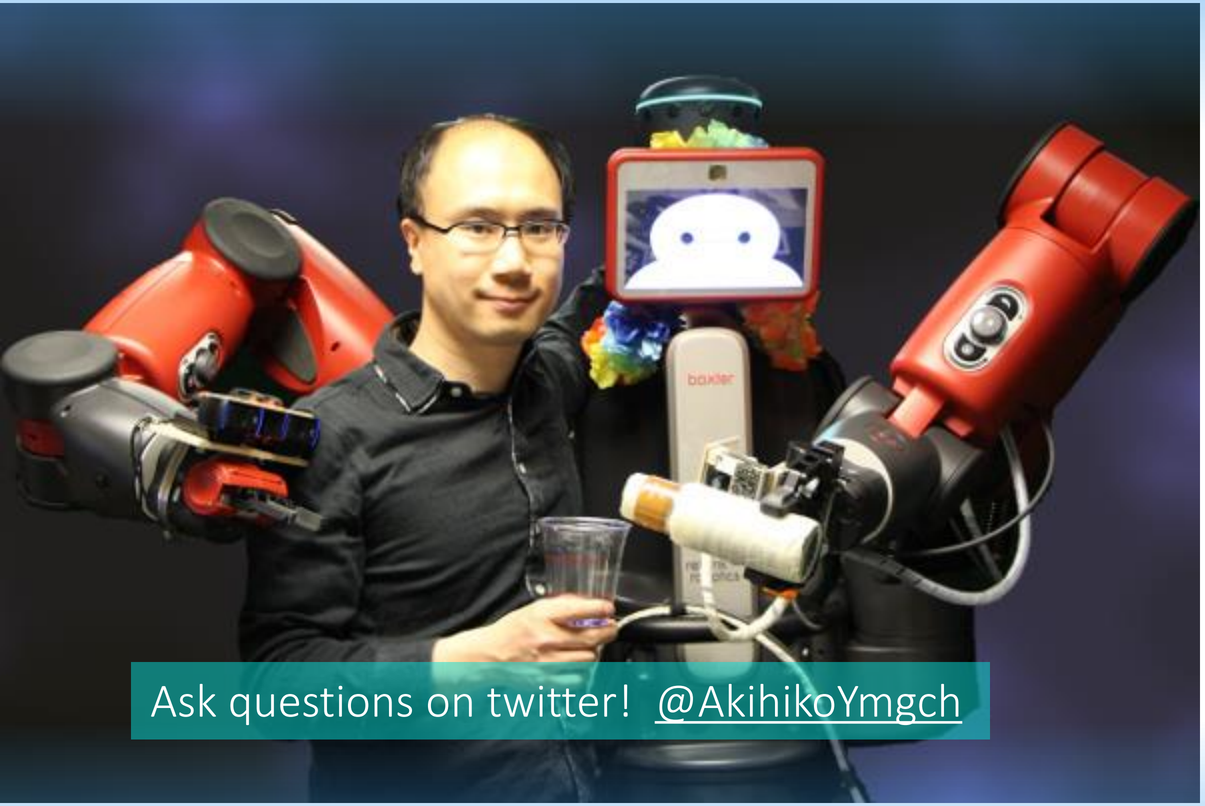
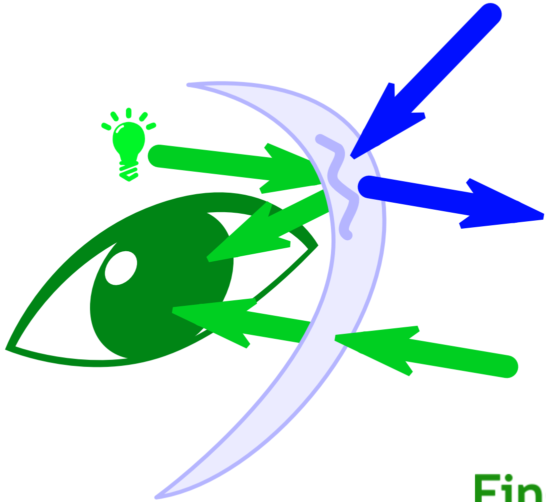
Vision-based Tactile Sensors and Their Applications to Robotic Manipulation



Ask questions on twitter! @AkihikoYmgch

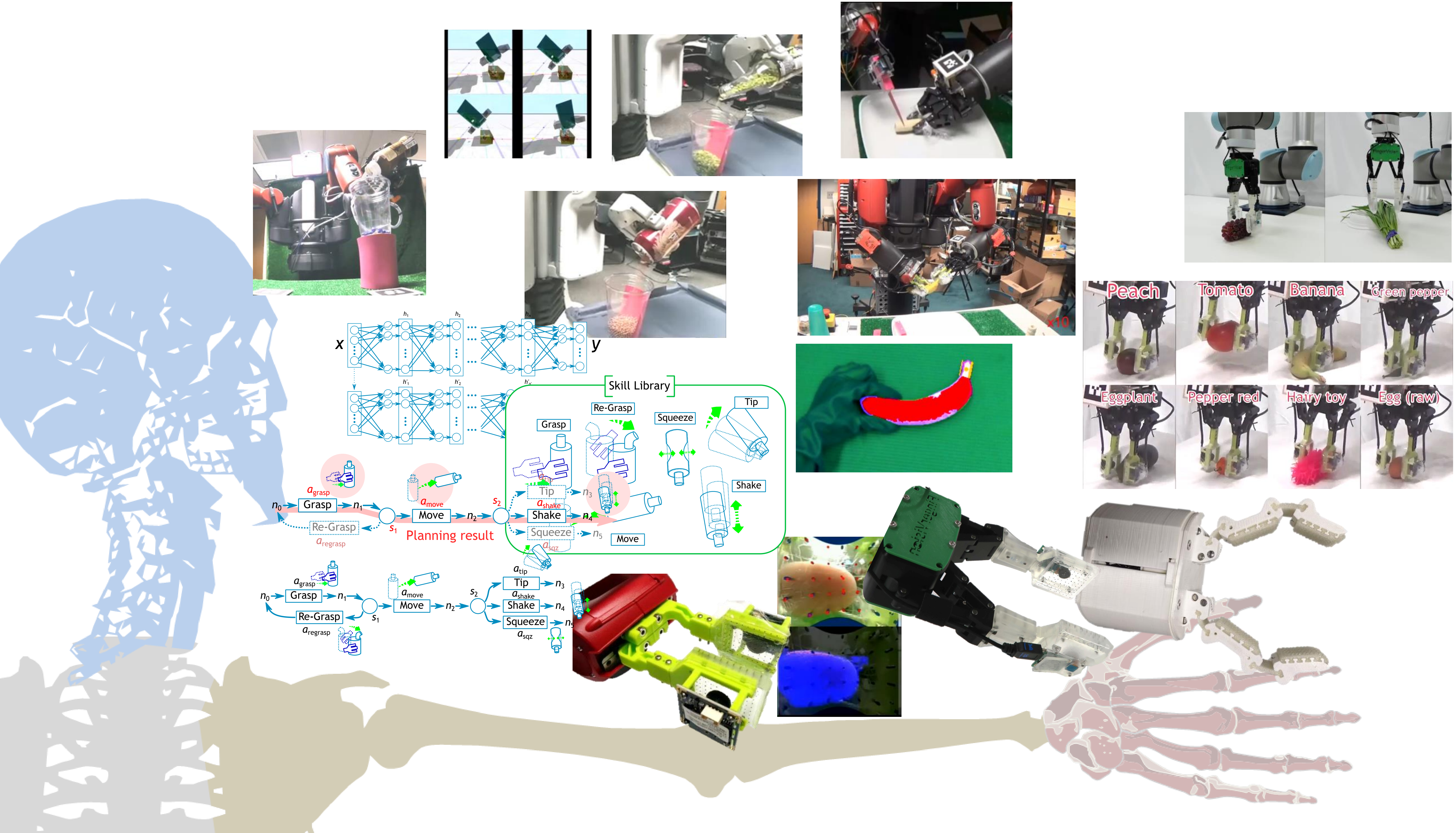
Slides are available online:
http://akihikoy.net/p/ssii2020-fv.pdf

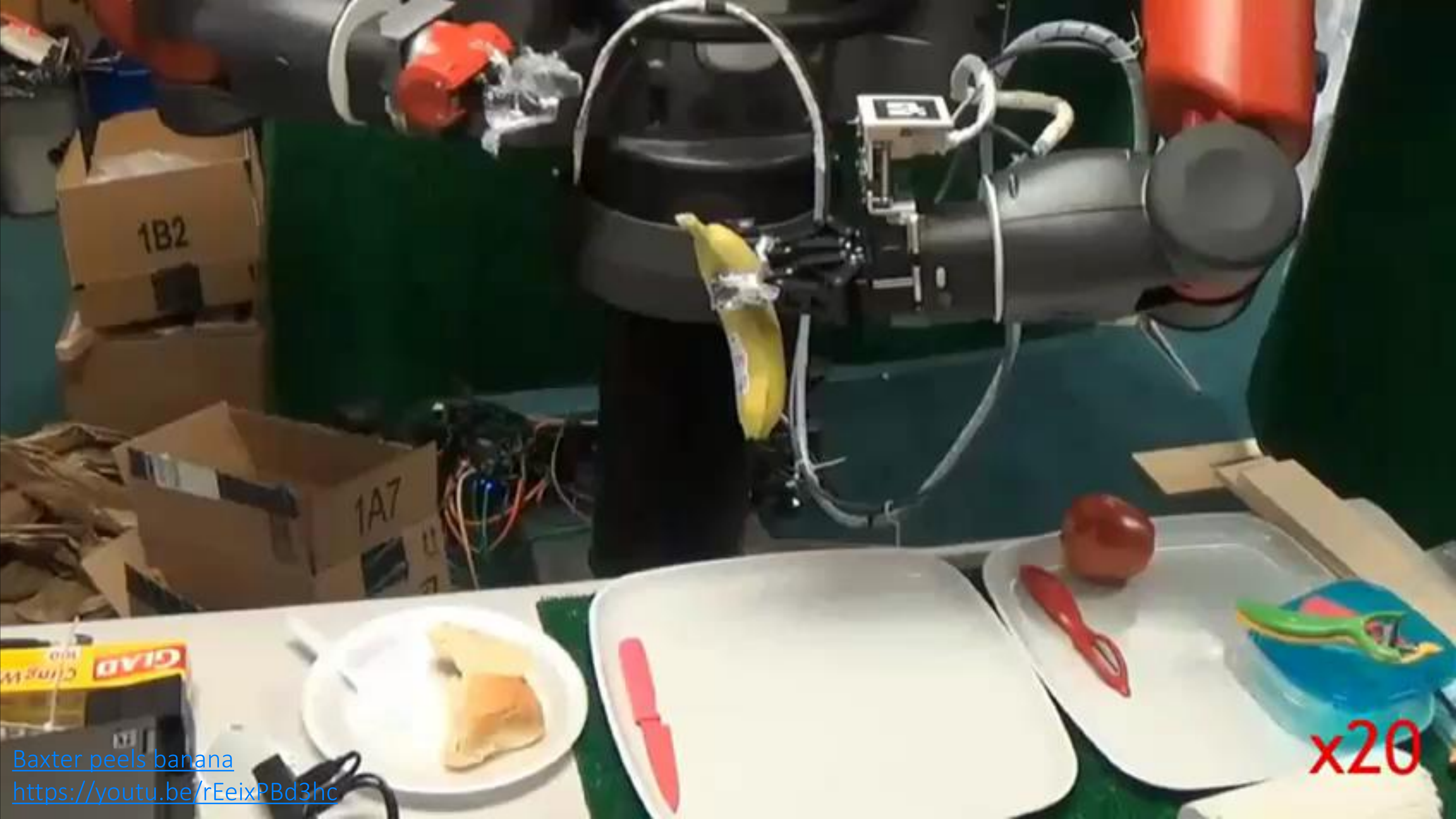


FingerVision

http://akihikoy.net/

Akihiko Yamaguchi(*1)
*1 Grad Schl of Info Sci, Tohoku University

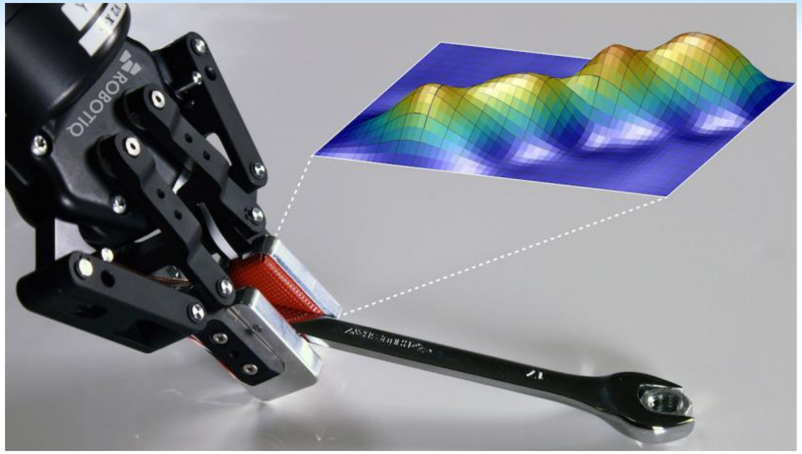

x
y
Skill Library
Grasp
Re-Grasp
Squeeze
Tip
Shake
Move
n_0
a_{grasp}
Grasp
n_1
Re-Grasp
$a_{regrasp}$
s_1
a_{move}
Move
n_2
s_2
Tip
n_3
a_{shake}
Shake
n_4
Squeeze
n_5
a_{sqz}
a_{tip}
Planning result
×10
Peach
Tomato
Banana
Green pepper
Eggplant
Pepper red
Hairy toy
Egg (raw)



Baxter peels banana
https://youtu.be/rEeixPBd3hc

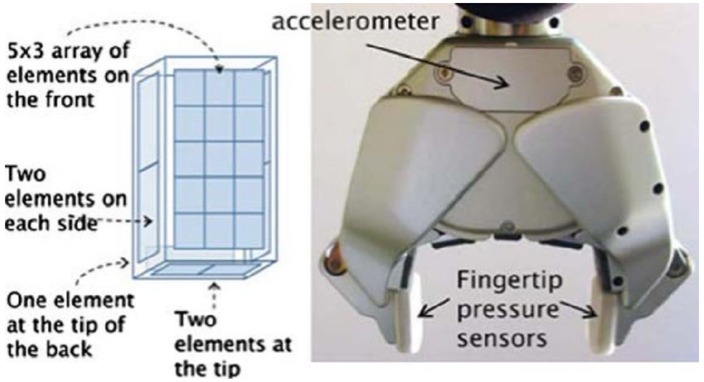
[A Compilation of Robots Falling Down at the DARPA Robotics Challenge](https://www.youtube.com/watch?v=g0TaYhjpOfo)
https://www.youtube.com/watch?v=g0TaYhjpOfo

Tactile Sensing for Manipulation



Tactile sensor for Robotiq gripper
“Why Tactile Intelligence Is the Future of Robotic Grasping”
IEEE Spectrum, 2016

RightHand Labs : ReFlex TakkTile Robot Hand
https://youtu.be/5yiE6hzwcJk



Fingertip pressure array of PR2
Dsouza et al. “The Art of Tactile Sensing: A State of Art Survey”

BioTac and NumaTac, SynTouch

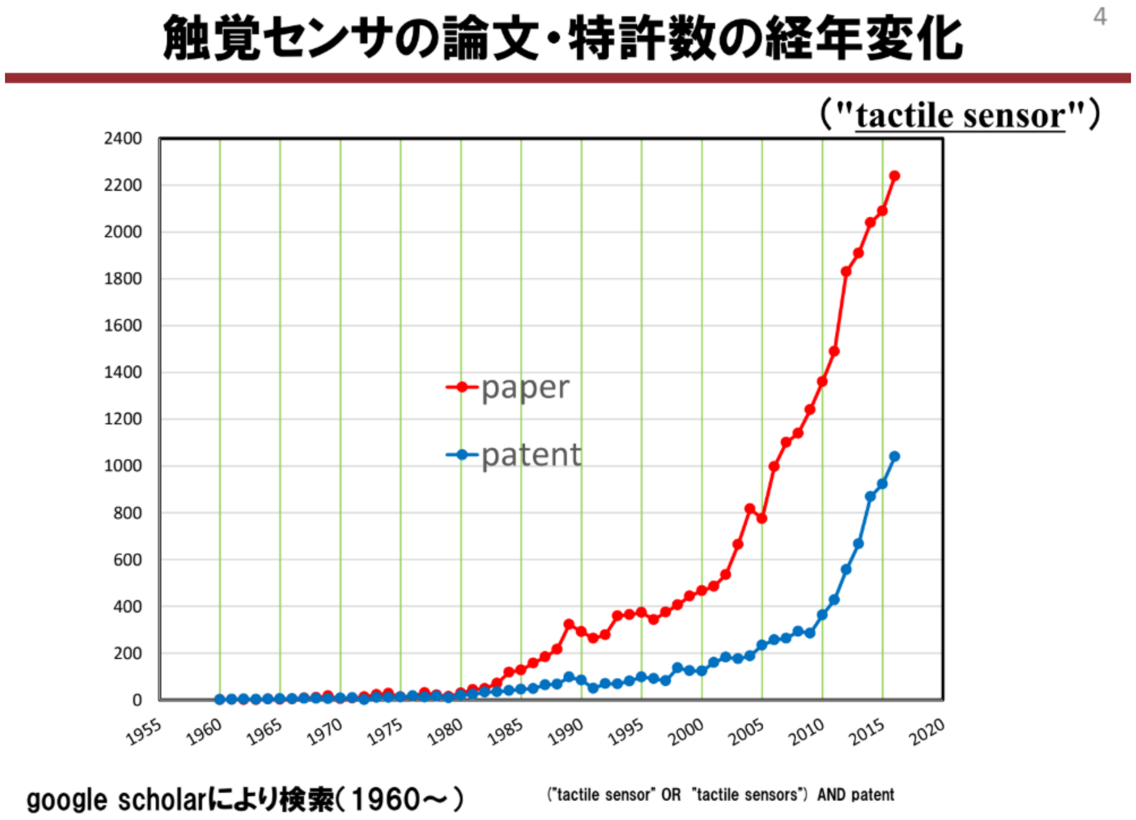
To Know More About Tactile Sensing

触覚・近接覚センサ 解説V2

下　条　誠

電気通信大学名誉教授

参考資料：
触覚認識メカニズムと応用技術(増補版), 全666頁, サイエンス＆テクノロジー株式会社, 2014



触覚センサの論文・特許数の経年変化

google scholarにより検索(1960～)

[下条,2019] Tactile technology and new development. 触覚・近接覚センサ解説
https://www.slideshare.net/makotoshimojo/ss-151495670
[Yamaguchi+,2019]
Recent progress in tactile sensing and sensors for robotic manipulation: can we turn tactile sensing into vision?

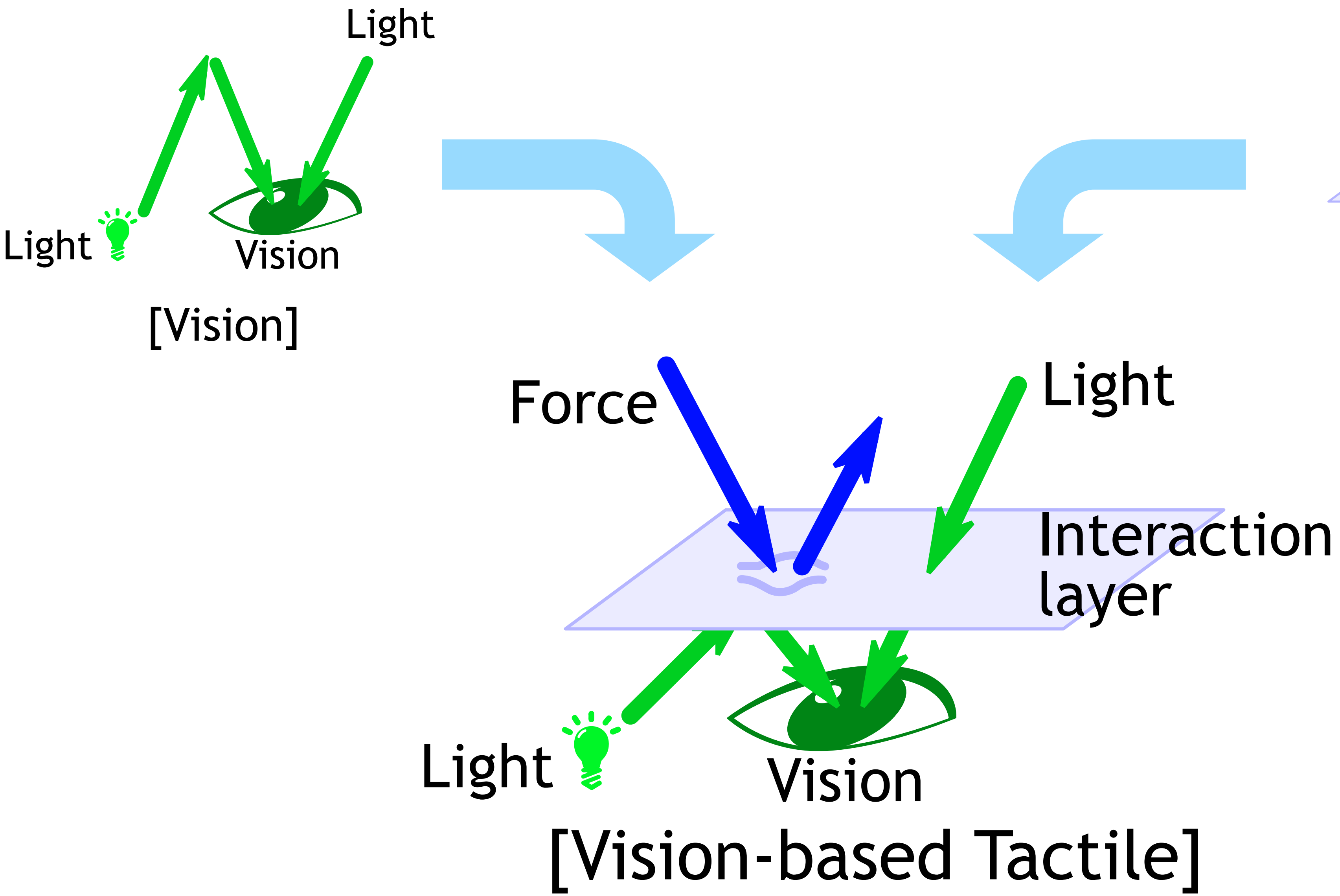
Issues of Tactile Sensing for Robotic Hands (1)

- Fabrication & installation difficulties
  - Fabricating sensors need skills and experience
  - Physically & mechanically embedding on robotic hands
  - Wiring, power supply, and processing
  - Expensive
- Durability
  - Low durability, fragility
  - Maintenance becomes complicated
- Performance issues
  - Sensing modalities (force distribution, slip distribution, thermal sensitivity, …)
  - Resolution, FPS
  - Reliability

Issues of Tactile Sensing for Robotic Hands (2)

- **Programming issues**
  - Less compatibility with the other tactile sensors
  - It is unclear what we can do with tactile sensors
  - Programming becomes complicated
- **No ecosystem to accumulate knowledge** (hardware/software)
- **Roboticists can find alternative ways** (which could be research topics)

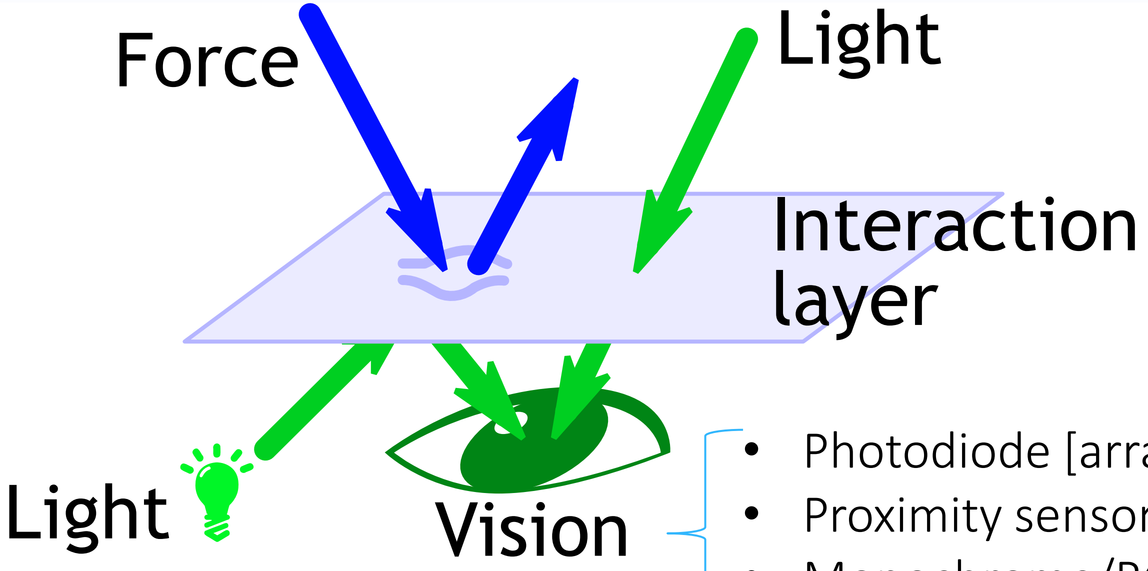
Can We Turn Tactile into Vision?



Cf. [Yamaguchi+,2019]
[Recent progress in tactile sensing and sensors for robotic manipulation: can we turn tactile sensing into vision?]

Vision-based tactile sensor
視覚に基づく触覚センサ
(視触覚センサ)

Vision-based Tactile Sensors



Force

Light

Interaction layer

- Opaque vs Transparent surface
- Special coating
- Markers
- Surface shapes
- Elastic and/or acrylic layers

Light

Vision

- Photodiode [array]
- Proximity sensor [array]
- Monochrome/RGB/Depth/Compound-eye camera[s]

Sensing principle & Modalities:

- Light signal change → Contact, Normal/3D force
- Frustrated total internal reflection → Contact, Normal/3D force
- Photometric stereo → Object surface shape
- Marker displacement → Shear/3D force
- Proximity/Depth → Distance to object, Contact point cloud , Normal force
- Direct vision → Slip, Object texture
- Stereo vision → Object 3D shape

Potential of Vision-based Tactile Sensors

- Fabrication & installation difficulties
  - Fabricating sensors need skills and experience
  - Physically & mechanically embedding on robotic hands
  - Wiring, power supply, and processing
  - Expensive
- Durability
  - Low durability, fragility
  - Maintenance becomes complicated
- Performance issues
  - Sensing modalities (force distribution, slip distribution, thermal sensitivity, …)
  - Resolution, FPS
  - Reliability?

→ Sensor structure can be **simple** and **manufacturing is not difficult**

→ Embedding could be simplified; cameras can be allocated sparsely & are becoming smaller

→ We can use the established network infrastructure

→ Ingredients are affordable & cameras are becoming cheaper

→ Physically robust since the sensing device and the skin can be isolated

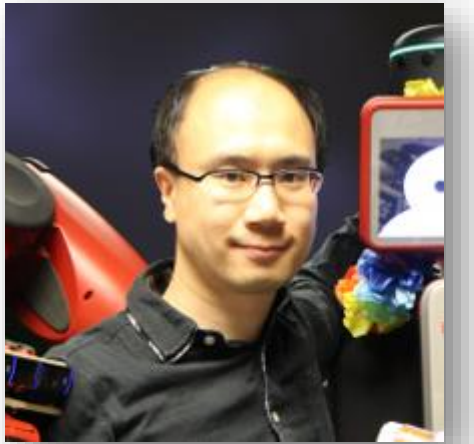
→ Replacing skin is not difficult and cheap

→ Could be multimodal

→ Achieving high resolution is not difficult (more than humans)

→ Highly reliable

This Organized Session

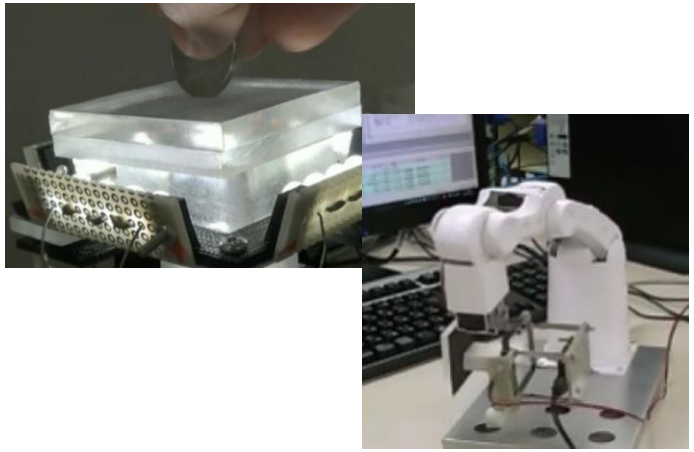

Dr Yamaguchi

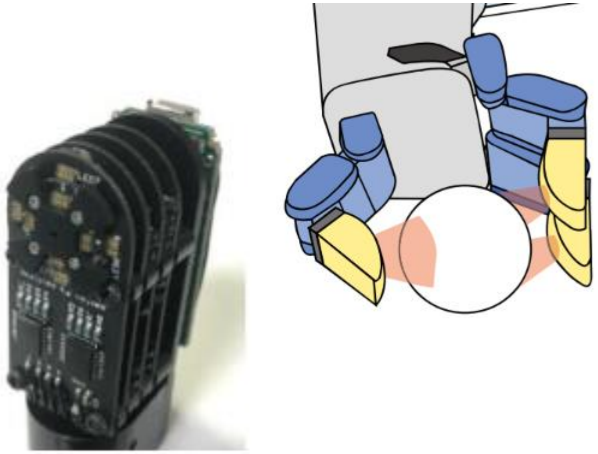

Dr Shimonomura


Dr Koyama


FingerVision

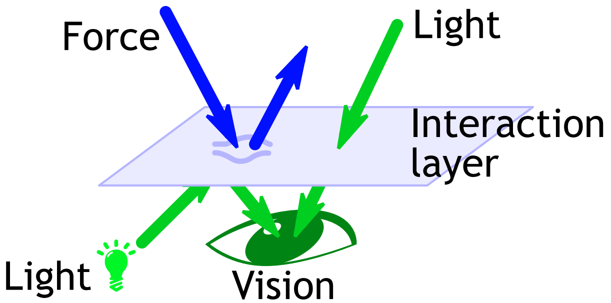
TechCrunch.com





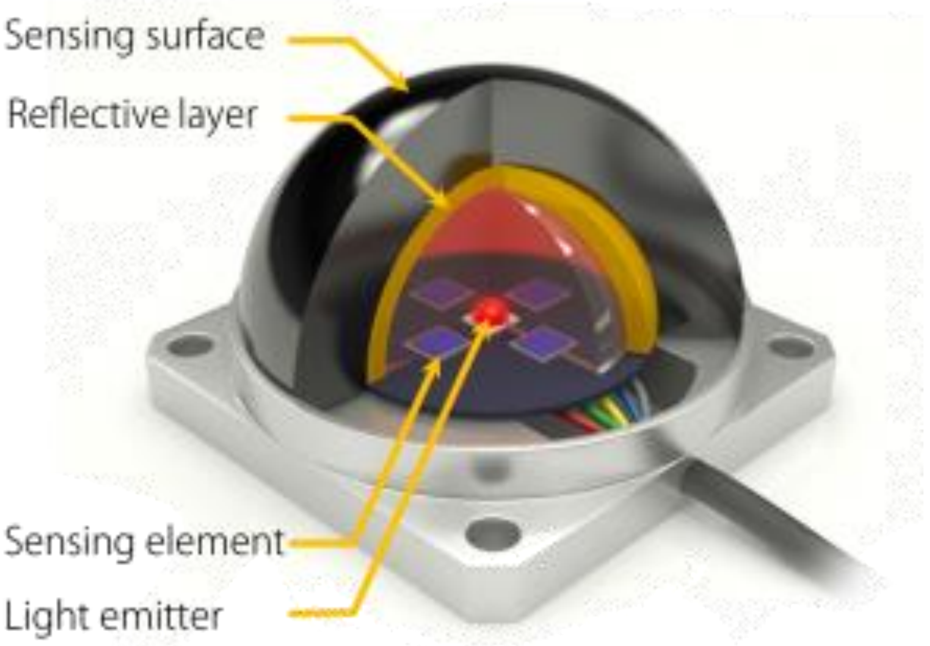
Examples of Vision-based Tactile Sensors

Estimating 3D Force from Light Signal Change



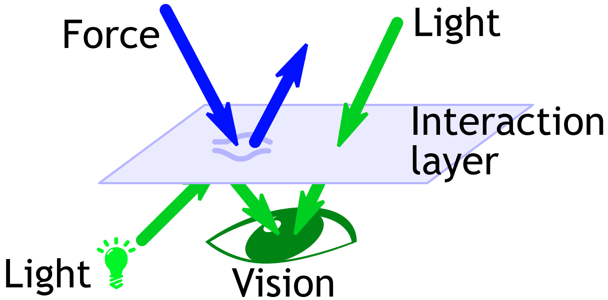
[Vision-based Tactile]

Vision = Photodiode
Interaction layer = Opaque surface
/ Elastic / Reflective
Internal light = LED
Sensing principle & modality:
Light signal change → 3D force

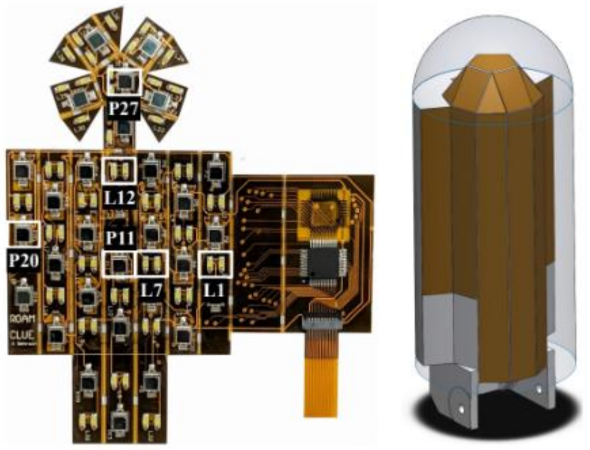


OptoForce
http://optoforce.com/technology/

Photodiode and LED Array



[Vision-based Tactile]



Vision = Photodiode array

Interaction layer = Opaque surface / Elastic

Internal light = LEDs

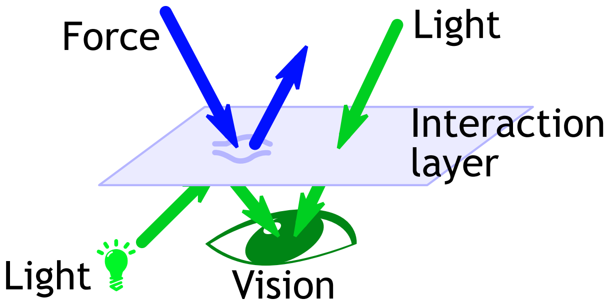
Sensing principle & modality:

Light signal change → Contact location, normal force

Fig. 1. A multicurved tactile finger. **Top:** finger through various stages of construction. We 3D-print a rigid skeleton, on which we attach a flexible circuit board with light emitters (LEDs) and receivers (photodiodes). We then mold a 7 mm thick transparent layer acting as a waveguide. Finally, we add a thin reflective outer layer. **Bottom:** finger performing touch localization and force detection. Location of red sphere shows predicted touch location, and sphere radius is proportional to predicted normal contact force.

[Piacenza+,2019]

Normal Force from Frustrated Total Internal Reflection



[Vision-based Tactile]

Vision = Monochrome camera

Interaction layer = Transducer membrane / Transparent plate

Internal light = A light source

Sensing principle & modality:

Frustrated total internal reflection → Normal force

[Wikipedia:Frustrated TIR]

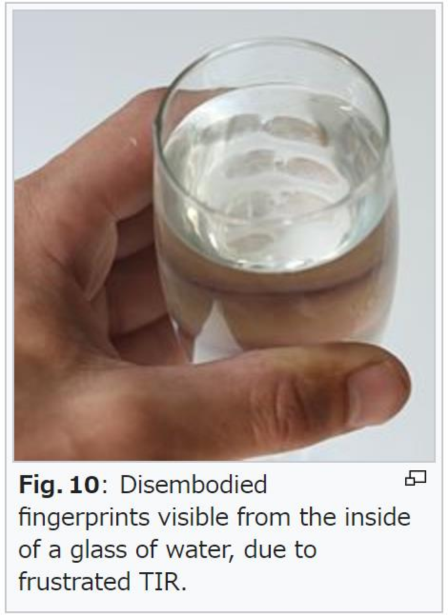


Fig. 10: Disembodied fingerprints visible from the inside of a glass of water, due to frustrated TIR.

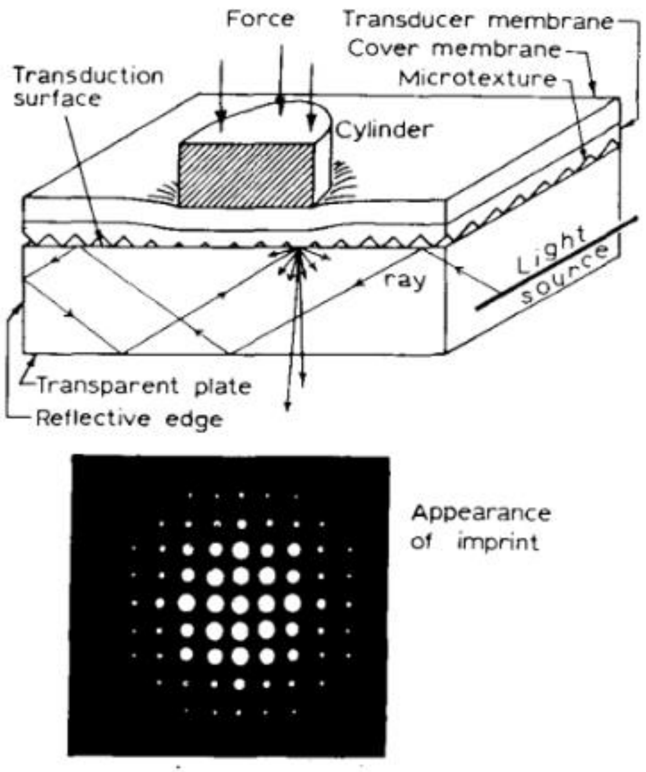
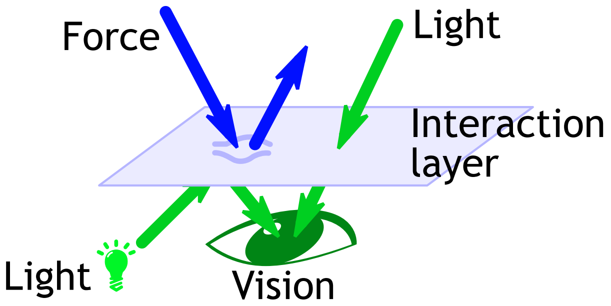


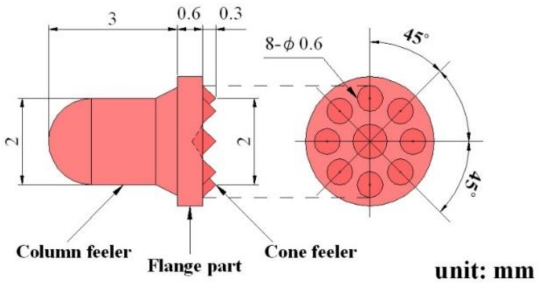
Fig. 1. General arrangement of components for sensing force or pressure distributions by frustration of total internal reflection. Bottom diagram illustrates how areas subject to higher pressures appear as regions of higher light intensity.

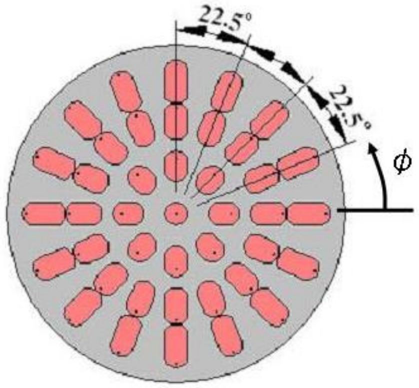
[Begej,1988]

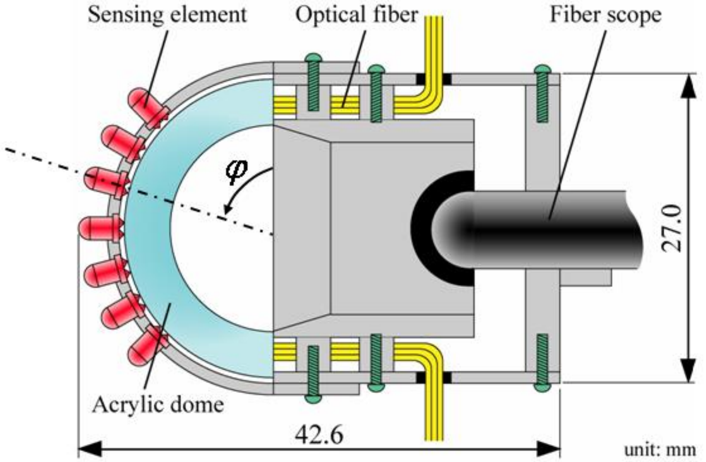
3D Force from Frustrated Total Internal Reflection



[Vision-based Tactile]







Vision = Monochrome camera

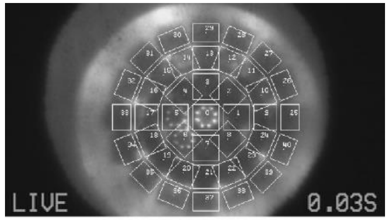
Interaction layer = Rubber sensing element / Acrylic dome

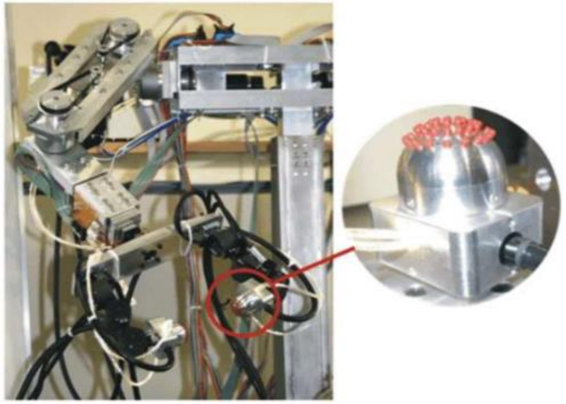
Internal light = A light source

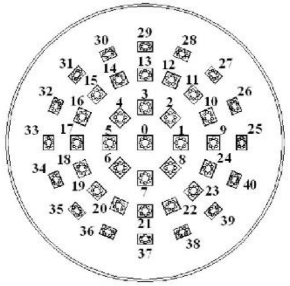
Sensing principle & modality:

Frustrated total internal reflection

→ 3D force

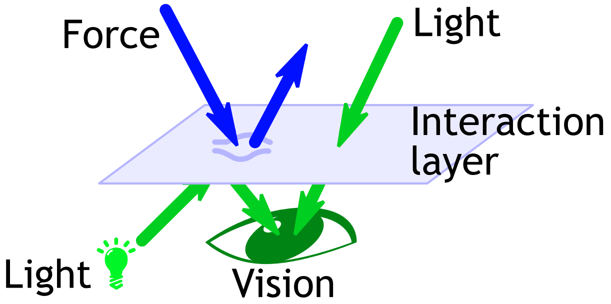






[Ohka+,2011][Yussof+,2010]

Multimodalities with Compound-eye Camera



[Vision-based Tactile]

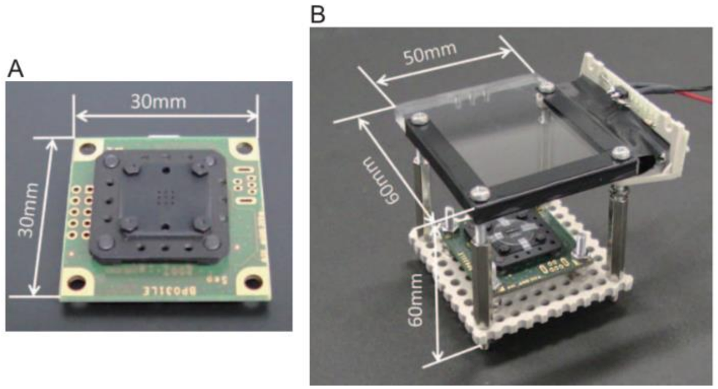
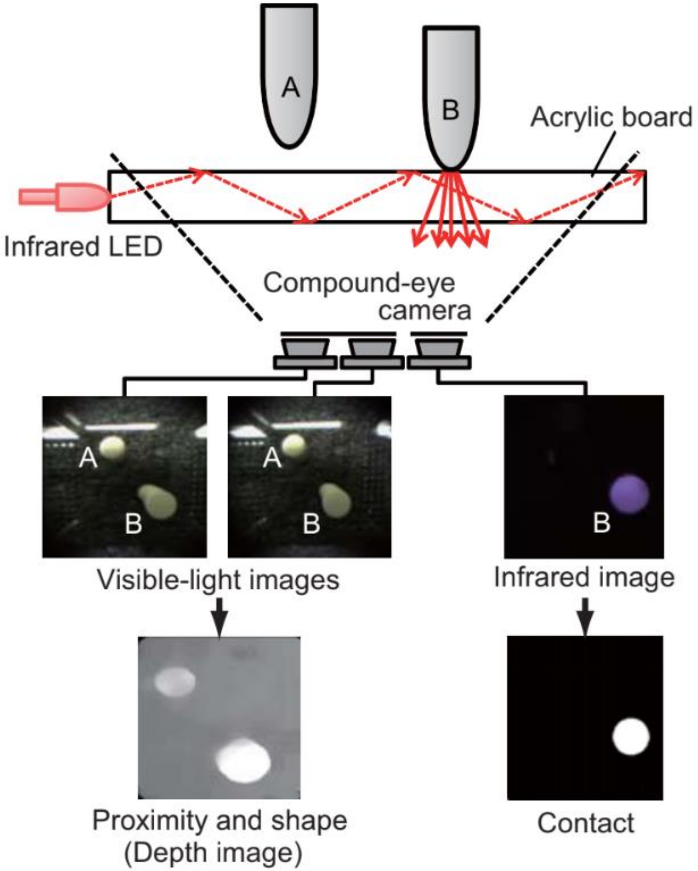


Fig. 2. Pictures of the device. (A) compound-eye camera, (B) overview of the device, (B) compound-eye camera.



[Shimonomura+,2013] [Shimonomura+,2016]

Vision = Compound-eye camera

Interaction layer = Acrylic board

Internal light = IR LED

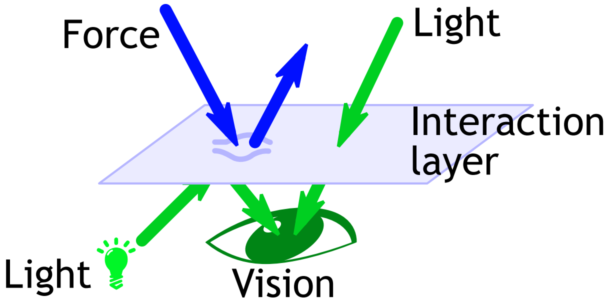
Sensing principle & modalities:

Frustrated total internal reflection

→ Contact

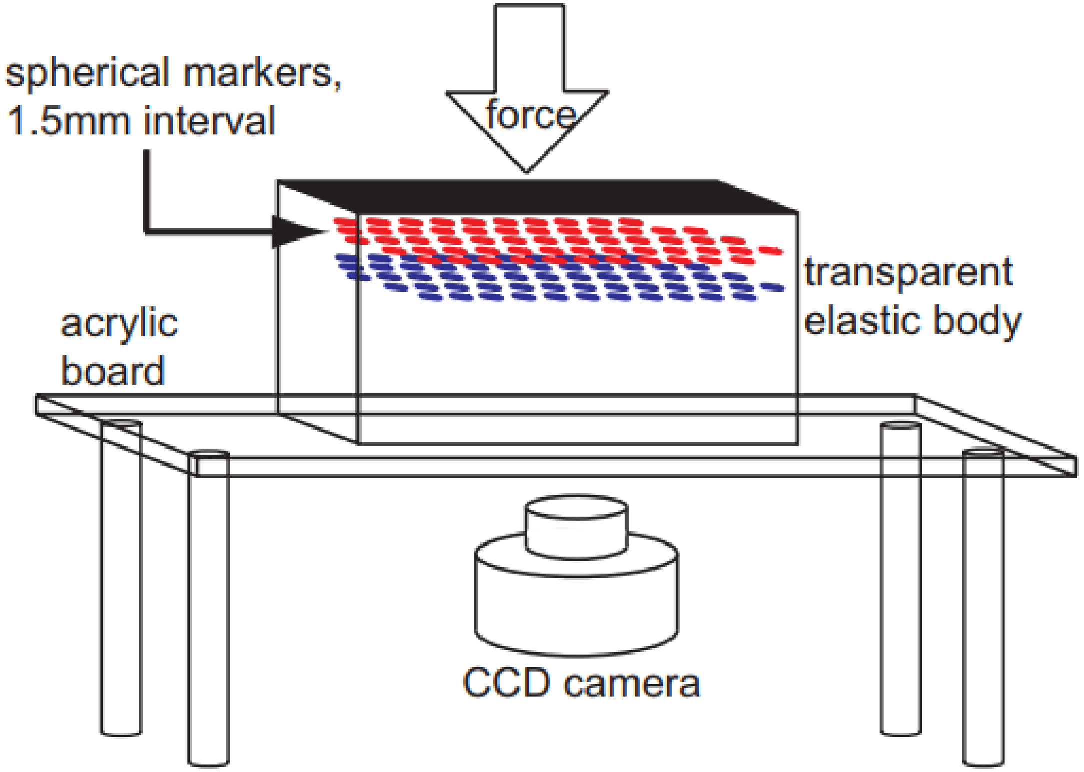
Stereo vision → Object 3D shape

3D Force from Marker Displacement



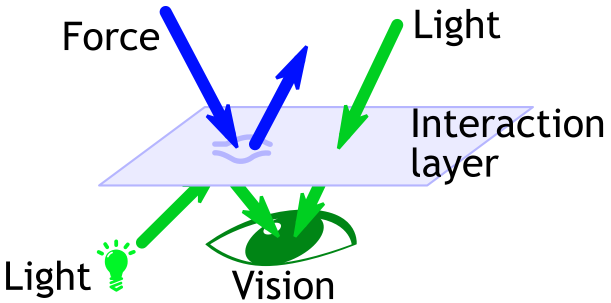
[Vision-based Tactile]

Vision = RGB camera
Interaction layer = Opaque sheet
/ Marker / Elastic / Acrylic
Sensing principle & modality:
Marker displacement → 3D force

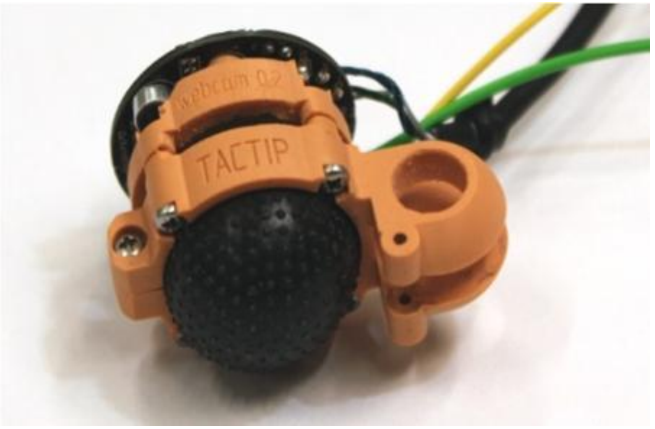


[Kamiyama+,2004]

Variation of Markers



[Vision-based Tactile]



TacTip

http://www.brl.ac.uk/researchthemes/medicalrobotics/tactip.aspx

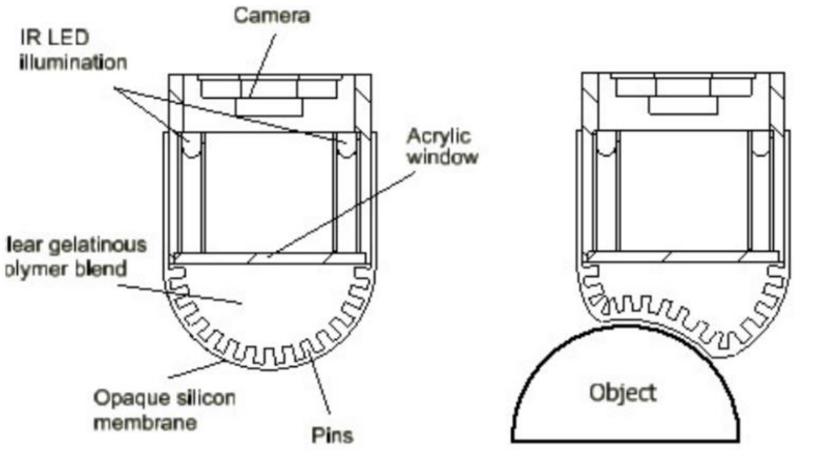


Fig. 3. Diagram of the TacTip (left) with pins shown on the inside surface of a silicon membrane, which are LED illuminated and imaged by an internal camera. The right diagram is a representation of the deformation of the membrane as it impinges on a test object (a 40 mm hemicylinder).

[Lepora+,2015]

Vision = RGB camera

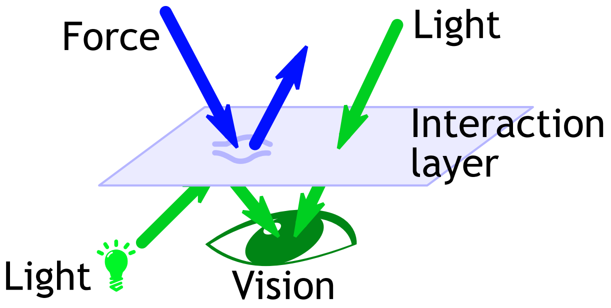
Interaction layer = Opaque membrane / Pins / Elastic / Acrylic

Internal light = IR LED

Sensing principle & modality:

Pin deformation displacement → 3D force

Transparent Skin for Multimodalities



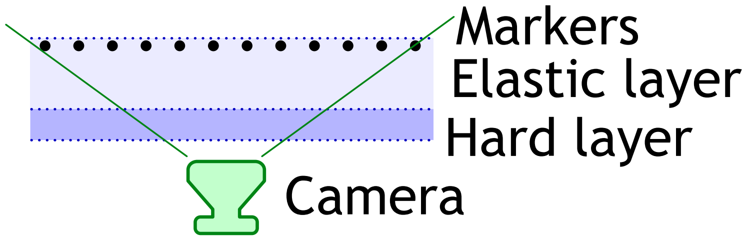
[Vision-based Tactile]

Vision = RGB camera
Interaction layer = Marker
/ Elastic / Acrylic
(No opaque skin)

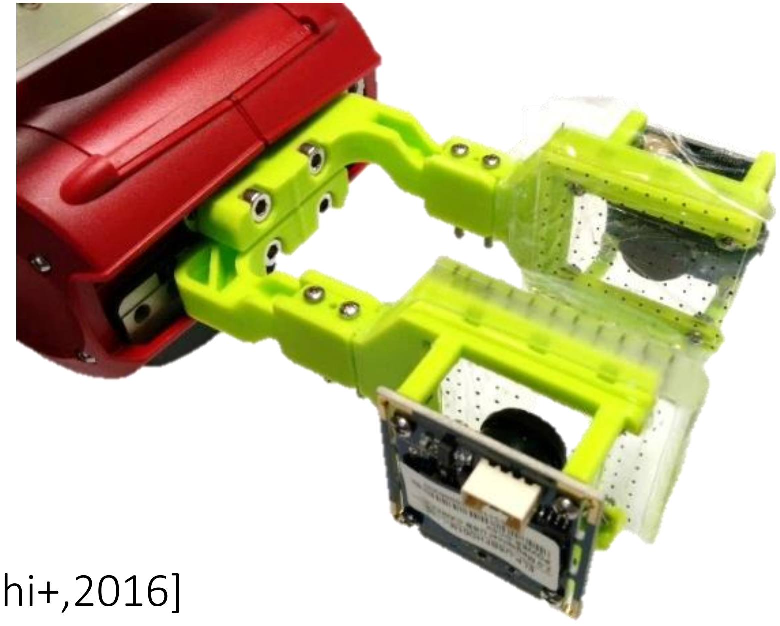
Sensing principle & modalities:
Marker displacement → 3D force
Direct vision → Slip, Object texture

FingerVision

All layers are transparent
(see-through)

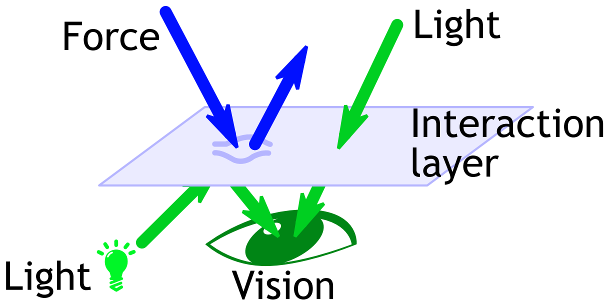


http://akihikoy.net/p/fv



[Yamaguchi+,2016]

Object Surface Shape from Photometric Stereo



[Vision-based Tactile]

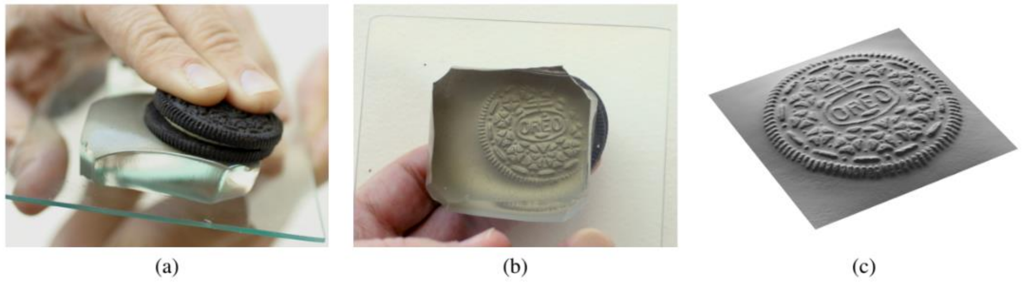


Figure 1. (a) A cookie is pressed against the skin of an elastomer block. (b) The skin is distorted, as shown in this view from beneath. (c) The cookie's shape can be measured using photometric stereo and rendered at a novel viewpoint.

[Johnson+,2009]

Vision = RGB camera

Interaction layer = Coating

/ Elastic / Acrylic

Internal light = Multi-color LEDs

Sensing principle & modality:

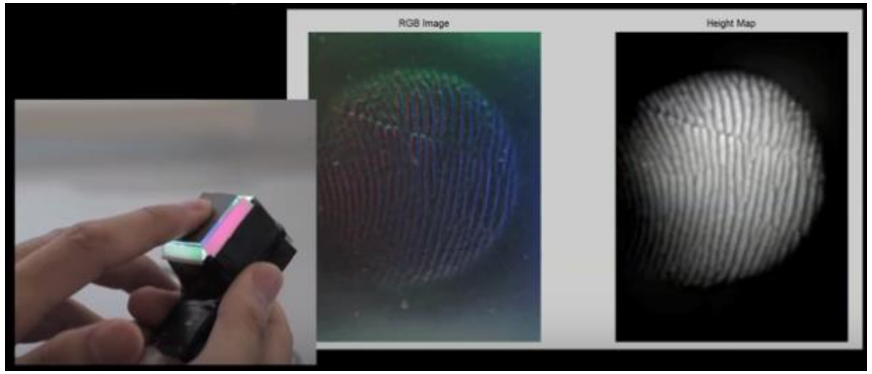
Photometric stereo

→ Object surface shape

Marker displacement → 3D force

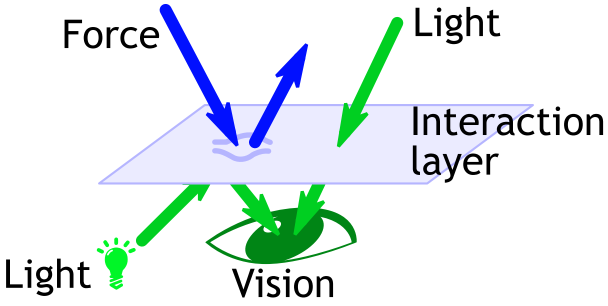
GelSight

http://news.mit.edu/2014/fingertip-sensor-gives-robot-dexterity-0919



GelSlim
[Donlon+,2018]

GelSight with Multiple RGB Cameras



[Vision-based Tactile]

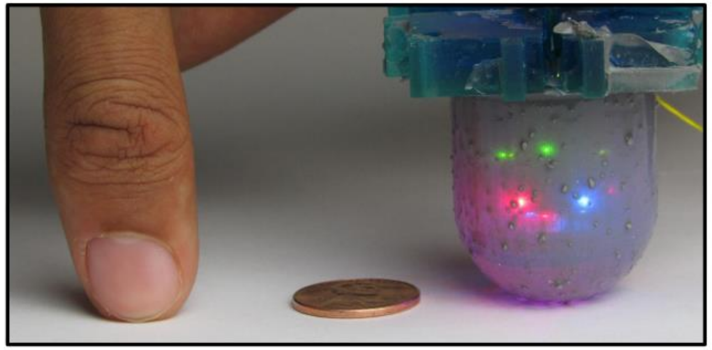
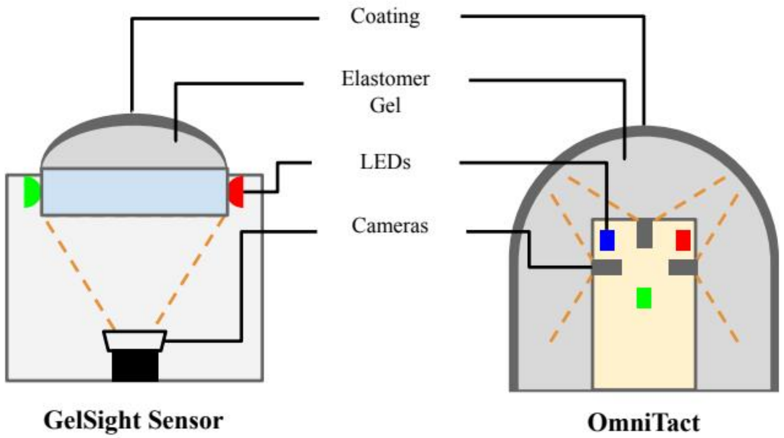


Fig. 1: Human thumb next to OmniTact, and a US penny for scale. OmniTact is a high-resolution multi-directional tactile sensor designed for robotic manipulation.



Vision = Multiple RGB cameras

Interaction layer = Coating / Elastic / Acrylic

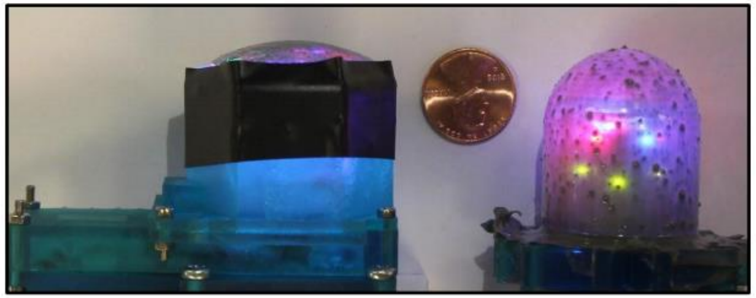
Internal light = Multi-color LEDs

Sensing principle & modality:

Photometric stereo → Object surface shape

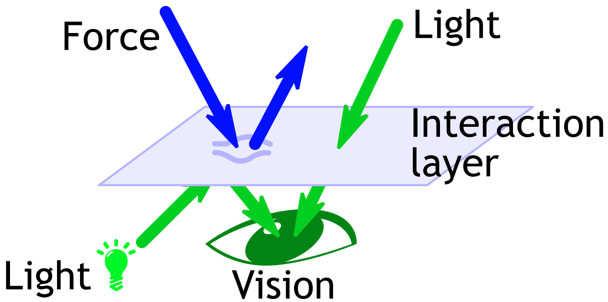
OmniTact

https://bair.berkeley.edu/blog/2020/05/14/omnitact/



[Padmanabha+,2020]

Proximity Sensor for Tactile Sensing



[Vision-based Tactile]

Vision = Proximity sensors

Interaction layer = PDMS

Sensing principle & modalities:

Proximity → Distance to object

Deformation → Normal force

[Patel+,2016]

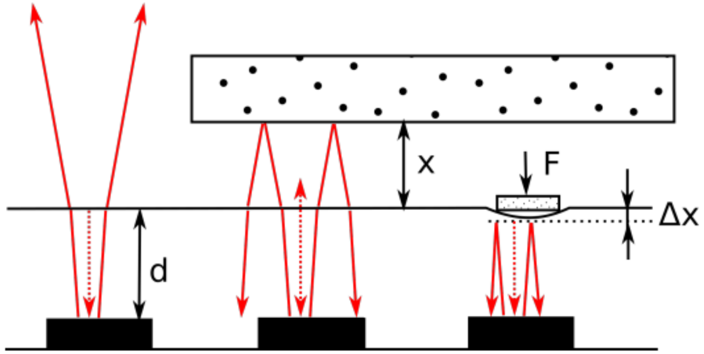
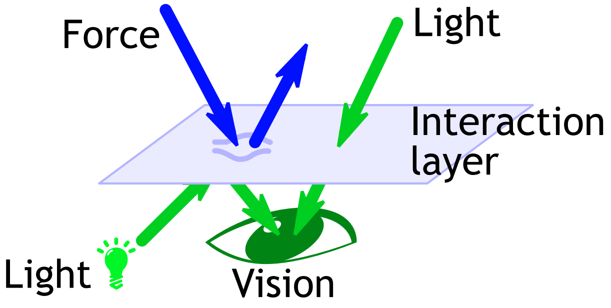


Fig. 2. Schematic sensor design illustrating key quantities. Infrared lobes are reflected at the interface of PDMS/air due to Fresnel reflection, as well as from close-by objects. Forces lead to deformation of the PDMS that reduces its width d by Δx.

Array of Proximity Sensors



[Vision-based Tactile]

Vision = Proximity sensor net

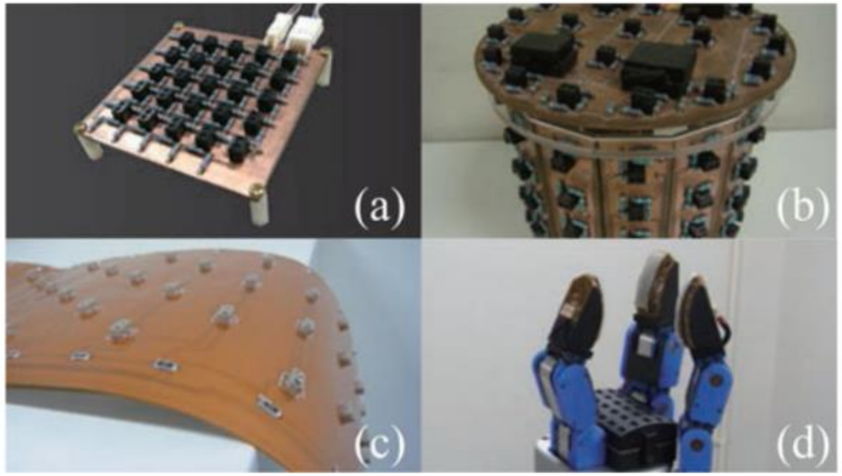


Fig. 1. Appearance of NSPS. (a) Basic configuration on a plane. (b) Whole surface mounting on a cylindrical end-effector. (c) Sensor on a flexible substrate for free-form surface. (d) Robot hand covered with the sensors on its palm and fingertips.

[Hasegawa+,2015]

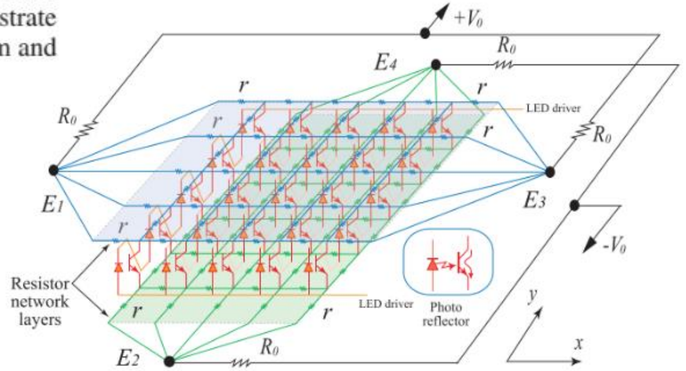
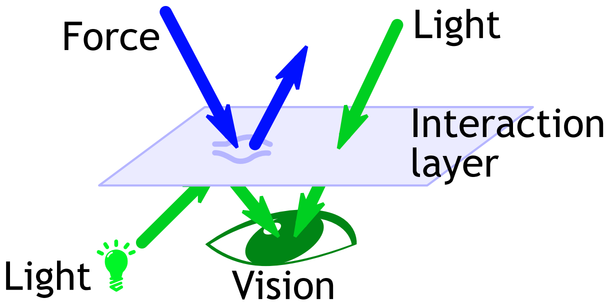


Fig. 2. Structure of the sensor. A detector layer is sandwiched by matrix arrayed resistor layers. Two resistor lattices, layer A and B have the function to calculate primary moments of photocurrent distribution about x- and y-axis, respectively. Four read-out electrodes (E_1, E_2, E_3 and E_4) are connected each side of the resistor lattices. This structure requires only six external wires; four to readout plus two to drive LEDs.

Depth Camera for Tactile Sensing



[Vision-based Tactile]

Vision = Depth camera

Interaction layer = Membrane
/ Marker

Sensing principle & modality:

Deformation → Contact point cloud

Marker displacement → Shear force

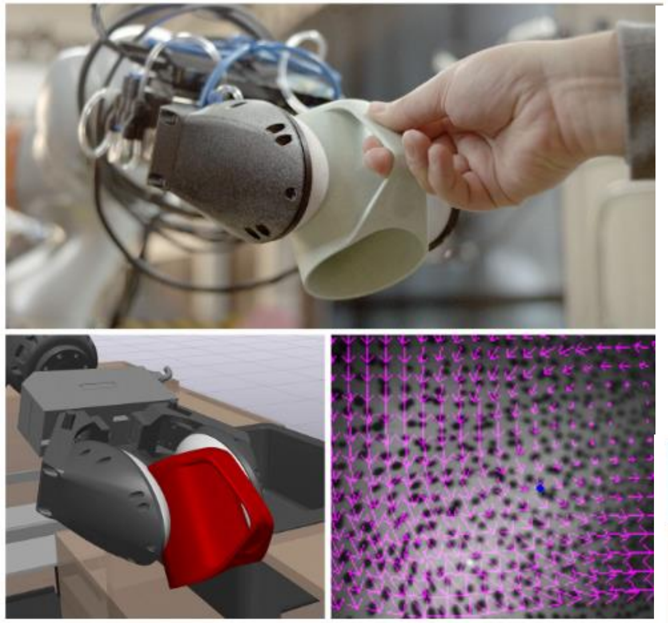
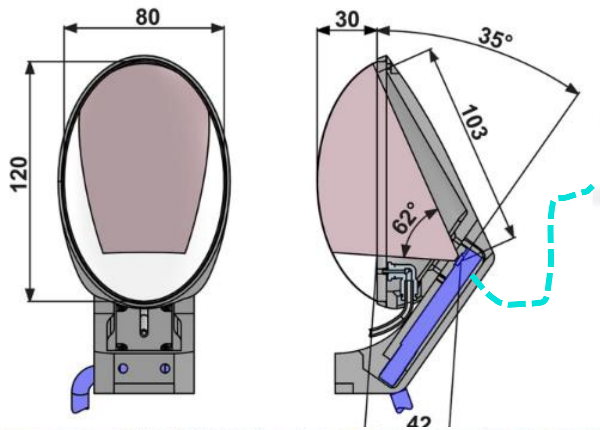


Fig. 1: Top: Highly compliant *Soft-bubble* parallel gripper o a robot arm grasping an object. Bottom-left: In-hand pos estimate during this interaction; Bottom-right: Shear-induce displacements tracked on the interior of this sensor.



Shorter-range (4-11cm) version of [Pico Flexx/PMD]

Soft-bubble

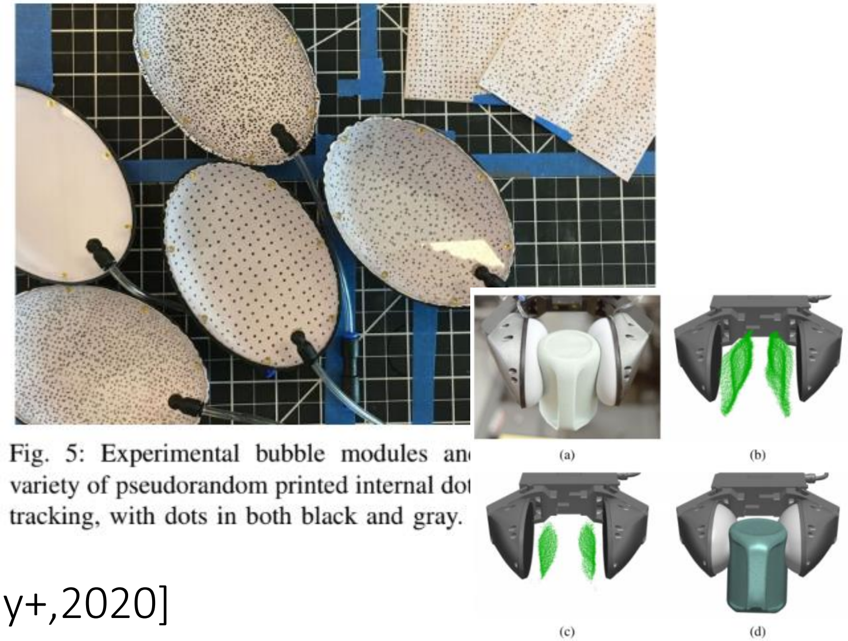
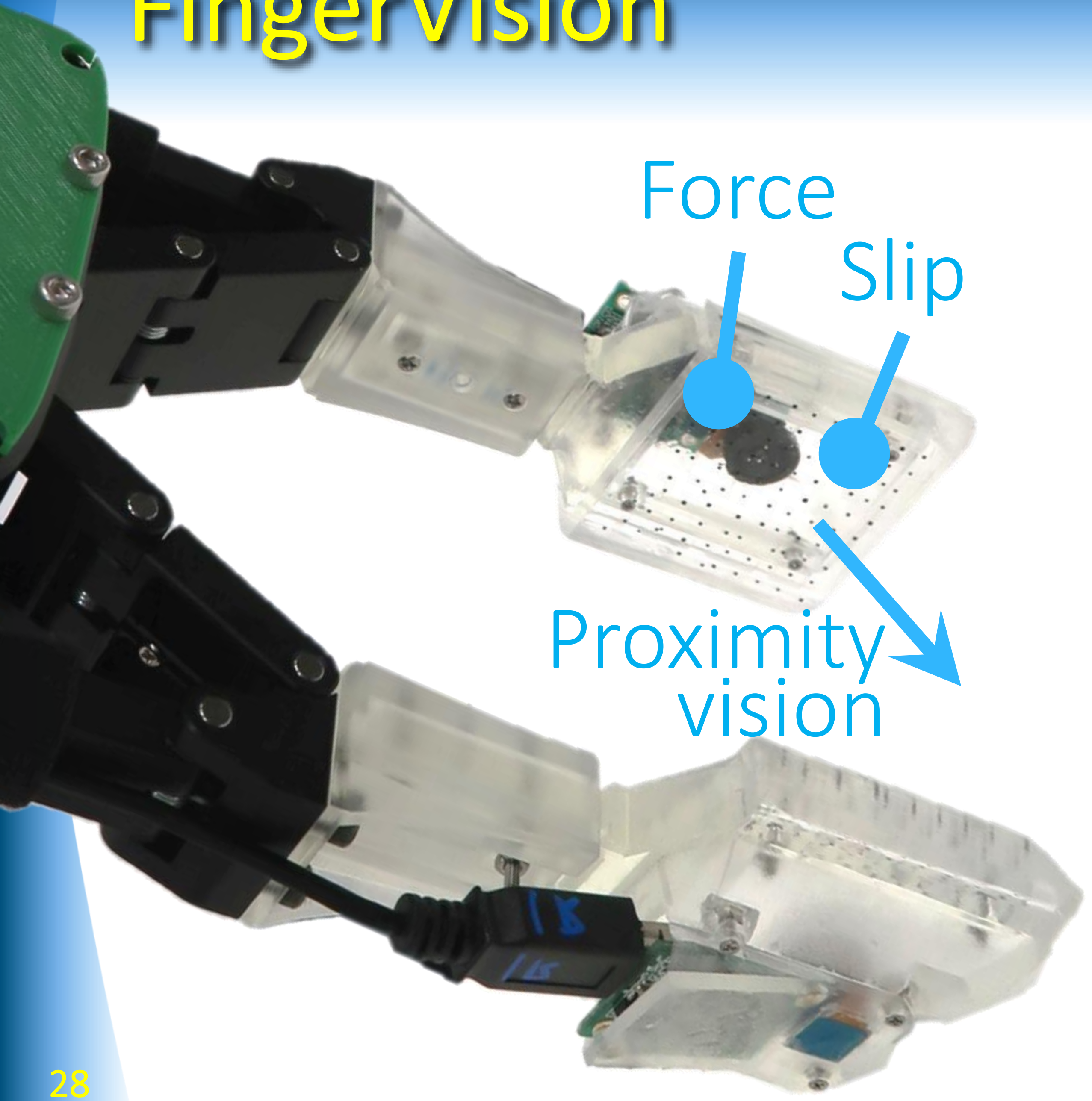


Fig. 5: Experimental bubble modules an variety of pseudorandom printed internal dot tracking, with dots in both black and gray.

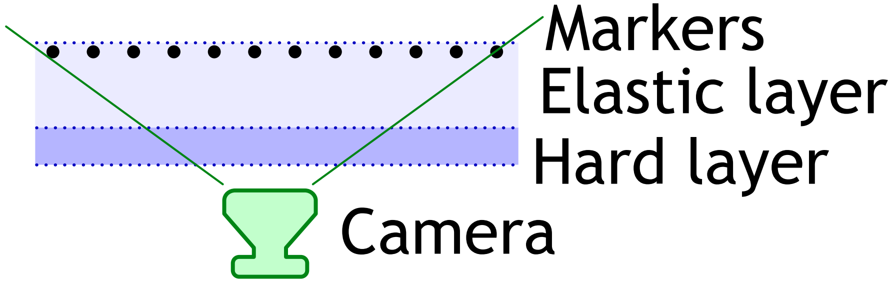
[Kuppuswamy+,2020]

Sensing Modalities

FingerVision

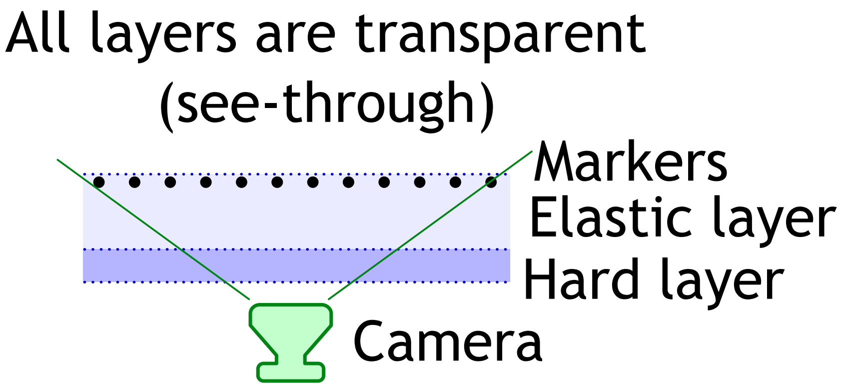


All layers are transparent (see-through)

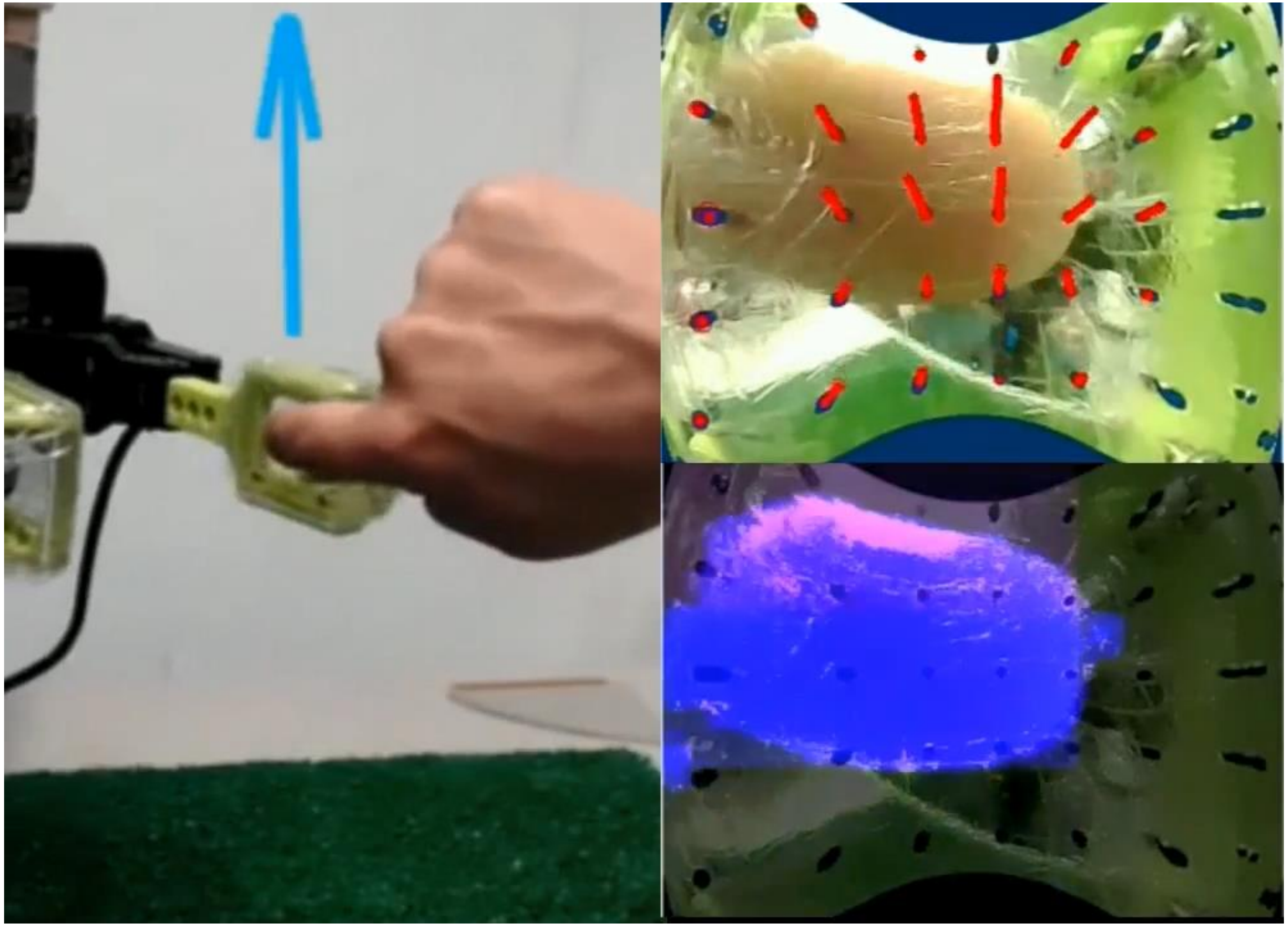


- Multimodal
  - Force distribution
  - Slip distribution (**Independent from object weight**)
  - Proximity Vision
    - ✓ Object pose, texture, shape
- Low-cost and easy to manufacture
- Physically robust

Sensing Principle of FingerVision



- Force Distribution
  - Marker tracking
- Slip detection
  - Optical flow, background subtraction
- Object detection
  - Color-based background elimination and nearby object detection



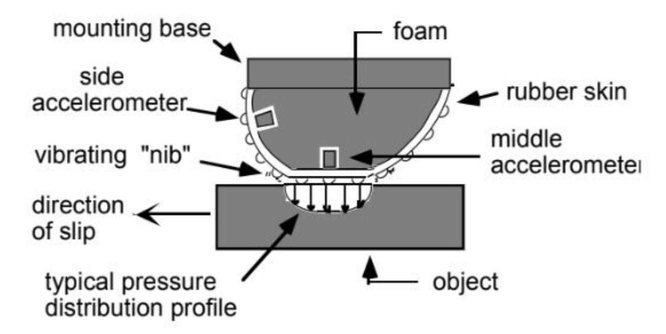
Modalities of Vision-based Tactile Sensing

- **Contact** (on/off) → Frustrated TIR, Photometric stereo
- **Pressure distribution** → Frustrated TIR, Marker displacement
- **Shear force distribution** → Marker displacement
- **Slip** → (Especially good with) Direct vision
- **Vibration** → Using high-speed camera
- **Temperature** → Using IR camera
- **Object surface shape** → Photometric stereo
- **Object visual texture** → Direct vision
- **Proximity** → Proximity/Depth, Stereo vision

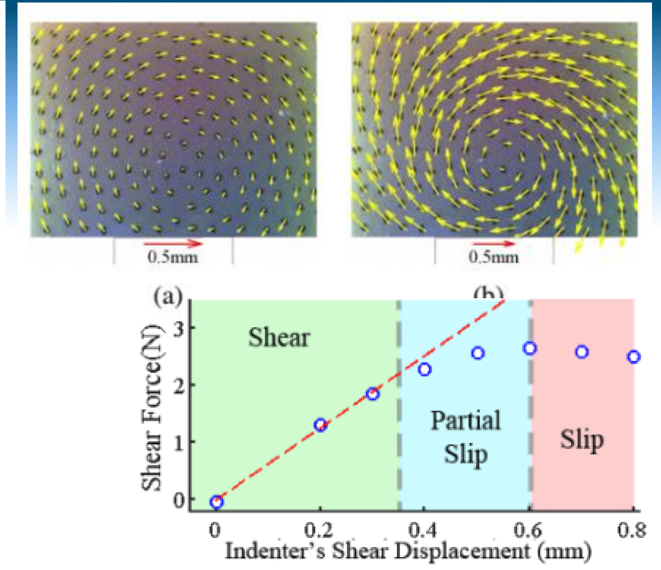
Sensing Slip

- Two axes to understand
  - **Direct** vs. **indirect** measurement
  - **Single data** per sensor vs. **distribution**
- **Indirect** measurement
  - Acoustic emission [Dornfeld+,1987]
  - Detecting slip from vibration (e.g. using accelerometers [Tremblay+,1993])
  - Detecting slip from force (*1) (e.g. using high-pass filter [Romano+,2011])
  - Detecting slip with a distributed sensor array (*2)
  - Slip detection with vision-based tactile sensors
    - ✓ Similar to *1, *2, e.g. [Yuan+,2015]
  - Some methods use machine learning (classification) (e.g. [Su+,2015])
- **Direct** measurement
  - Mechanical roller [Ueda+,1972]
  - Optical mouse
  - Analysis of video (FingerVision) [Yamaguchi+,2017]

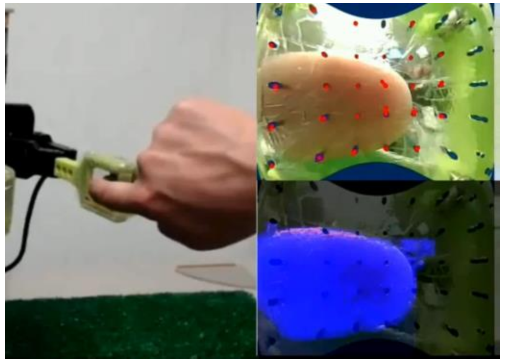
Cf. Yamaguchi & Atkeson, Recent progress in tactile sensing and sensors for robotic manipulation, Advanced Robotics 33-14, 2019



[Tremblay+,1993]



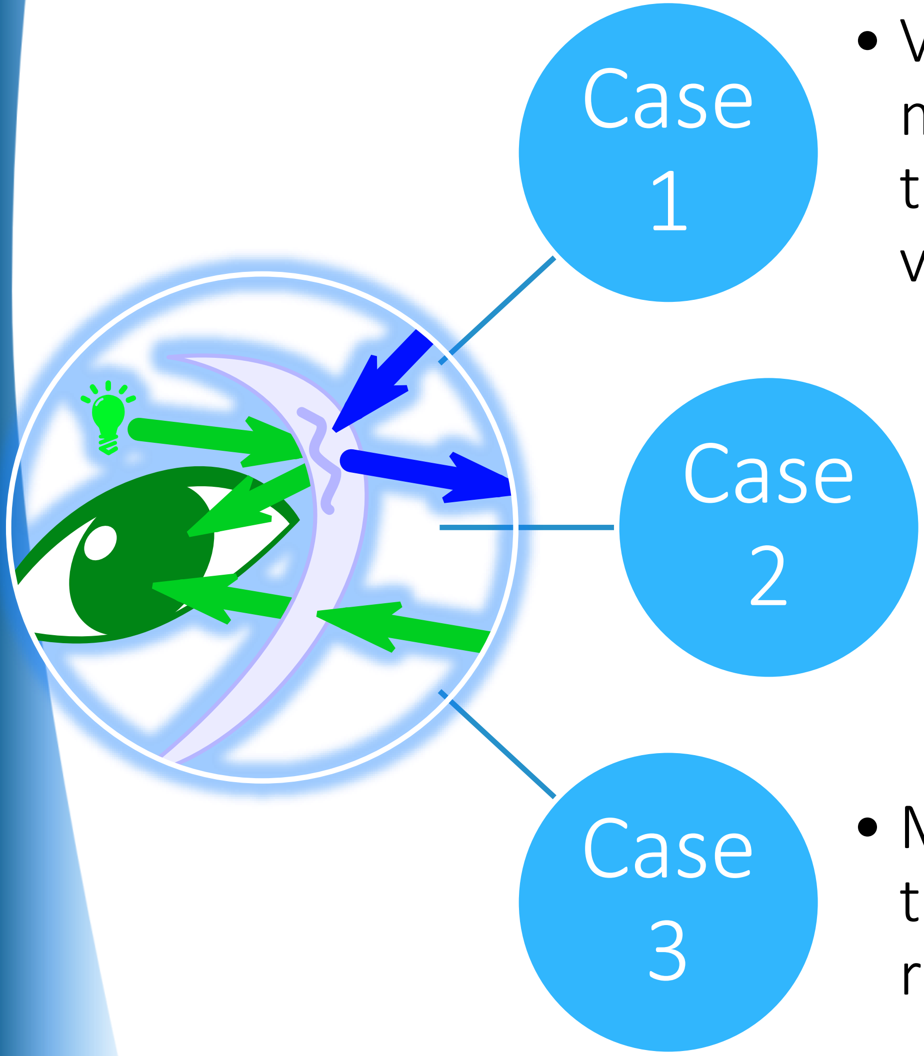
[Yuan+,2015]



[Yamaguchi+,2017]

Tactile Sensing Applications

When (Vision-based) Tactile Sensing is Useful?



- V-b Tactile is more accurate than external vision

- External vision is not available due to occlusion

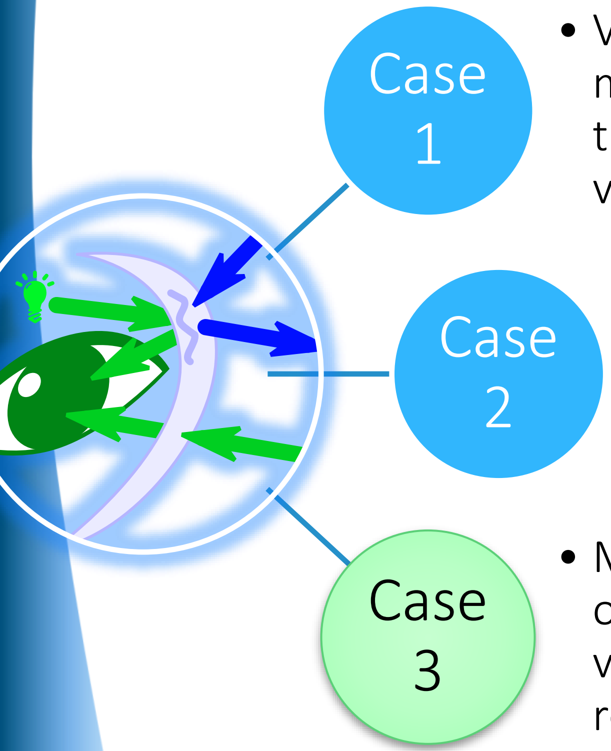
- Modality other than vision is required

Sense by touch:
- Existence, Shape, Texture
- Grasp state
- In-hand object pose/parts
- …

Grasping:
- Grasp adaptation
- Re-grasp

Tactile event-driven actions:
- Slip
- Touch on finger
- Touch on grasped object
- …

Exploring the Workspace without Vision



Case 1

- V-b Tactile is more accurate than external vision

Case 2

- External vision is not available due to occlusion

Case 3

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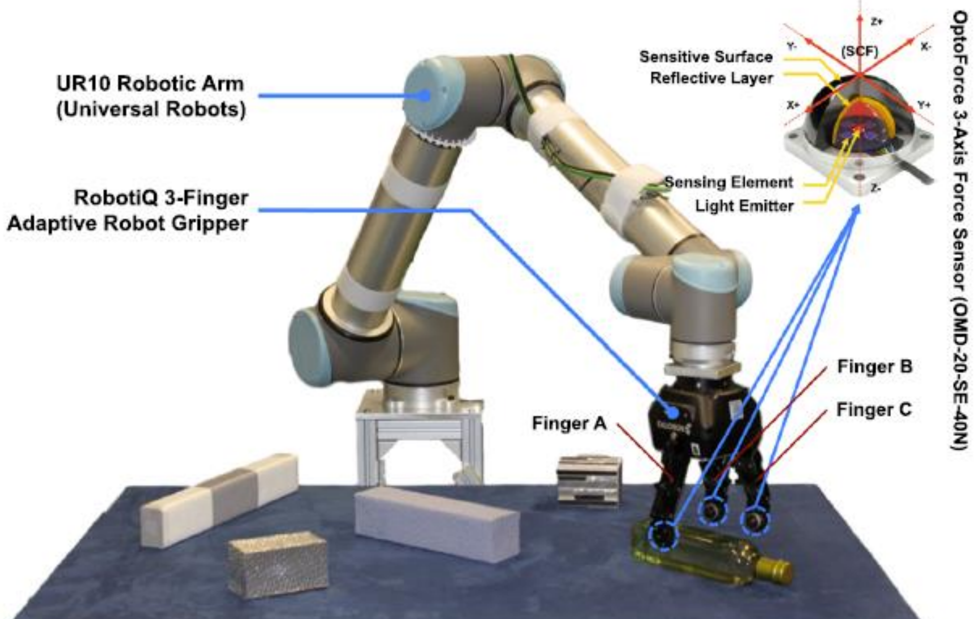
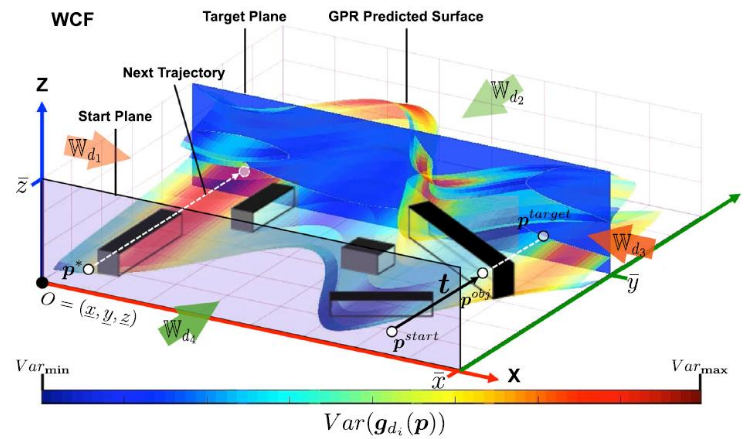
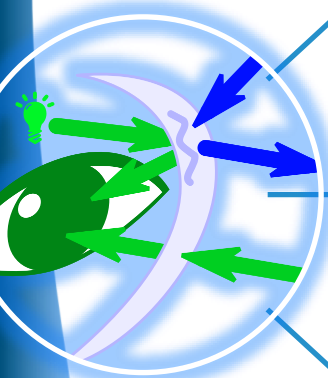


Active exploration to search for objects in unknown workspace [Kaboli+,2018]



Sense by Touch



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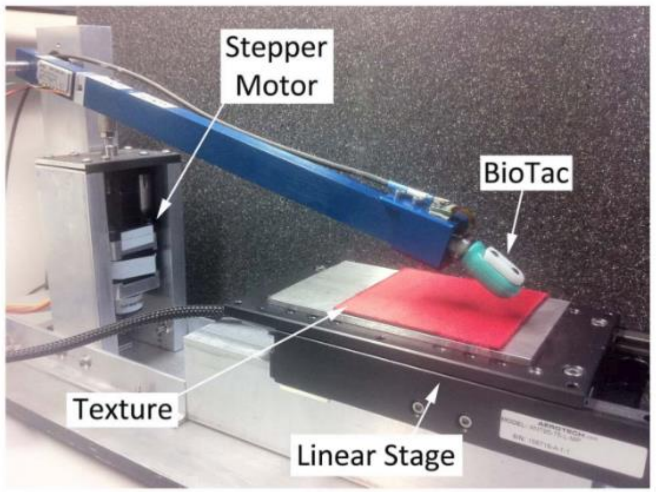
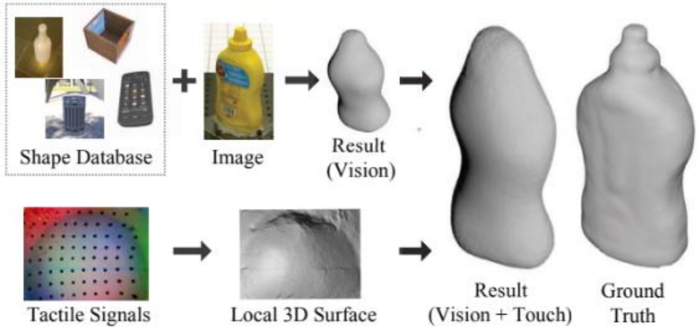
Estimating the object class by stroking (BioTac, 117 textures, 95.4%) [Fishel+,2012]



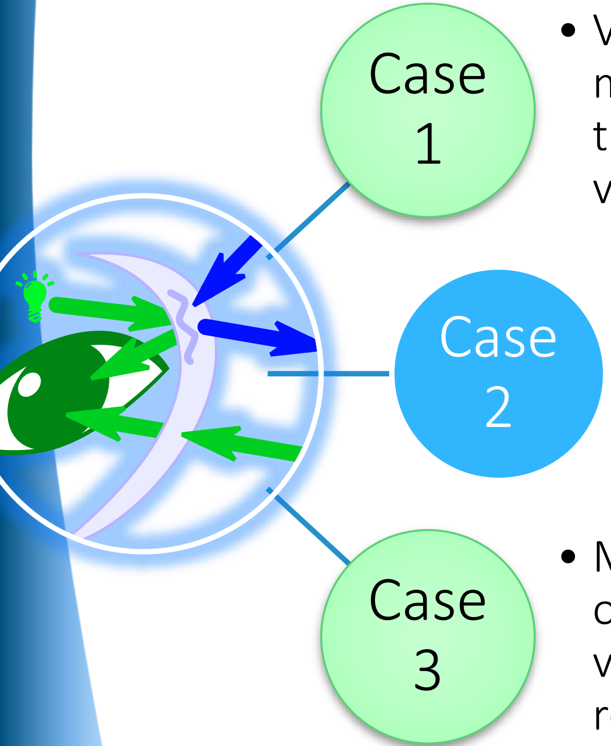
3D shape estimation with external vision + GelSight + stroking motion
Single-view color image → CNN → Rough 3D shape → Touch → Refined
[Wang+,2018]



Sense by Touch with GelSight

Object surface texture and shape detection: cookie, decorative pin, human fingerprint, twenty-dollar bill, USB connector, etc. [Johnson+,2009]

Clothing property estimation: thickness, smoothness, fuzziness, season to be used, textile type, and washing method (with deep neural networks) [Yuan+,2018]



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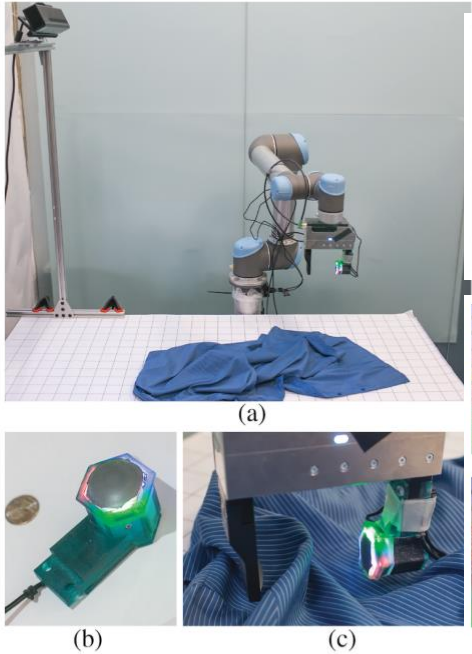
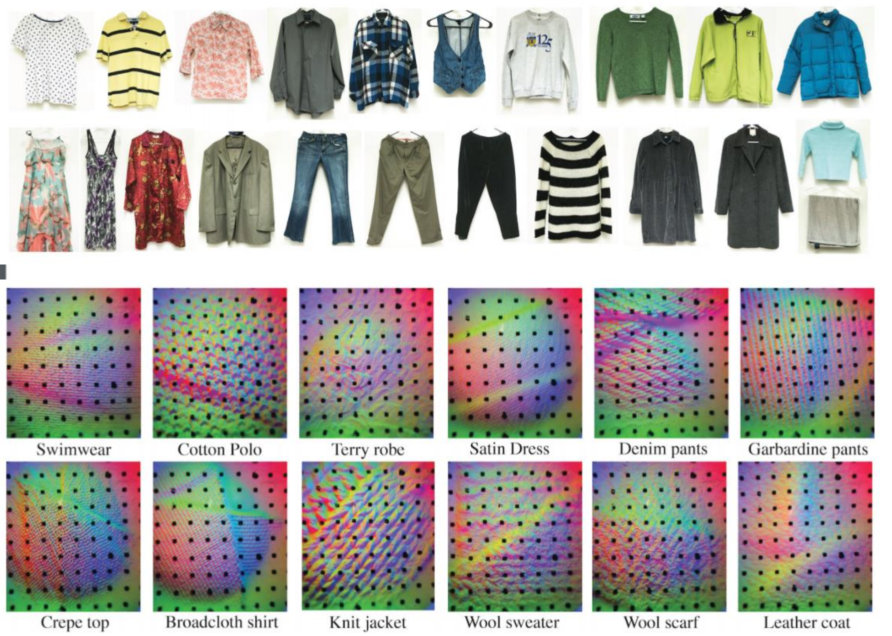
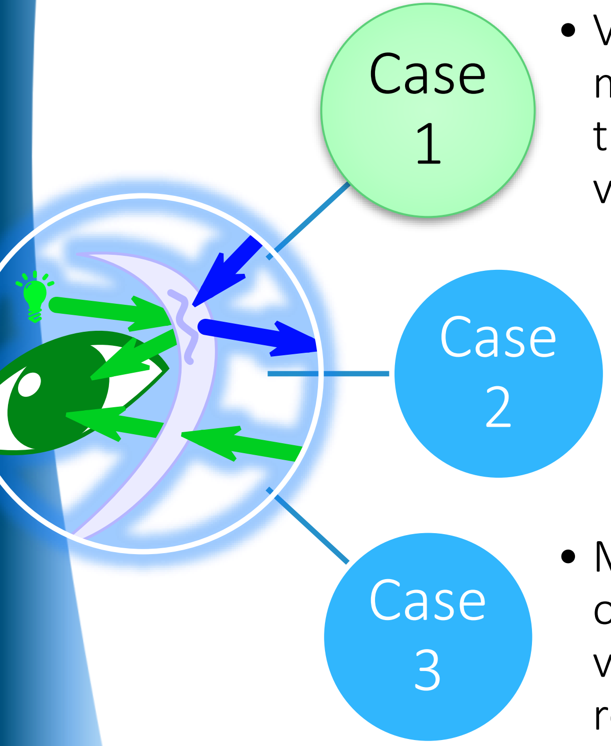




Grasp Failure Detection with FingerVision



- V-b Tactile is more accurate than external vision
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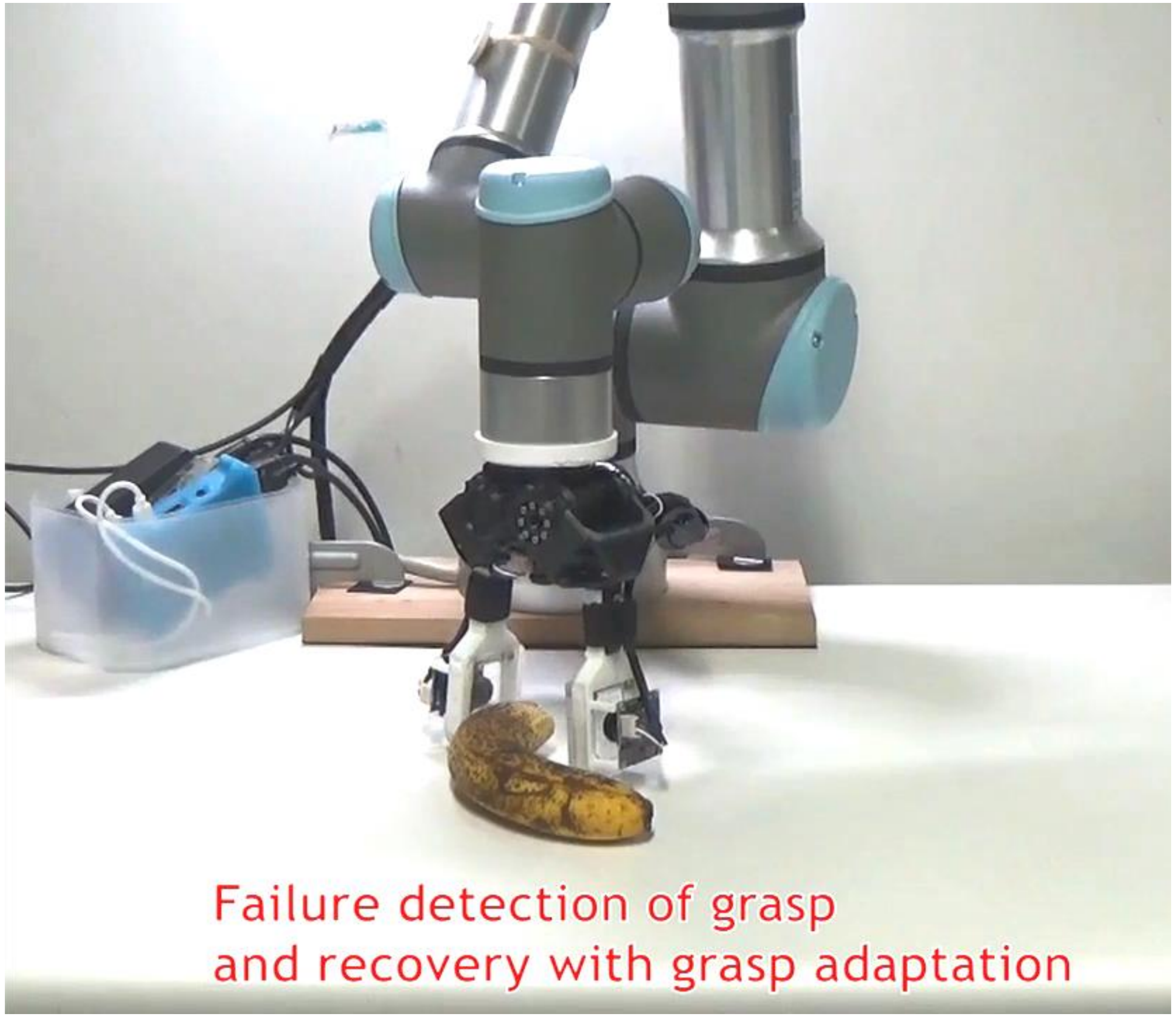
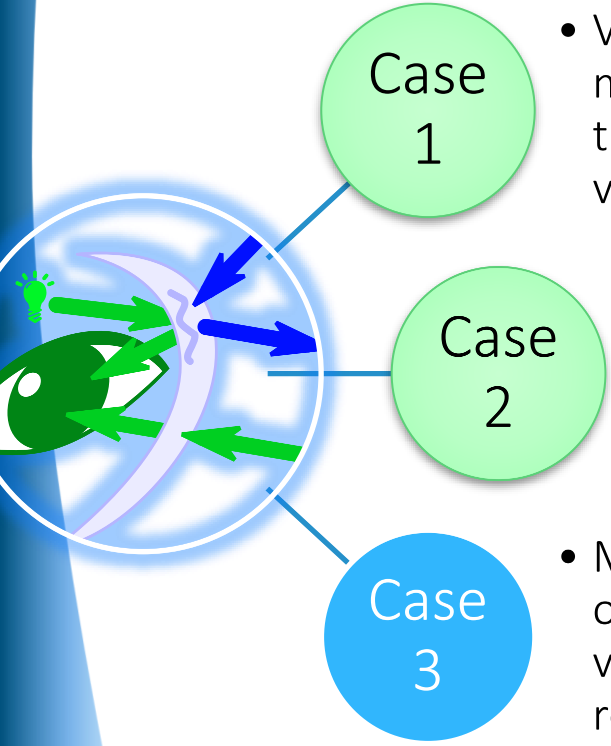


[Yamaguchi,2018]

Object Pose Estimation with GelSight



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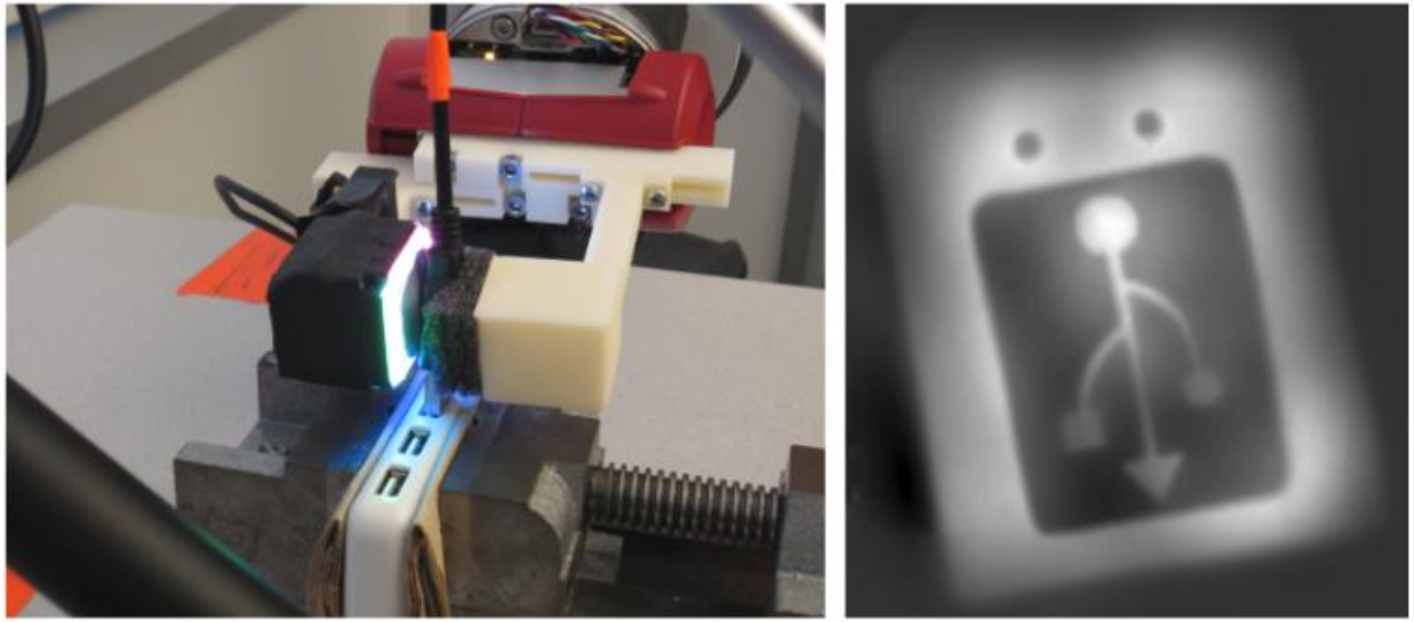
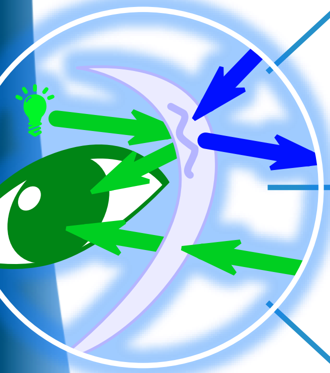


Insertion of USB connector with GelSight by Estimating USB connector pose [Li+,2014]

Screw State Estimation



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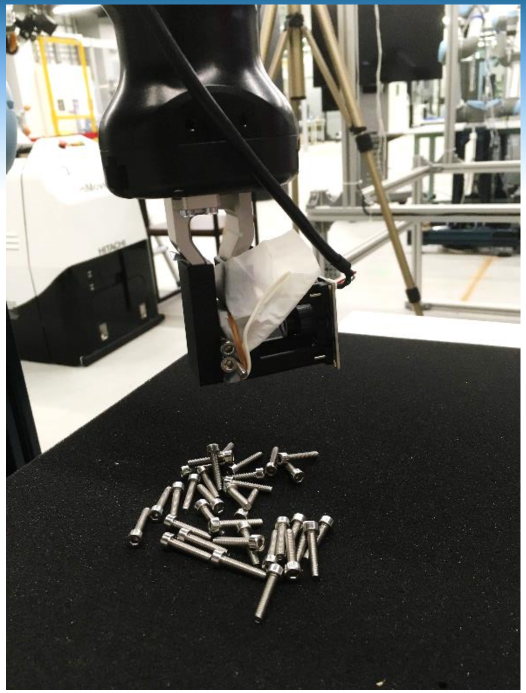
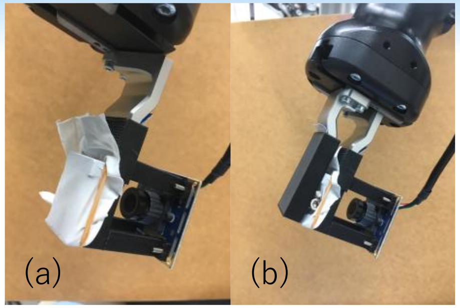
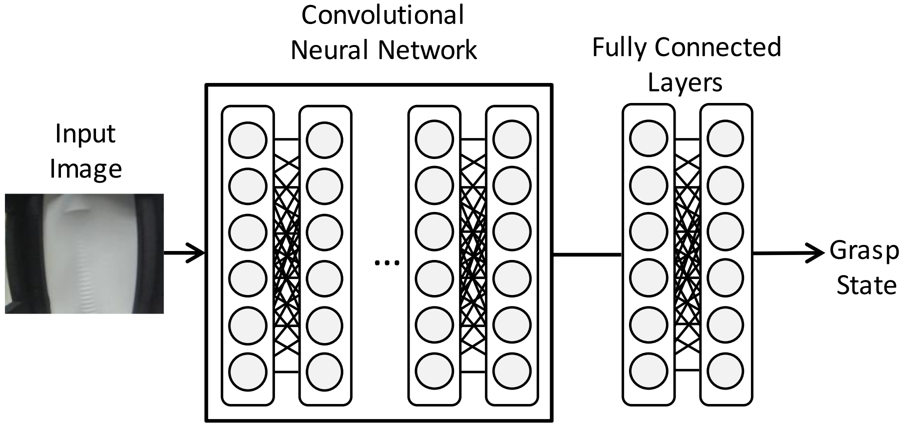
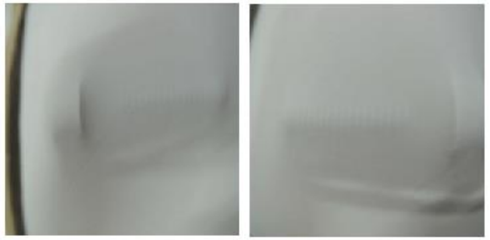






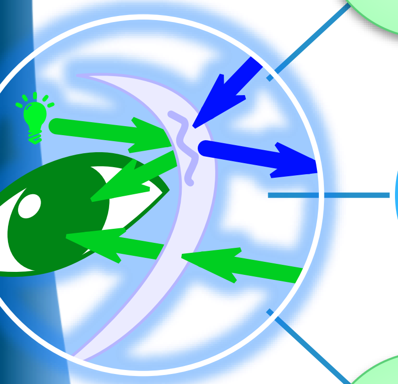
[Hanai+,2019]



(1) 1本で右向き (2) 1本で左向き

(3) 2本で右向き (4) 2本で左向き (5) 2本で異なる向き

In-hand Object Pose Estimation and Control



Case 1

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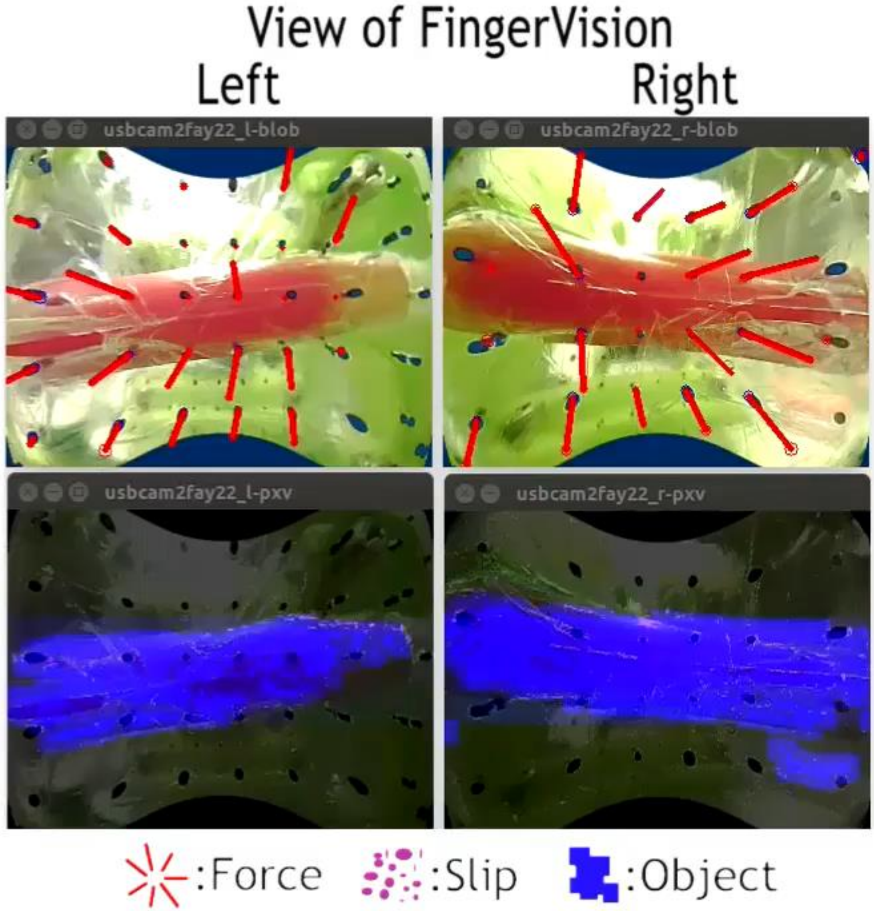
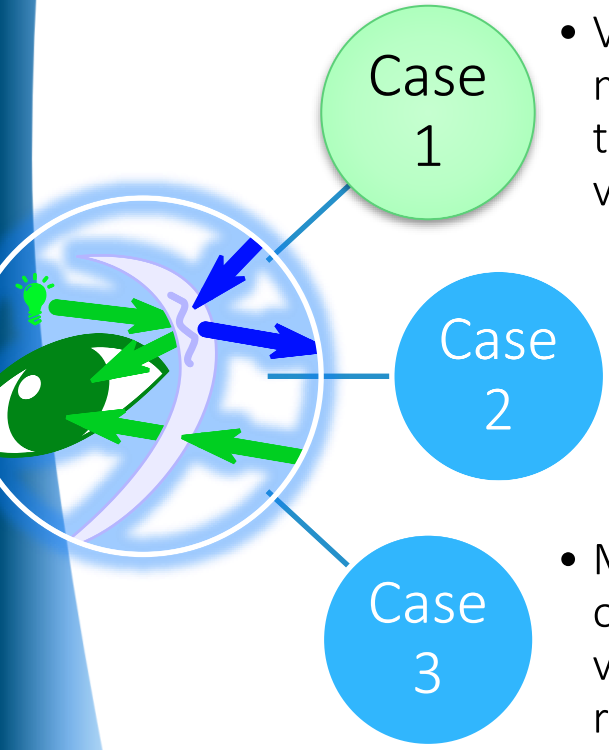


[Yamaguchi+,2017]

In-hand Object Part Estimation and Control



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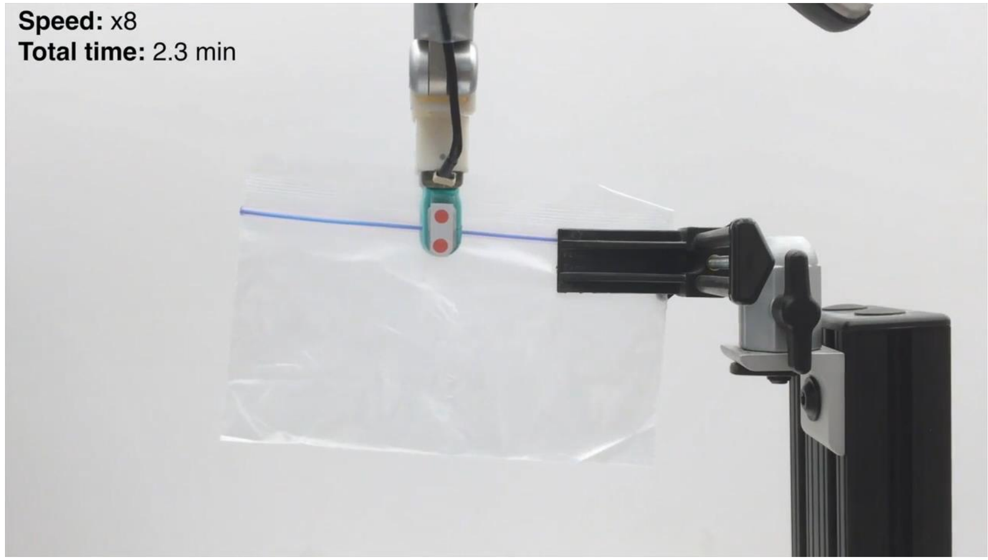
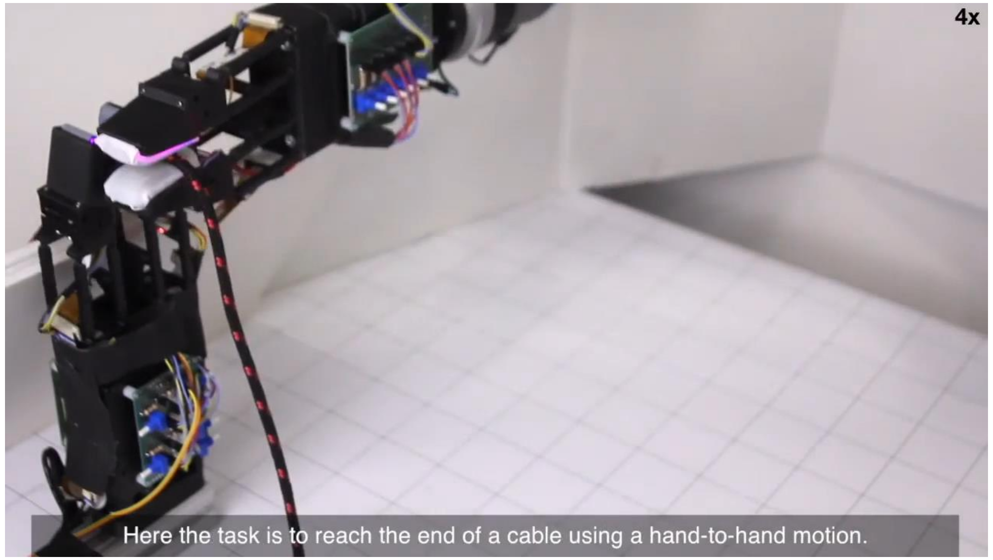
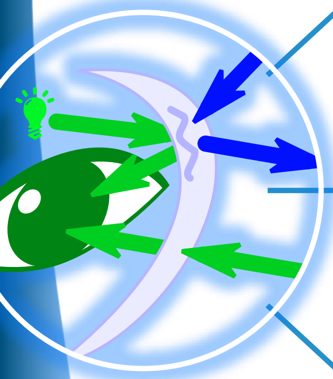


(BioTac)
Hellman et al., 2017: Functional Contour-following via Haptic Perception and Reinforcement Learning
https://www.youtube.com/watch?v=a_n67lHh020



(GelSight)
She et al., 2019: Cable Manipulation with a Tactile-Reactive Gripper
https://www.youtube.com/watch?v=-xKeWdrmuBc

Handover with Tactile Event Detection



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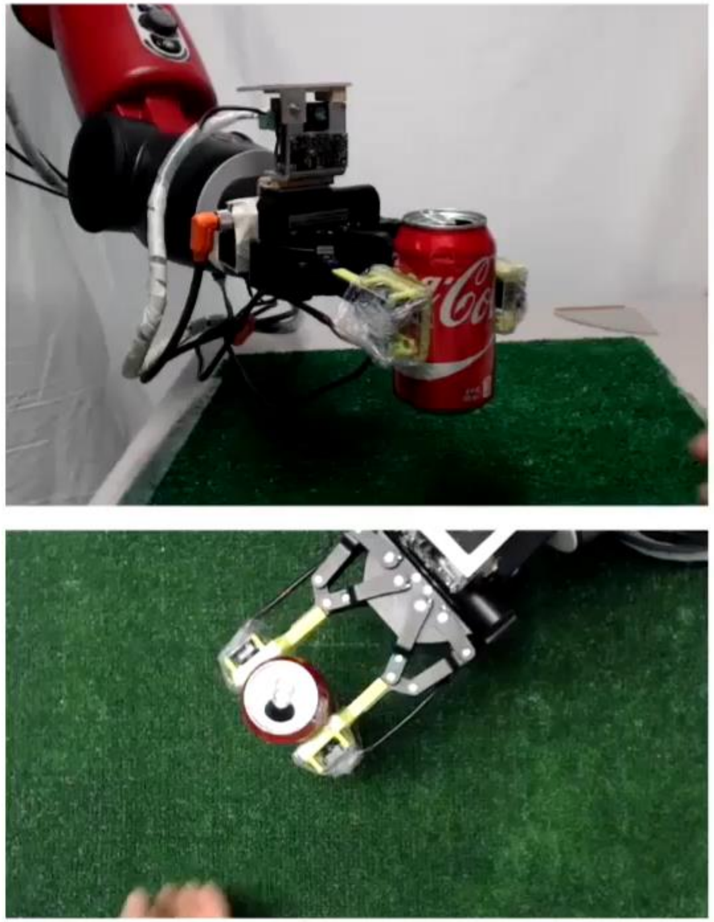
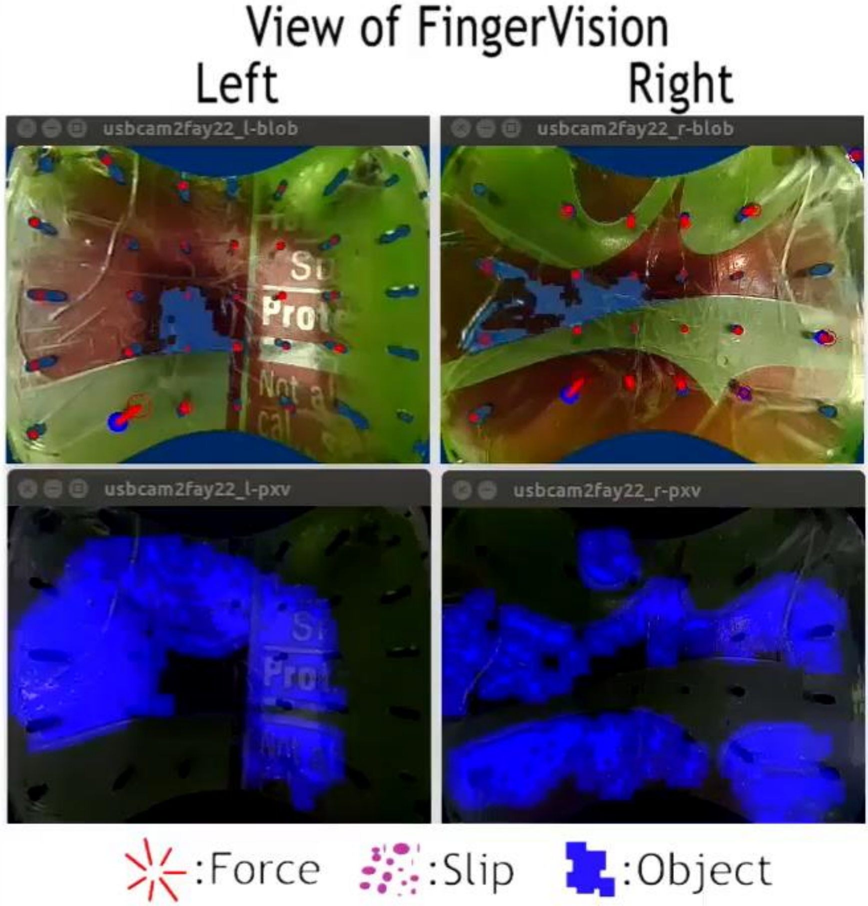
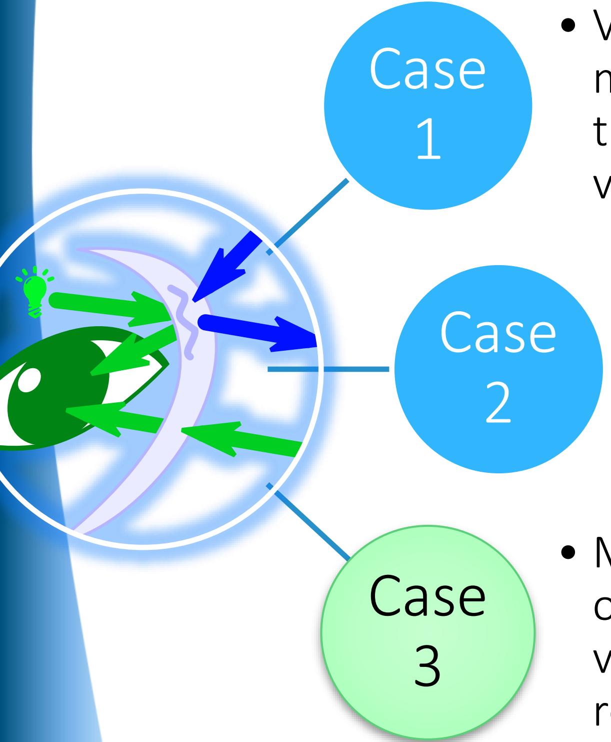



View of FingerVision

[Yamaguchi+,2017]

Grasp Adaptation with Slip-feedback



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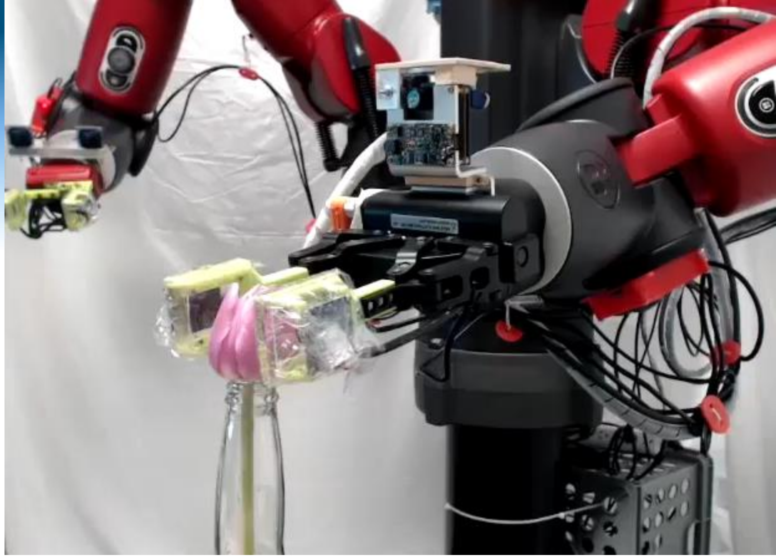
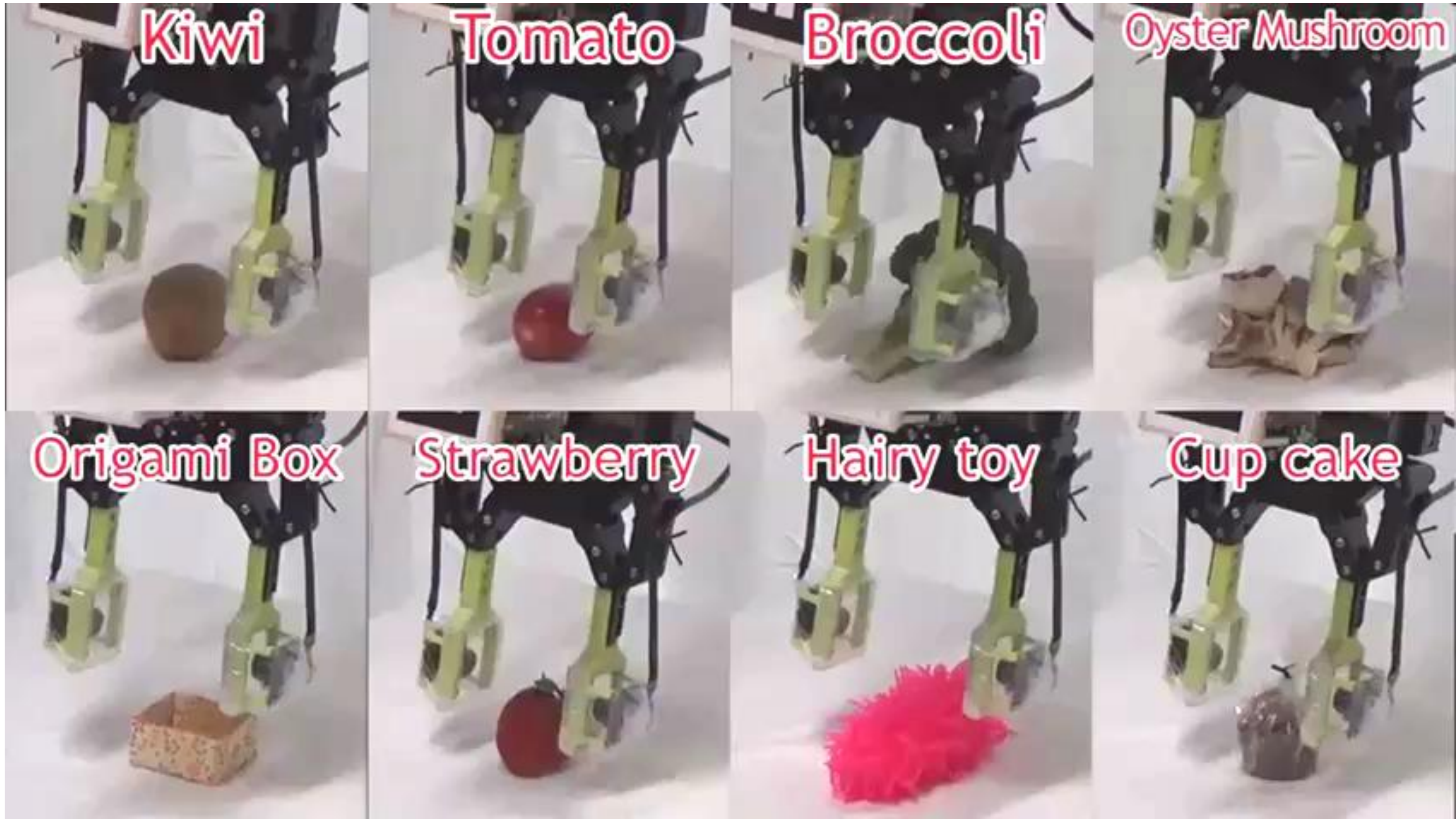
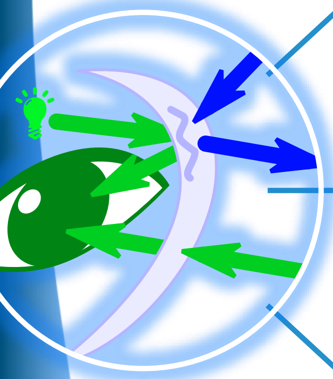


[Yamaguchi+,2017]



Dancing with Robot



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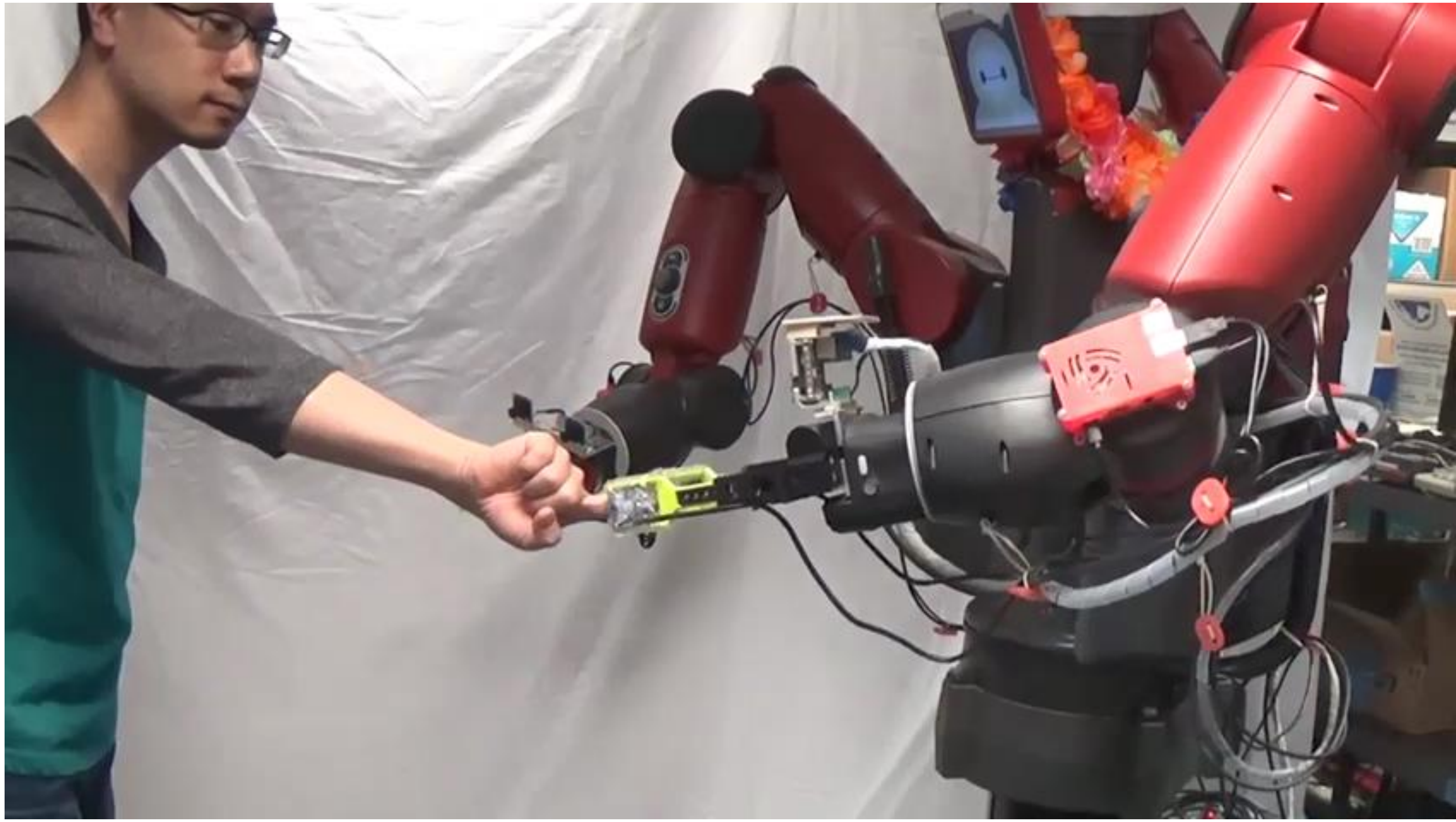
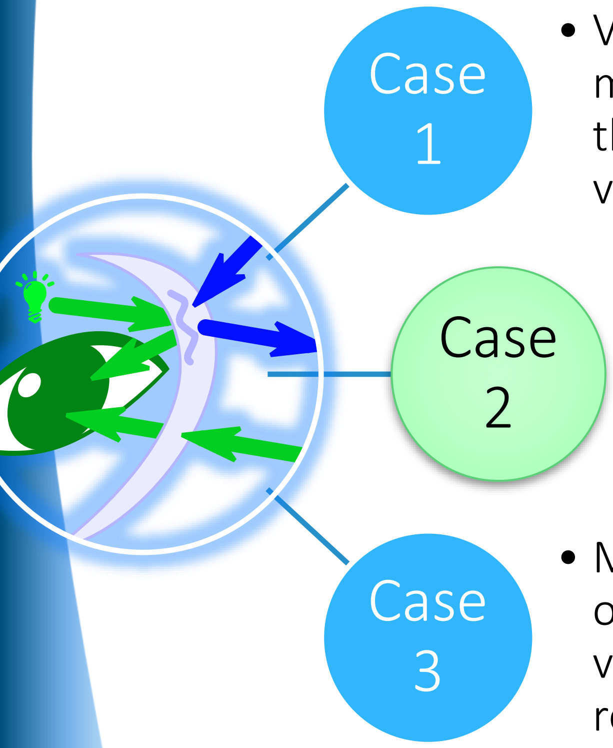


[Yamaguchi+,2017]

Tactile Event Detections and Reactions



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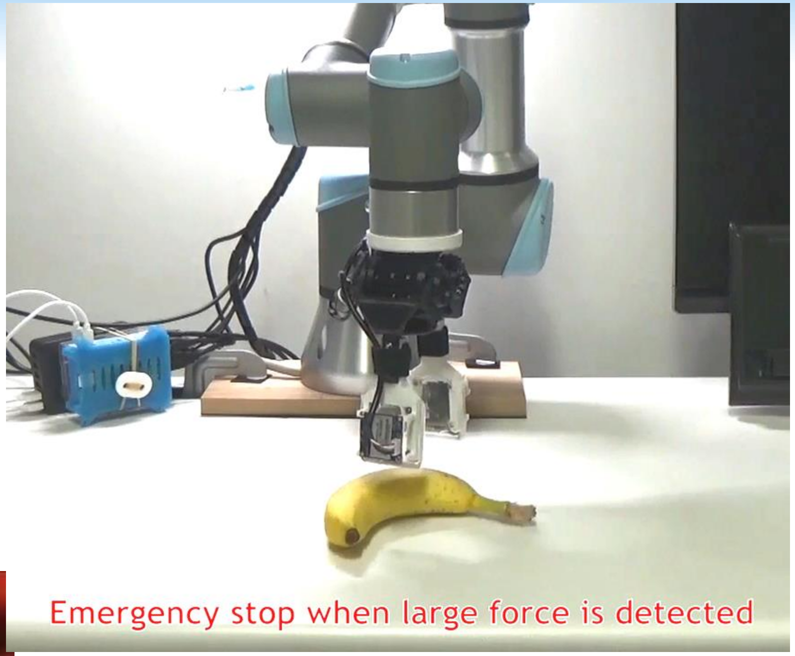
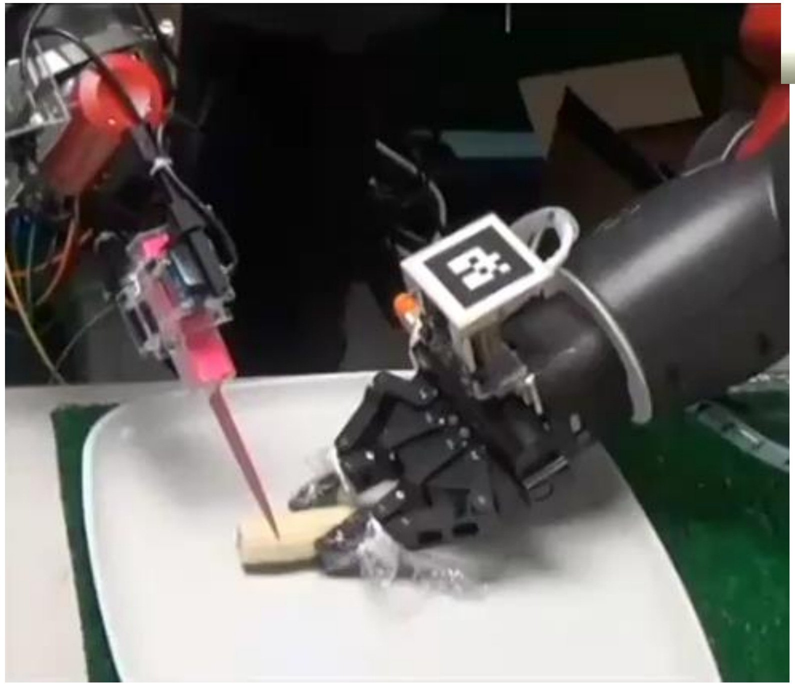
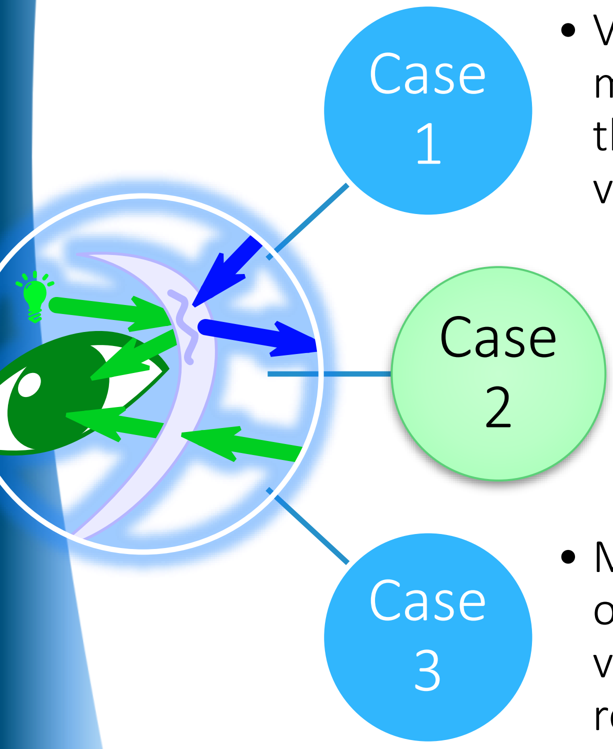


[Yamaguchi,2018]



[Yamaguchi+,2016]

Automatic Placing with FingerVision



- V-b Tactile is more accurate than external vision
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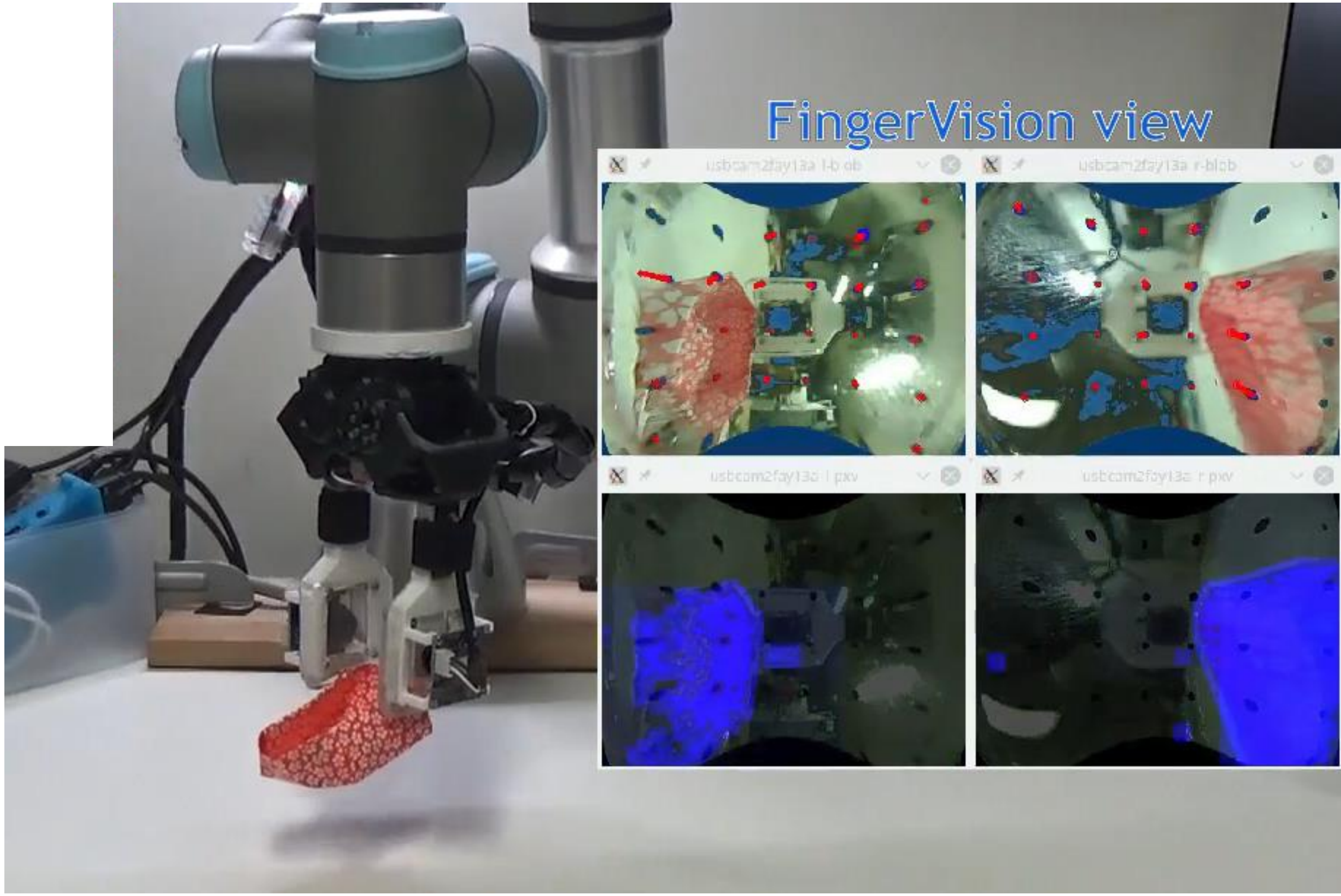
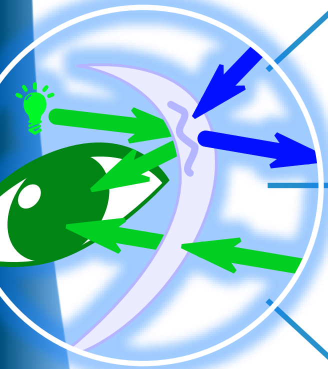
- Modality other than vision is required



[Yamaguchi,2018]

Grasp Stabilization with Slip-feedback Control



Case 1
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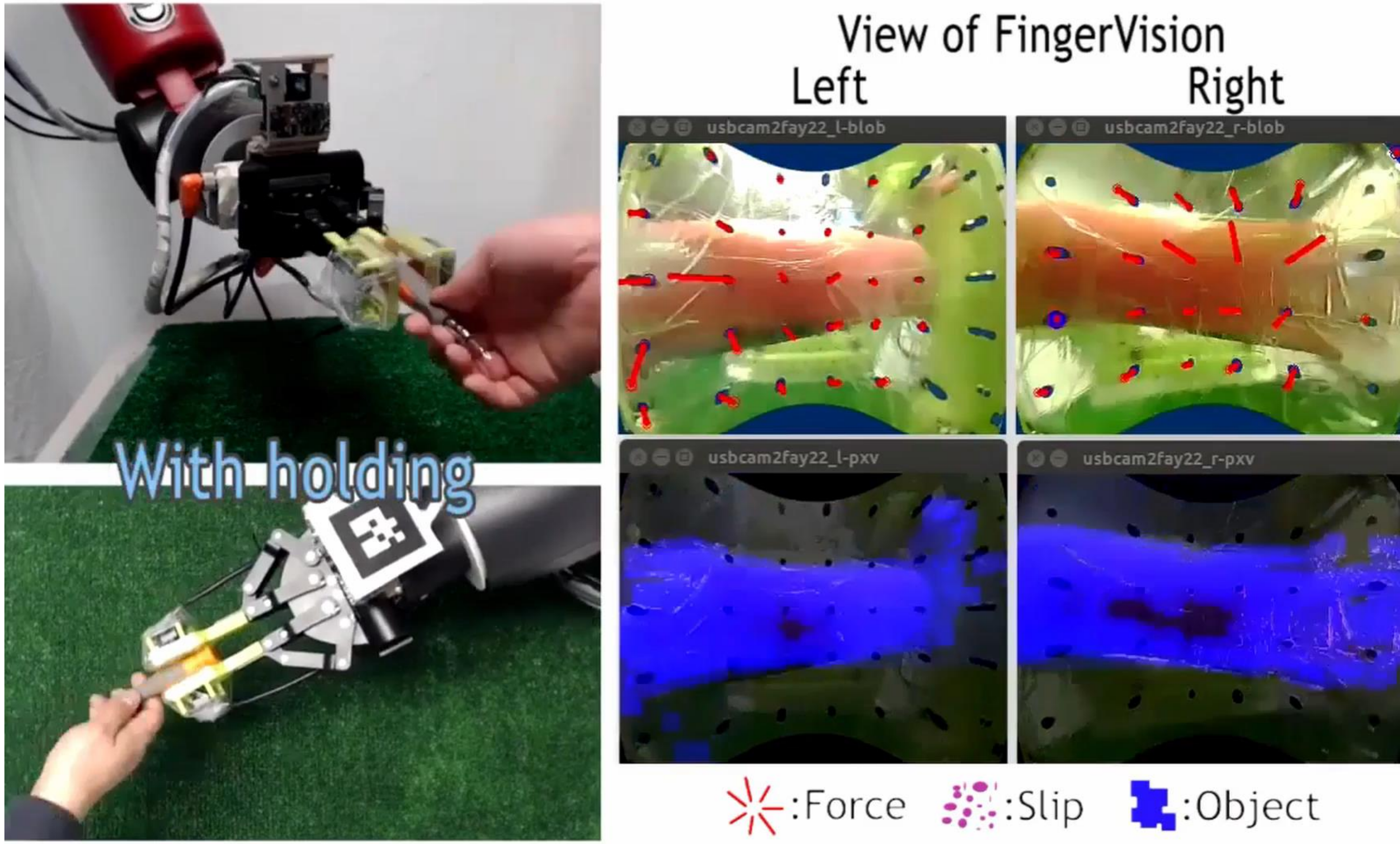
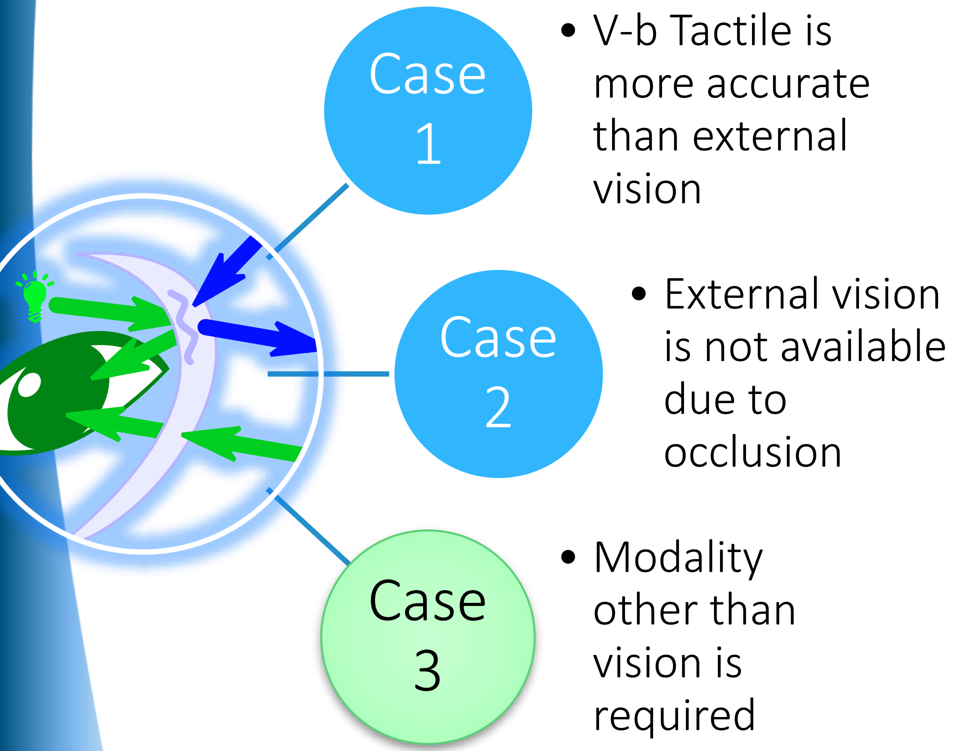


[Yamaguchi+,2017]

Grasp Adaptation



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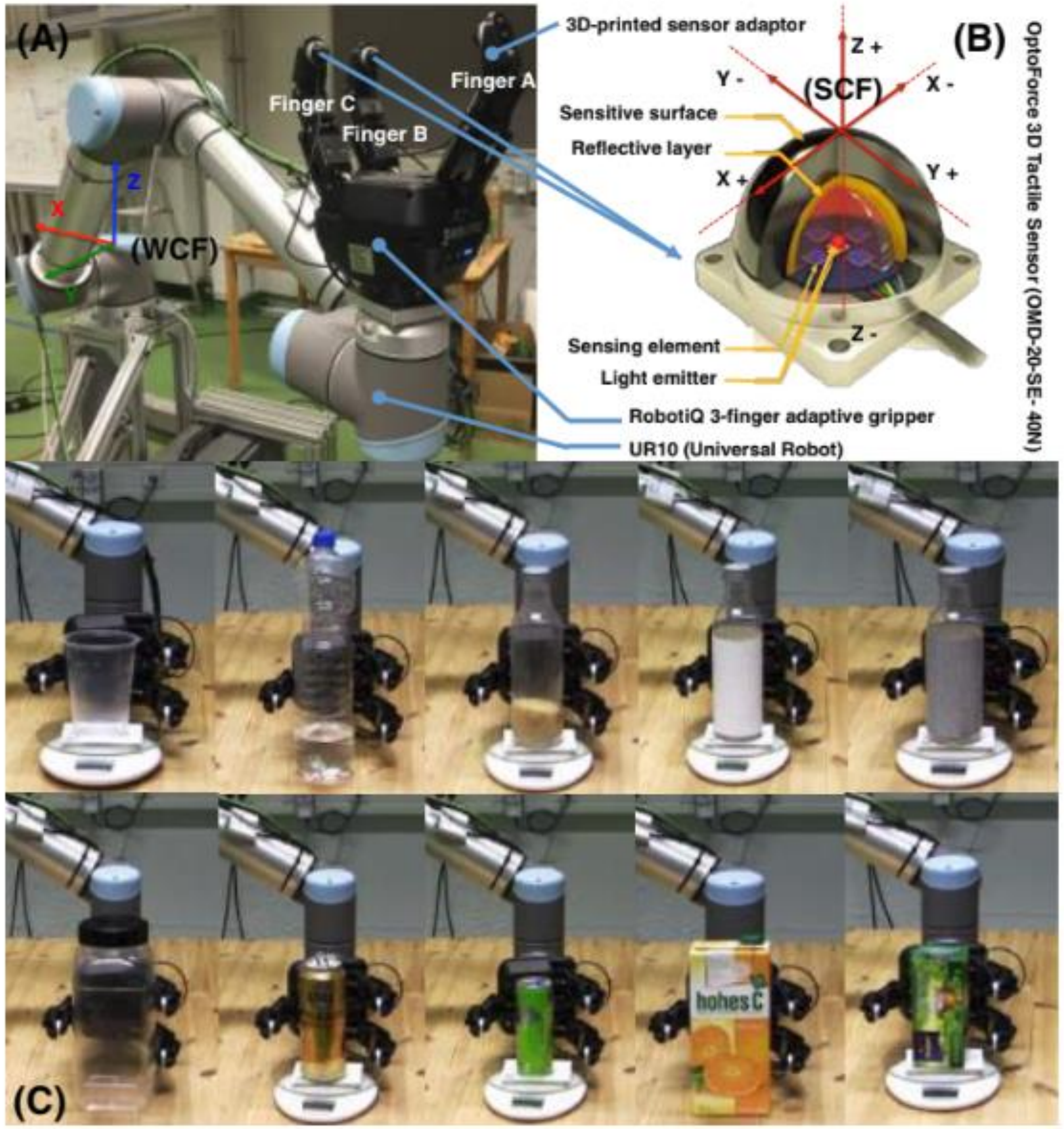
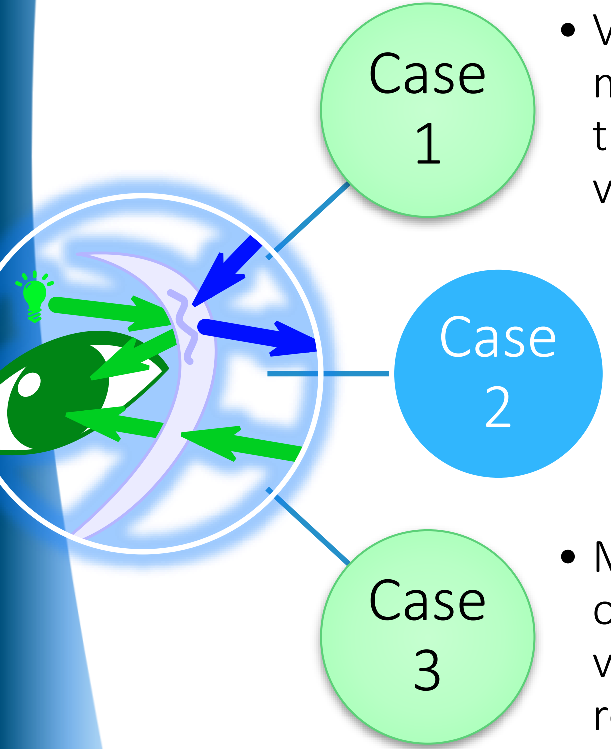


Grasp adaptation to deformable objects with dynamic centers of mass [Kaboli+,2016]

Tactile Event-driven Manipulation



- V-b Tactile is more accurate than external vision

- External vision is not available due to occlusion

- Modality other than vision is required

[Yussof+,2010]
Opening cap by twisting
Contact (touch) and slip were used as **triggers**

Open Source Tactile Sensor Project

OS Solves Some Issues of Tactile Sensing

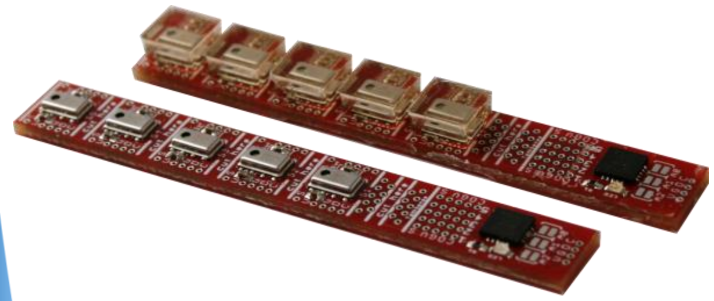
- Programming issues
  - Less compatibility with the other tactile sensors → We can standardize the sensors
  - It is unclear what we can do with tactile sensors → We can share knowledge of tactile skills
  - Programming becomes complicated → We can share programs
- No ecosystem to accumulate knowledge (hardware/software) → Software and hardware sharing mechanism can be established like ROS
- Roboticists can find alternative ways (which could be research topics) → If there is an easy solution, why don’t you use it?

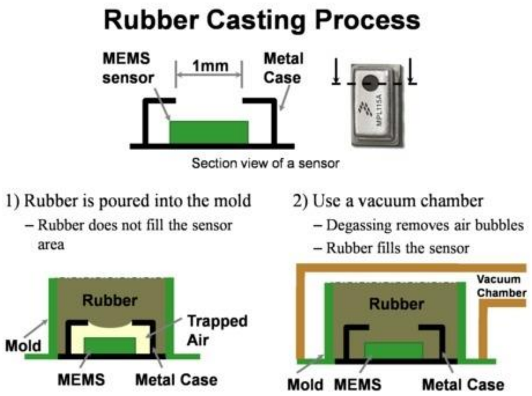
Soft Robotics Toolkit

soft robotics toolkit

Open platform of soft robotics

https://softroboticstoolkit.com/

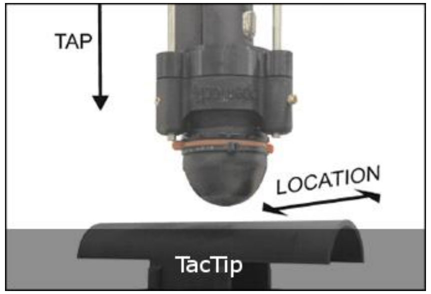


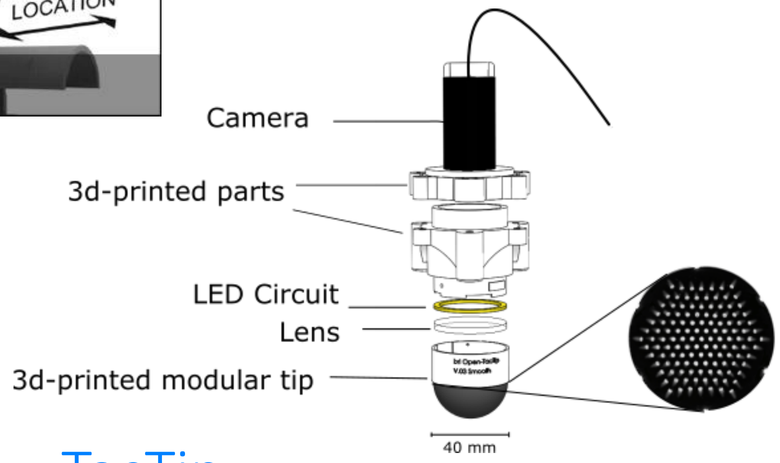

Rubber Casting Process

1) Rubber is poured into the mold
   - Rubber does not fill the sensor area

2) Use a vacuum chamber
   - Degassing removes air bubbles
   - Rubber fills the sensor

TakkTile Sensors





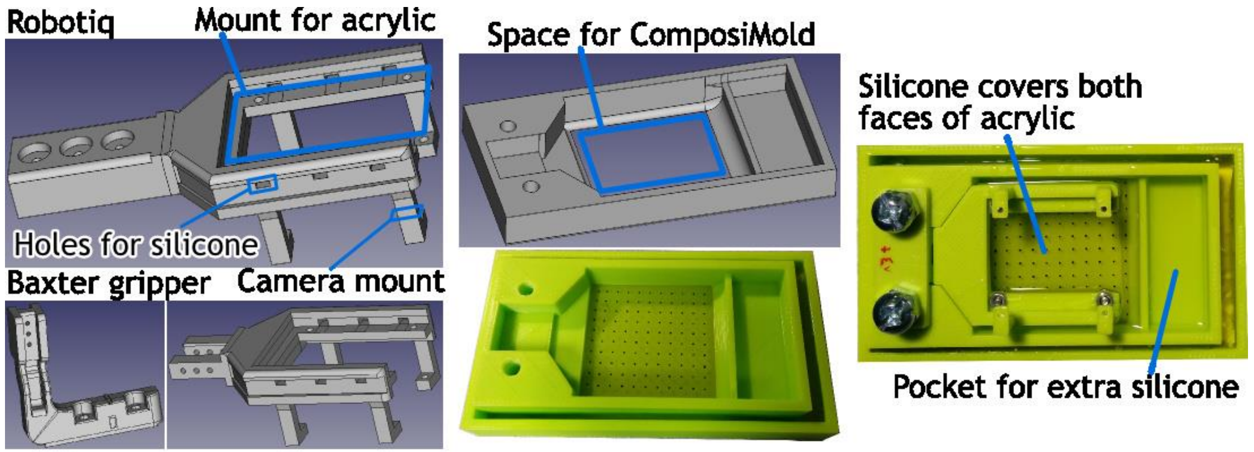
TacTip

FingerVision is Open Source

FingerVision

http://akihikoy.net/p/fv

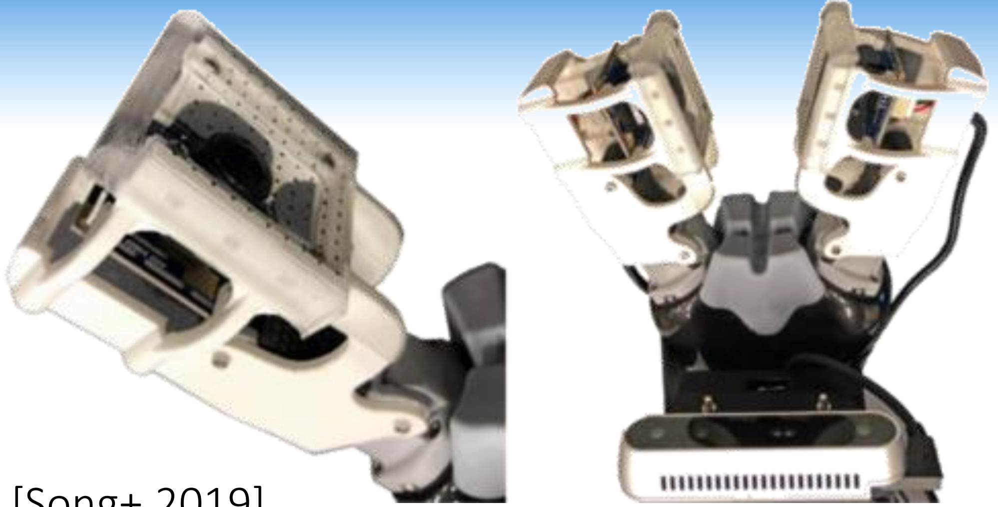
- Hardware design (CAD)
- Fabrication procedure
- Software (process FV data, control w FV)
- Publications
- Community (mailing list)



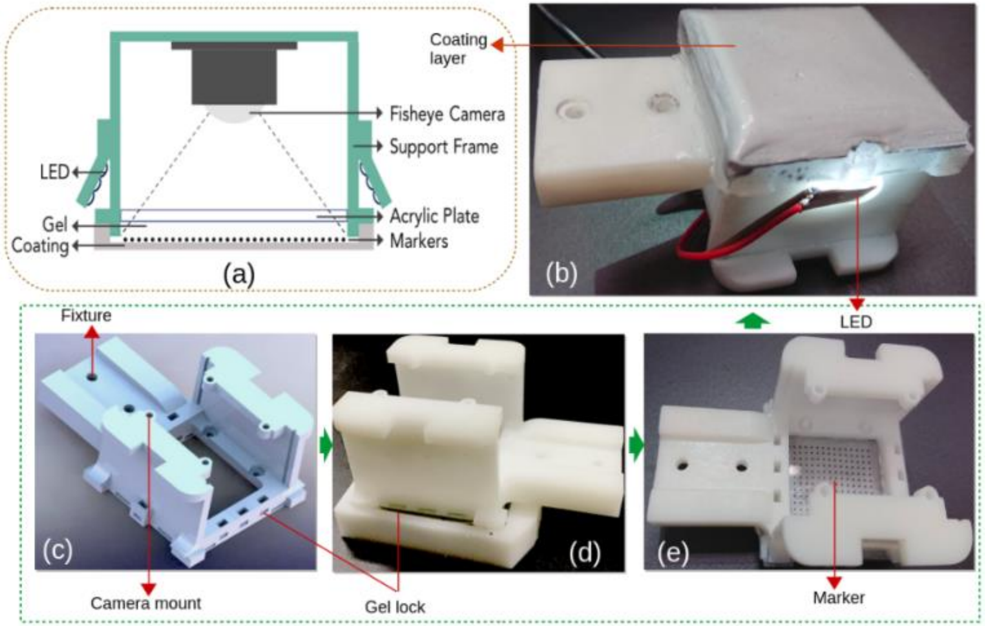
(a) Frames (b) Mold (c) Casting silicone

FingerVision Family

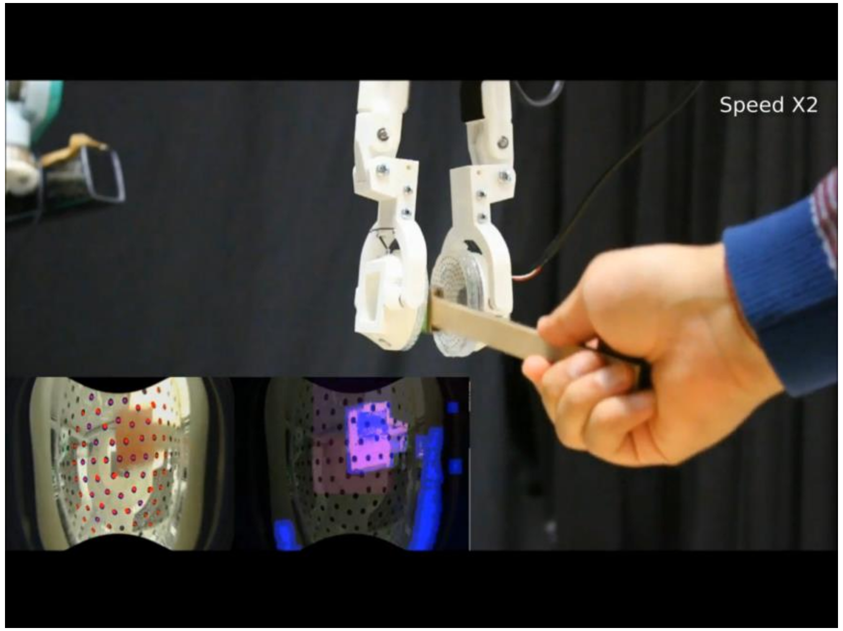
[Yamaguchi,…,2016]



[Song+,2019]



[Zhang+,2018]



[Belousov+,2019]

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NSK

JST