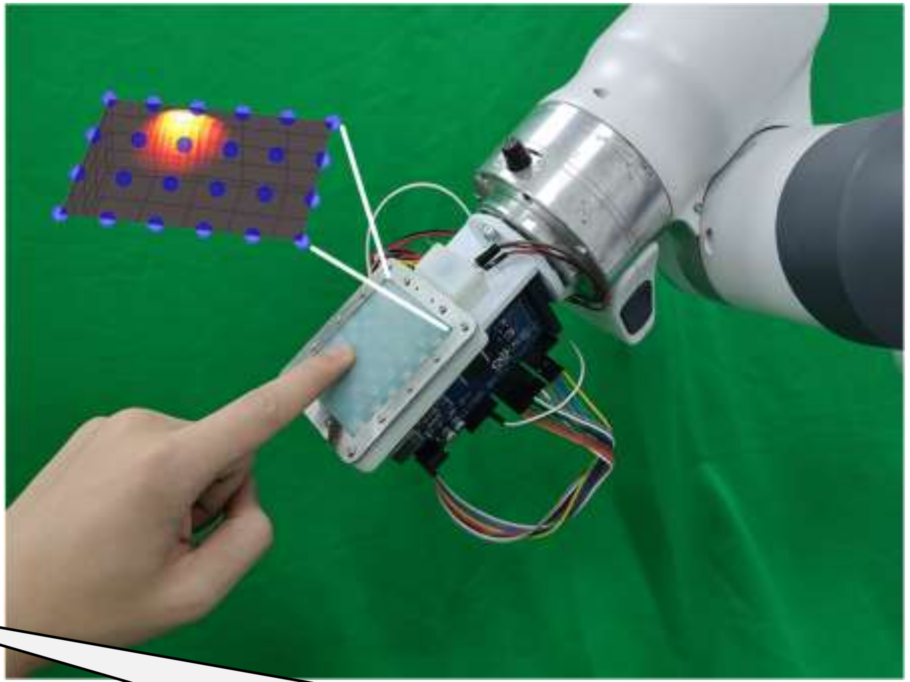


(b) Led based tactile sensor [38]



(c) Capacitive tactile sensor [39]

FIGURE 2.16: Tactile sensors

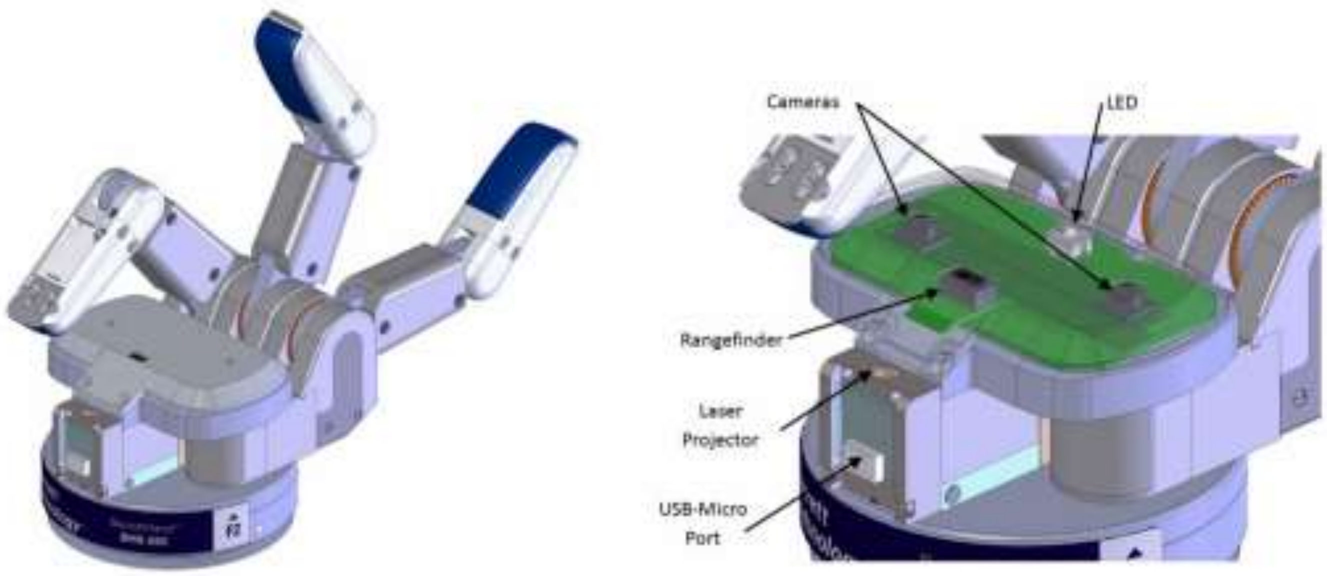


In case you need some tactile sensor for your design

A biomimetic tactile palm for robotic object manipulation

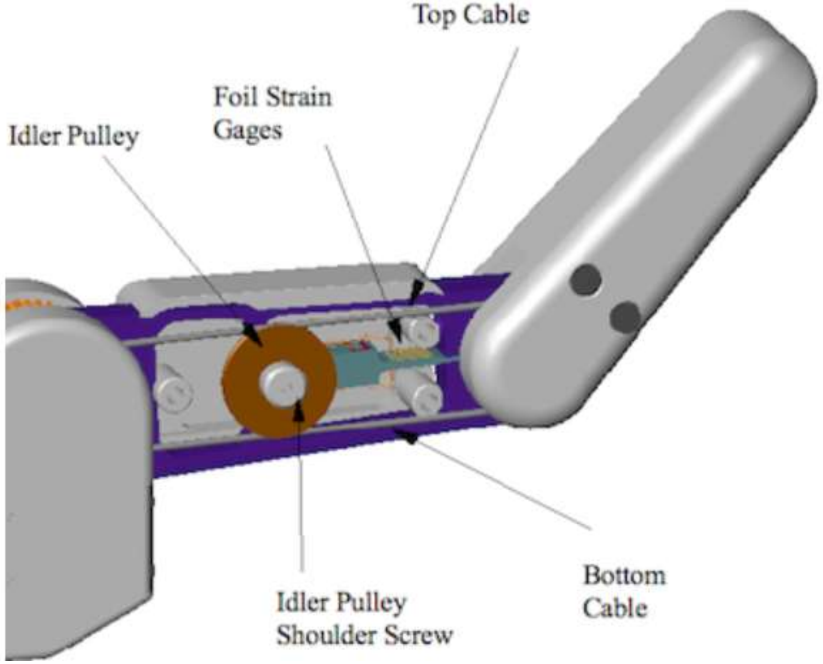
Ziwei Lei[1,3], Xutian Deng[1], Yi Wang[1], Xiaohui Xiao[2], Dong Han[3], Fei Chen[4,*], Miao Li[1,2,*]

Sensors

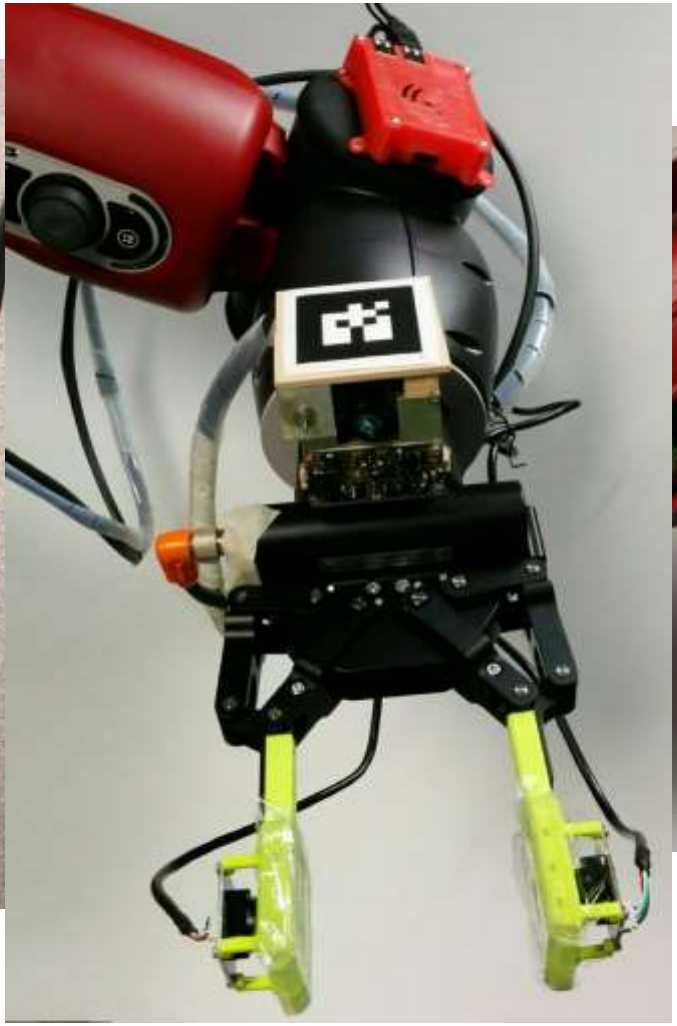
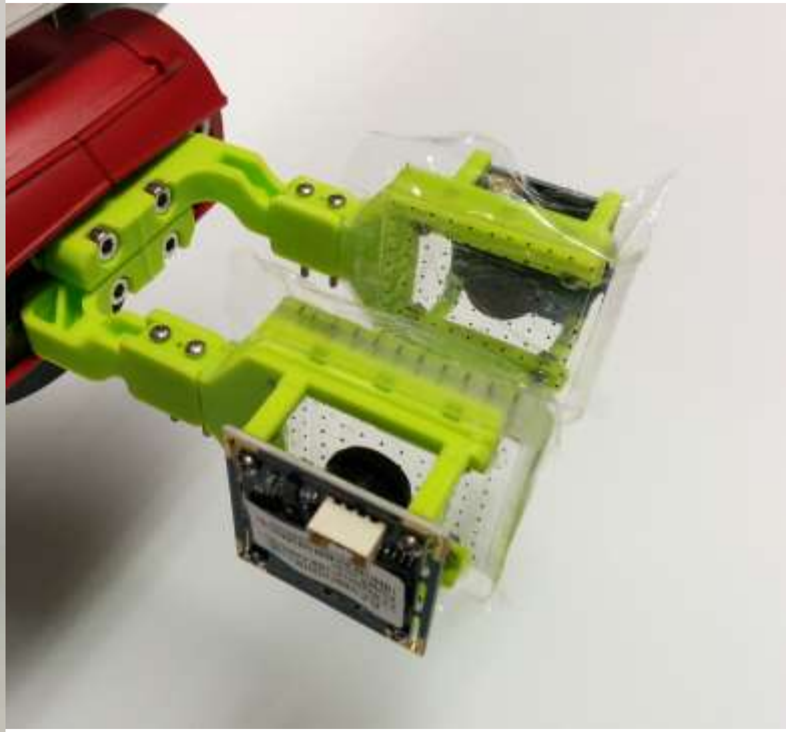


(a) Barrett Hand (b) In Hand Cam Integration

FIGURE 2.17: Patented Hand-Eye integration [32]



Sensors

Sensors

Finger Vision: Tactile Sensing Feeling With Your Eyes

Sensors

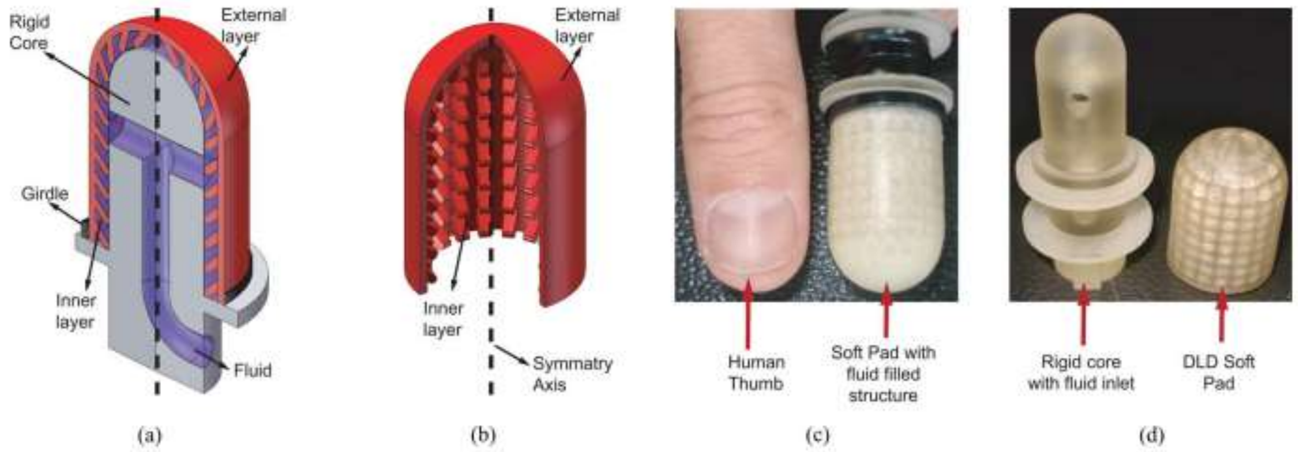
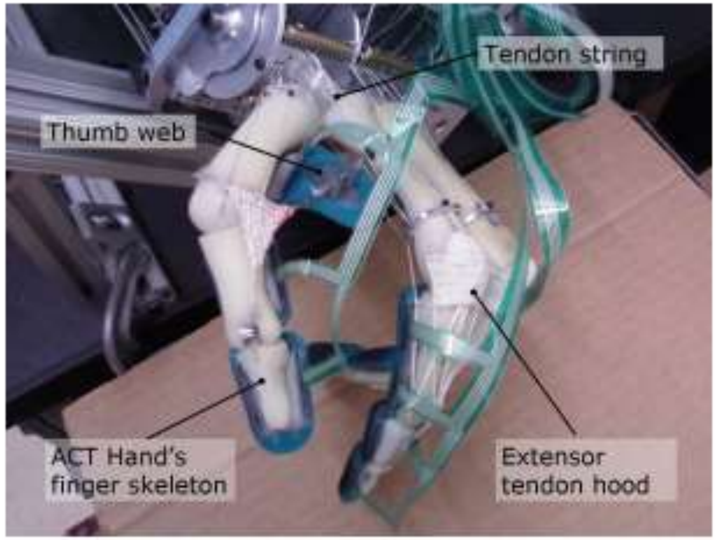


FIGURE 2.18: Fluid-filled soft-pad concept and prototype. (a) 3-D model. (b) Longitudinal cross section. (c) Prototype comparison with human-thumb dimensions. (d) Rigid core with fluid inlet and soft pad.

Sensors

(a) Sensorized artificial skin concept

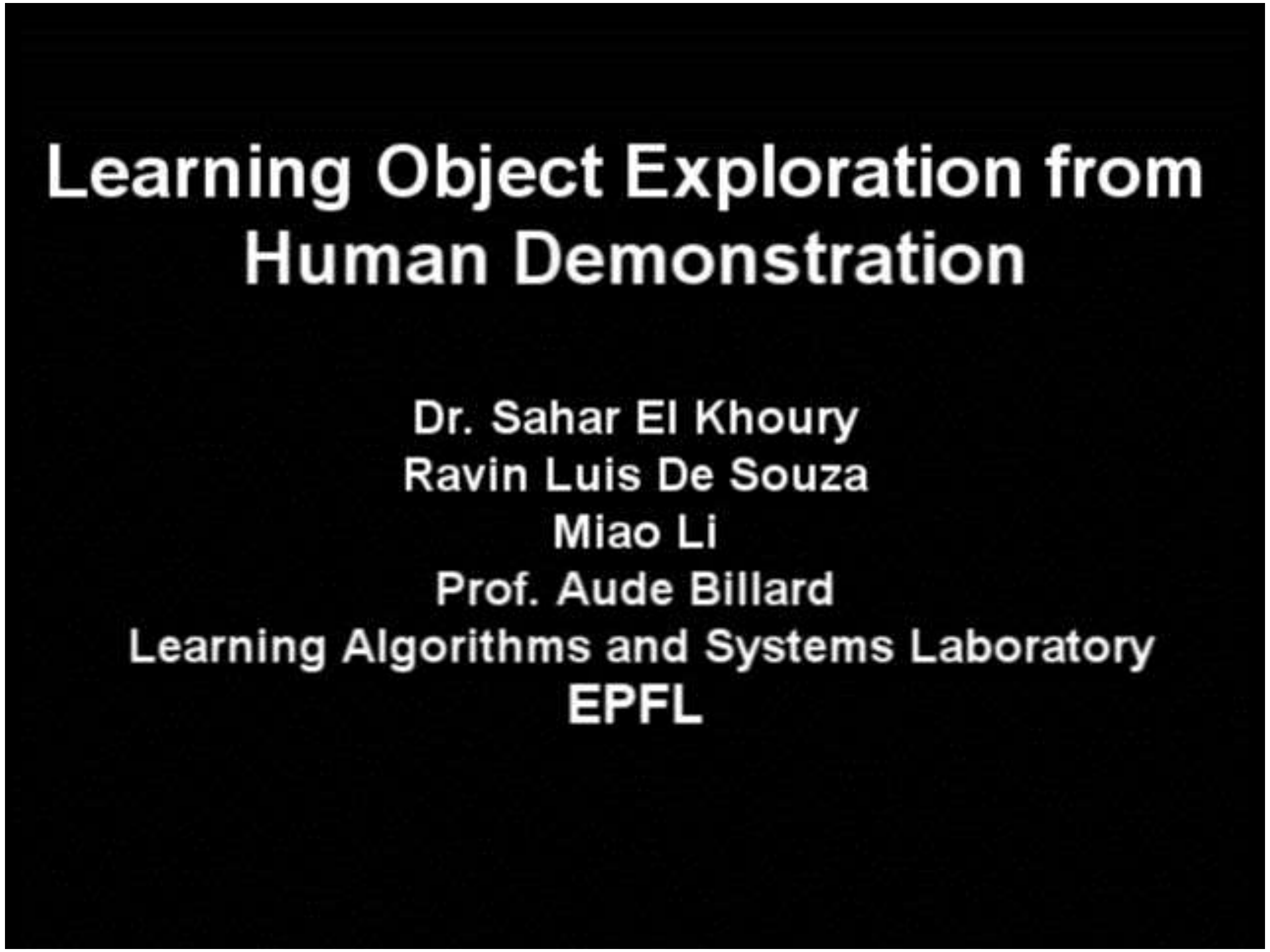


(b) Integration of the skin within the robotic hand

FIGURE 2.19: Artificial skin with integrated tactile sensors

Sensors


NESCAFÉ
GOLD


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

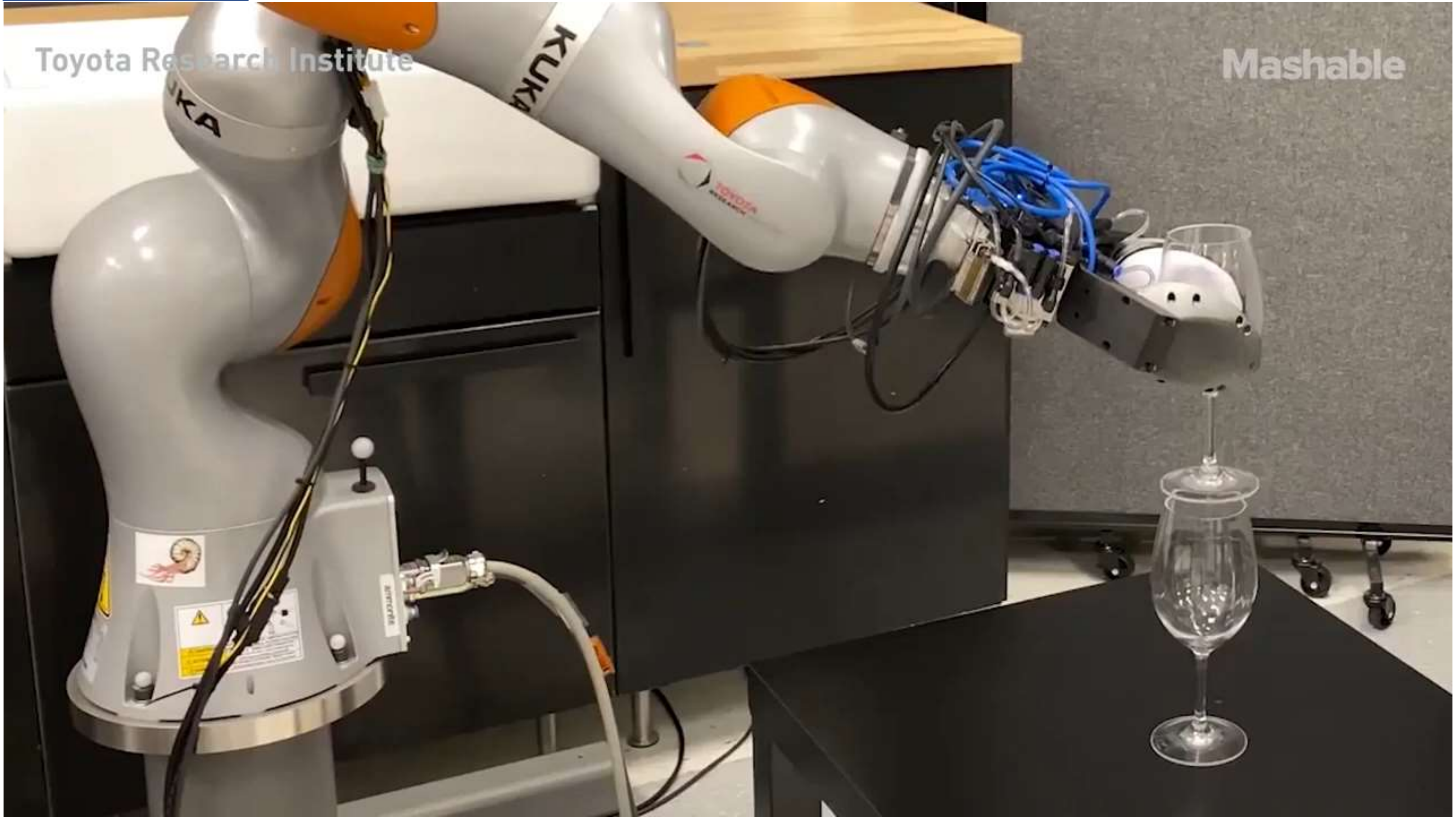
Video (2 mins)

Dexterous Bimanual Object Exploration with Whole-hand Tactile Sensing

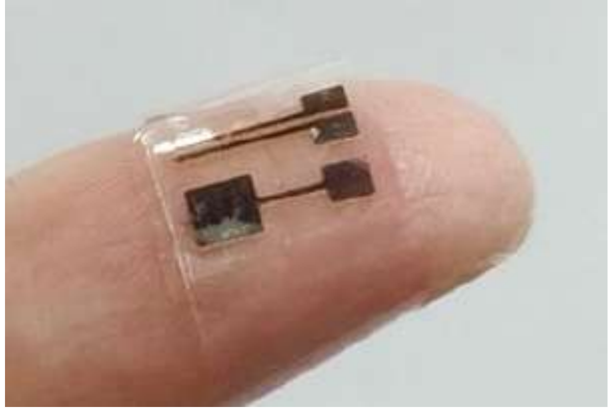
Nicolas Sommer, Miao Li
Aude Billard
Learning Algorithms and Systems Laboratory
EPFL

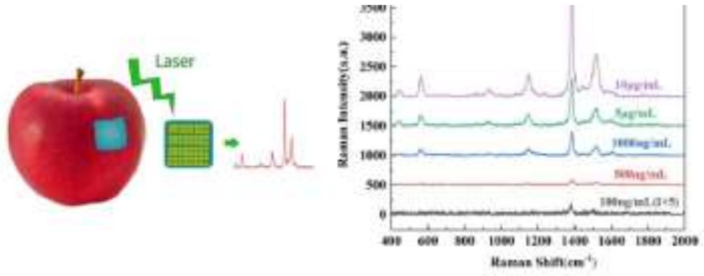
Sensors

Video (1 mins)

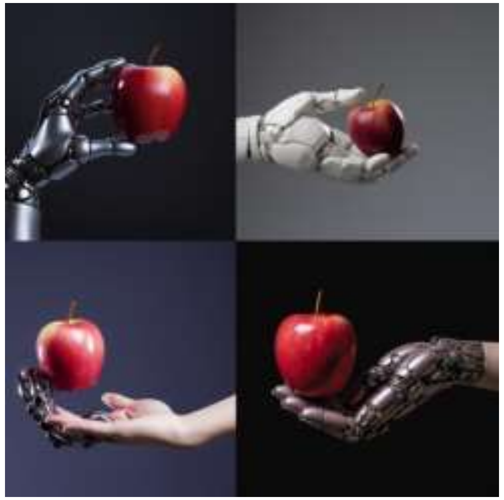


Sensors





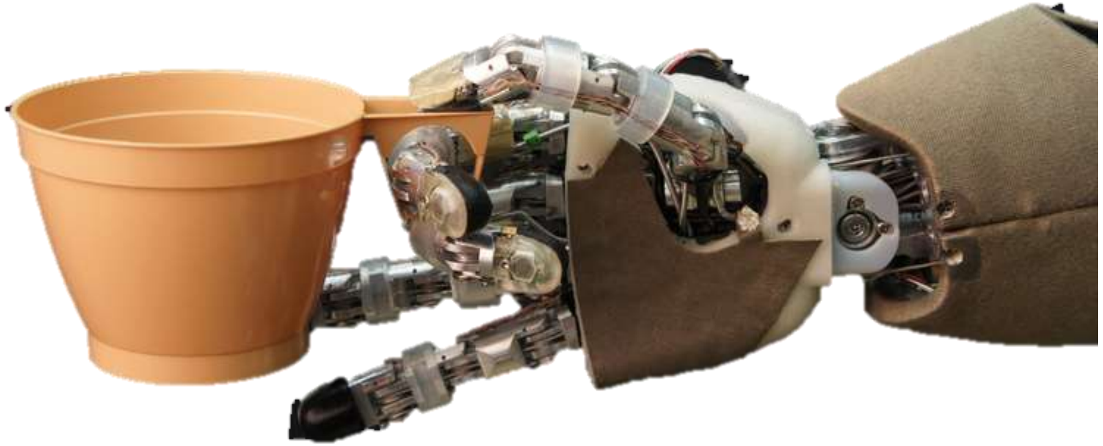
Can we attach this sensor to something else?



Please join us if you are interested in this project!

Today

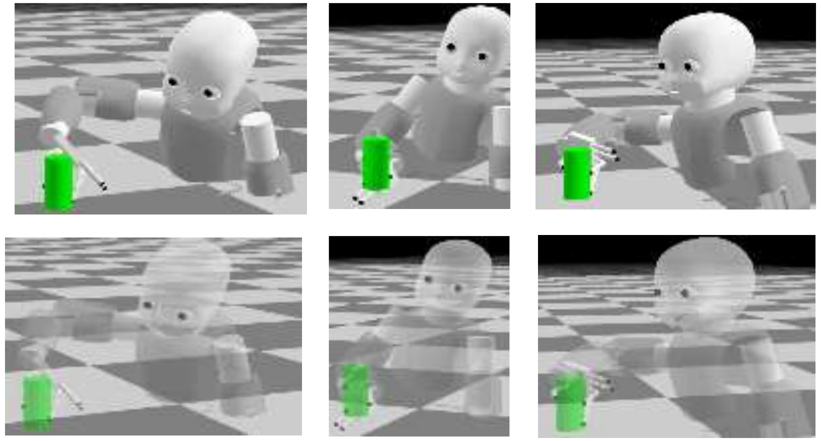
- **Design and Modelling of typical robotic arm/hand**
- **DH parameters**
- **Kinematics, IK, Jacobian**
- **Soft hand**
- **Grasp planning and control**
- **Simulation tool introduction**
- **Group list**



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

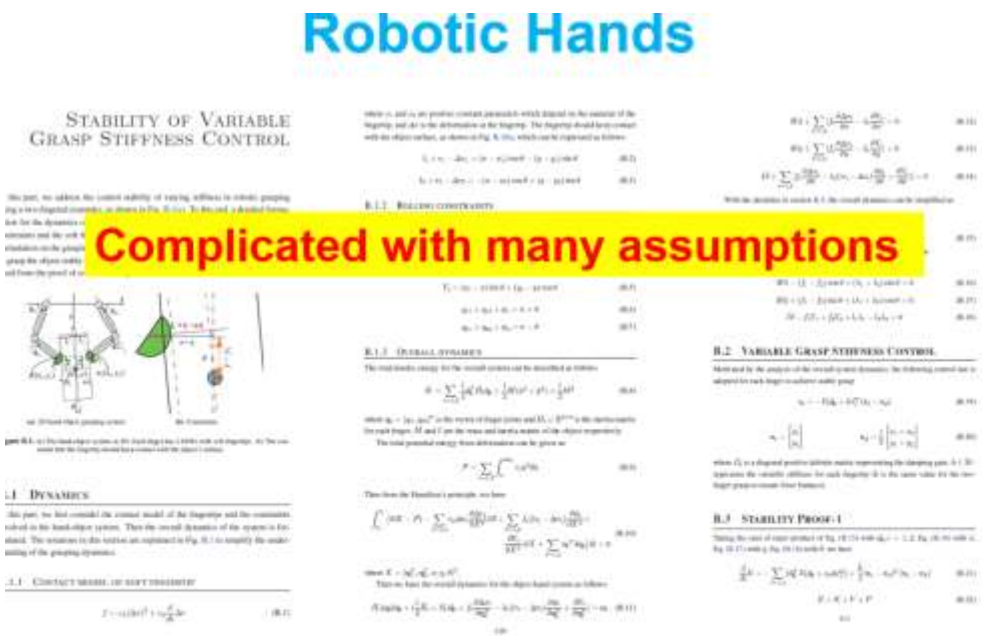


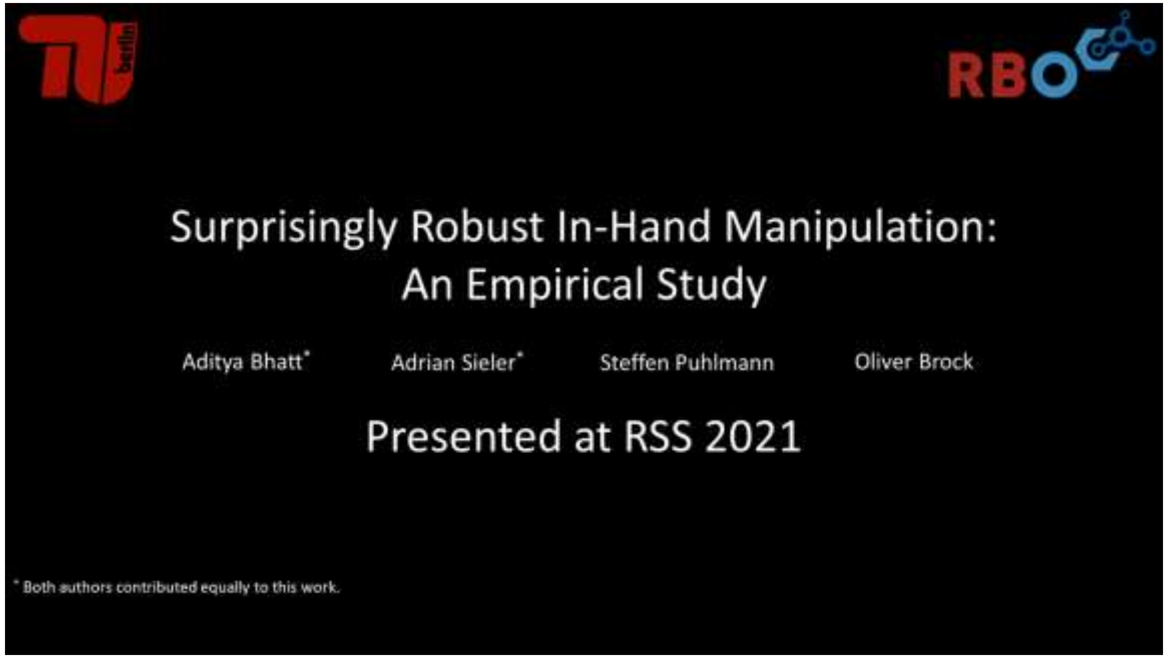
Grasp Planning as Optimization

$\underset{\boldsymbol{\theta},\mathbf{H},\mathbf{p},\mathbf{n}}{\arg\min}$	$f(\boldsymbol{\theta},\mathbf{H},\mathbf{p},\mathbf{n})$	objective function
subject to:	$h_i(\boldsymbol{\theta}_i,\mathbf{H}) - \mathbf{p}_i = \mathbf{0}$ $l_i(\boldsymbol{\theta}_i,\mathbf{H}) - \mathbf{n}_i = \mathbf{0}$	hand constraints
	$g(\mathbf{p}_i) = 0$ $\nabla g(\mathbf{p}_i) \times \mathbf{n}_i = \mathbf{0}$ $\nabla g(\mathbf{p}_i) \cdot \mathbf{n}_i < 0$	object constraints
	$Q_{\text{task}}(\boldsymbol{\theta},\mathbf{H},\mathbf{p},\mathbf{n}) \in \mathcal{G}_{\text{task}}$	task constraints

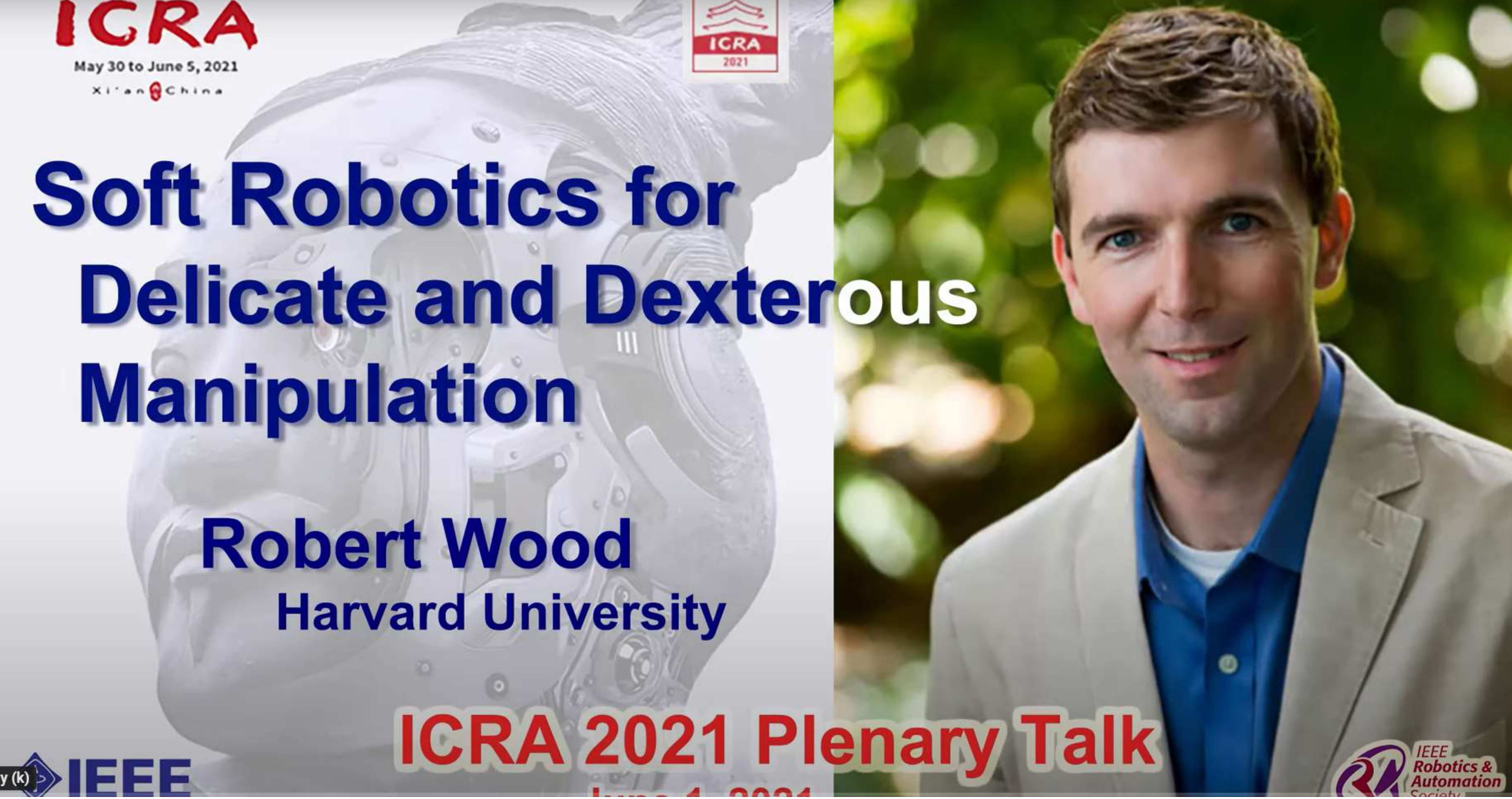
where $\boldsymbol{\theta} = (\boldsymbol{\theta}^{1T},...\boldsymbol{\theta}^{NT})^T$ is the vector of the generalized joint positions for N fingers. $\mathbf{H} \in SE(3)$ represents the hand position and orientation. $\mathbf{p} = (\mathbf{p}^{1^T},...\mathbf{p}^{N^T})^T$ and $\mathbf{n} = (\mathbf{n}^{1^T},...\mathbf{n}^{N^T})^T$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

Grasp control





Model-based → Learning-based



https://www.youtube.com/watch?v=gskX0cwCTZQ&ab_channel=IEEERoboticsandAutomationSociety

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