16-299 Intro to Feedback Control Systems Spring 2022

# Tactile Sensing for Robot Control

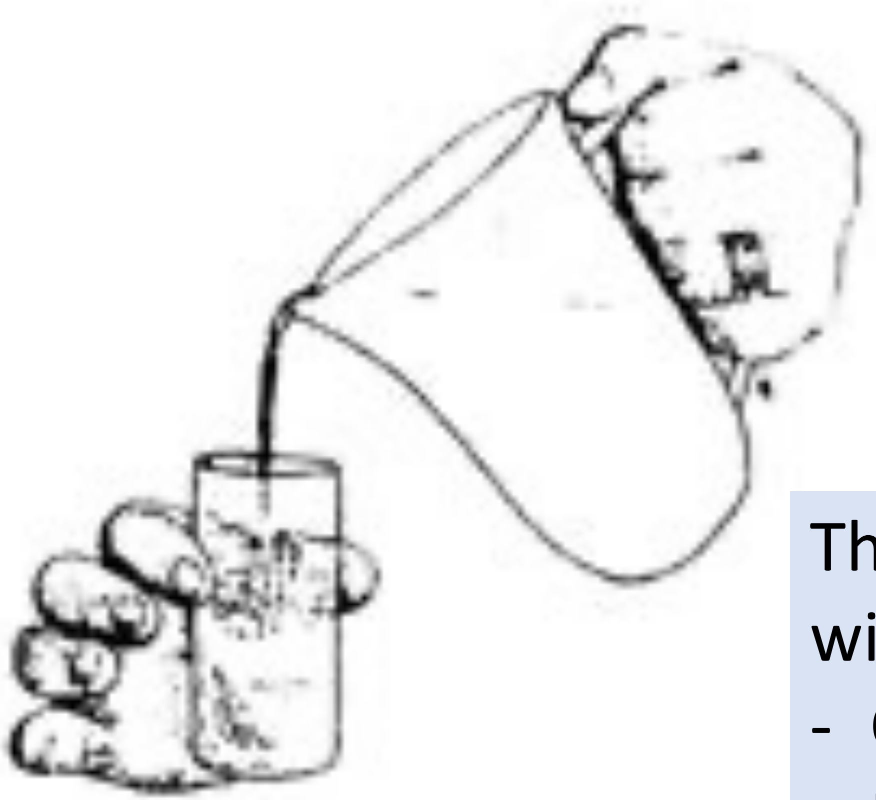
Wenzhen Yuan

4/12/2022

Carnegie Mellon University
The Robotics Institute

# What is the sense of touch?

**Kinesthesia**
Location/configuration
Motion
Force
Compliance

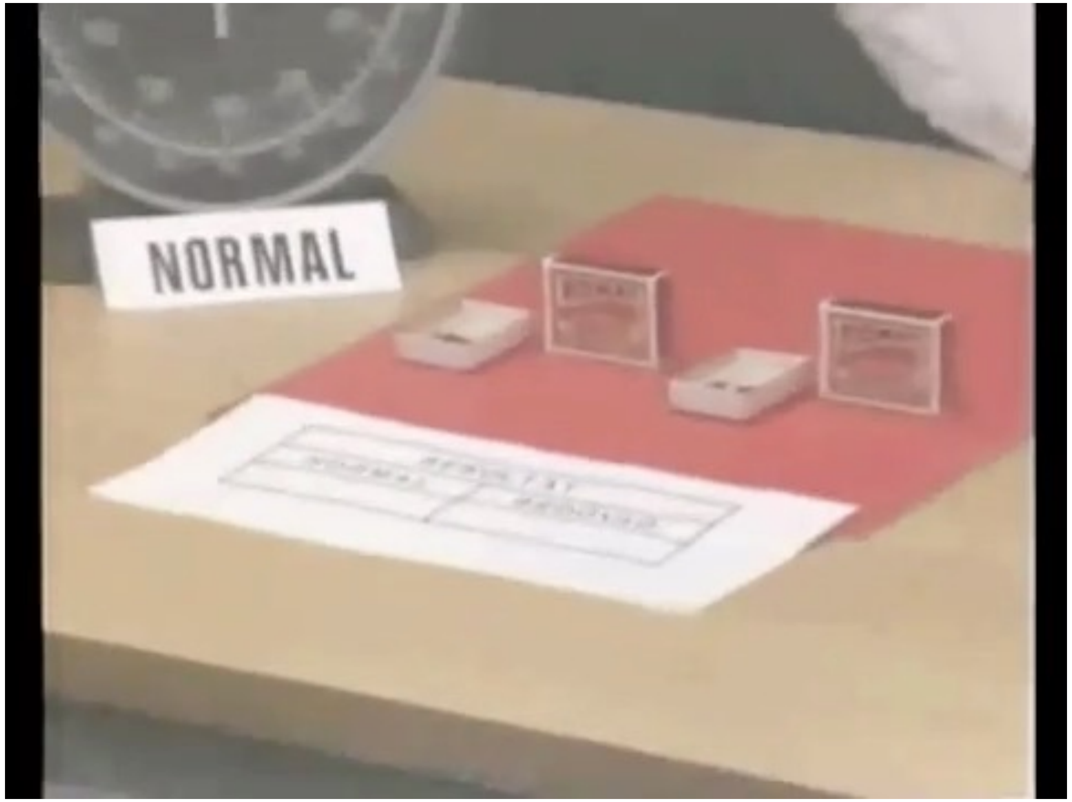


**Cutaneous**
Temperature
Texture
Slip
Vibration
Force

The haptic senses work together with the motor control system to:
- Coordinate movement
- Enable perception

J. Edward Colgate

# What would life be like without touch?




Pre-anesthetization

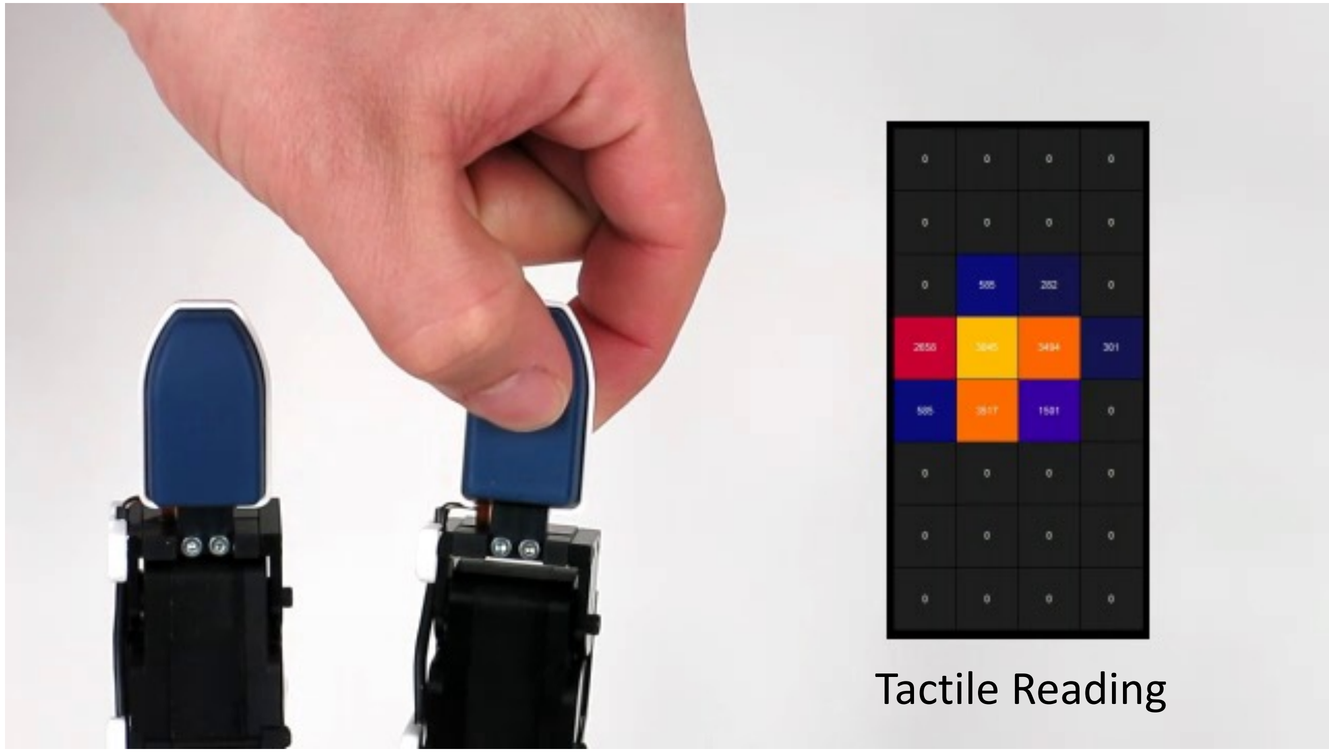

Post-anesthetization

video courtesy Roland Johansson
https://www.youtube.com/watch?v=0LfJ3M3Kn80

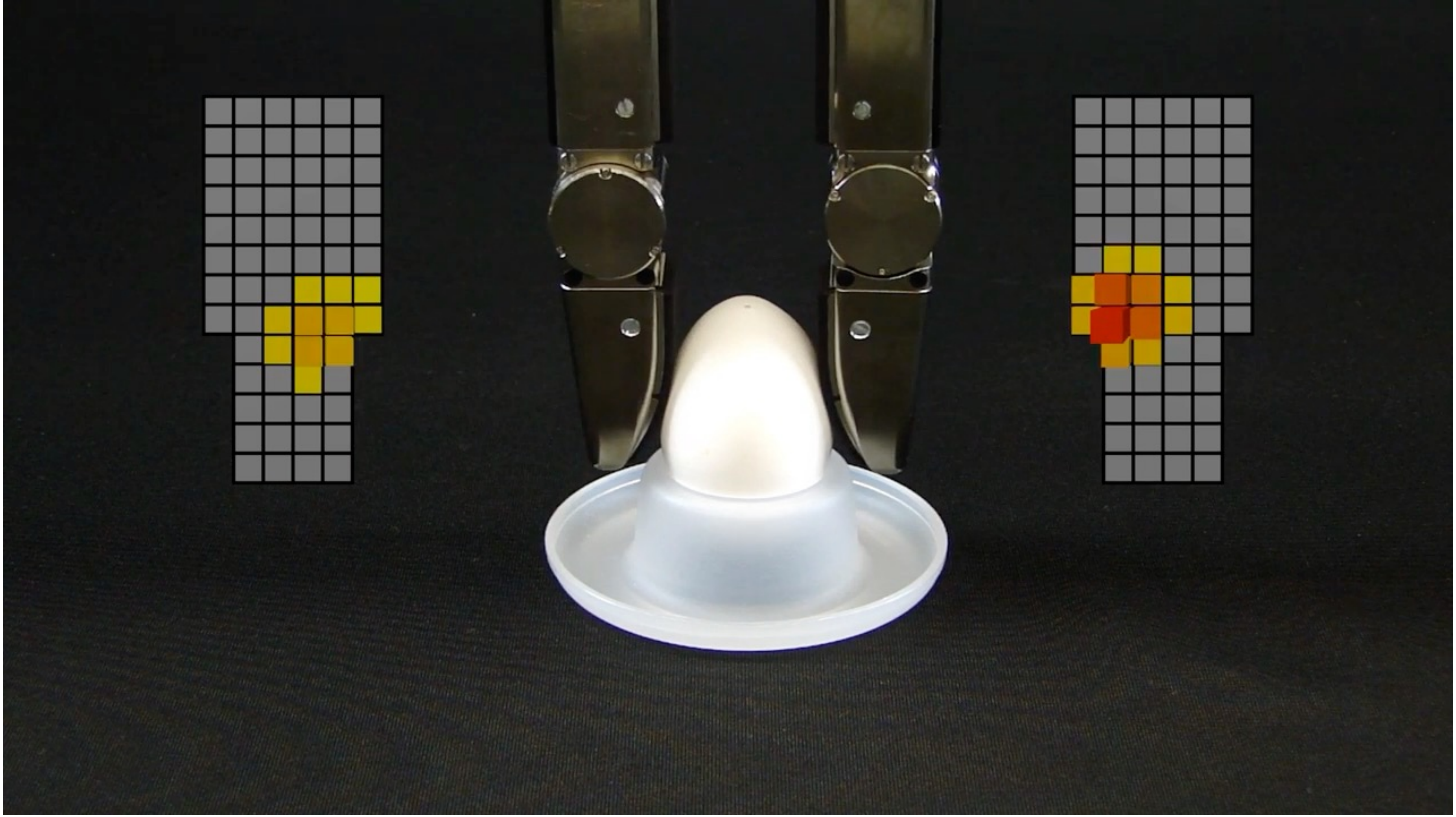

Video by HaptX https://www.youtube.com/watch?v=R-sP_pju81E

# Tactile sensing array from Weiss robotics

Measuring normal force distribution over an area



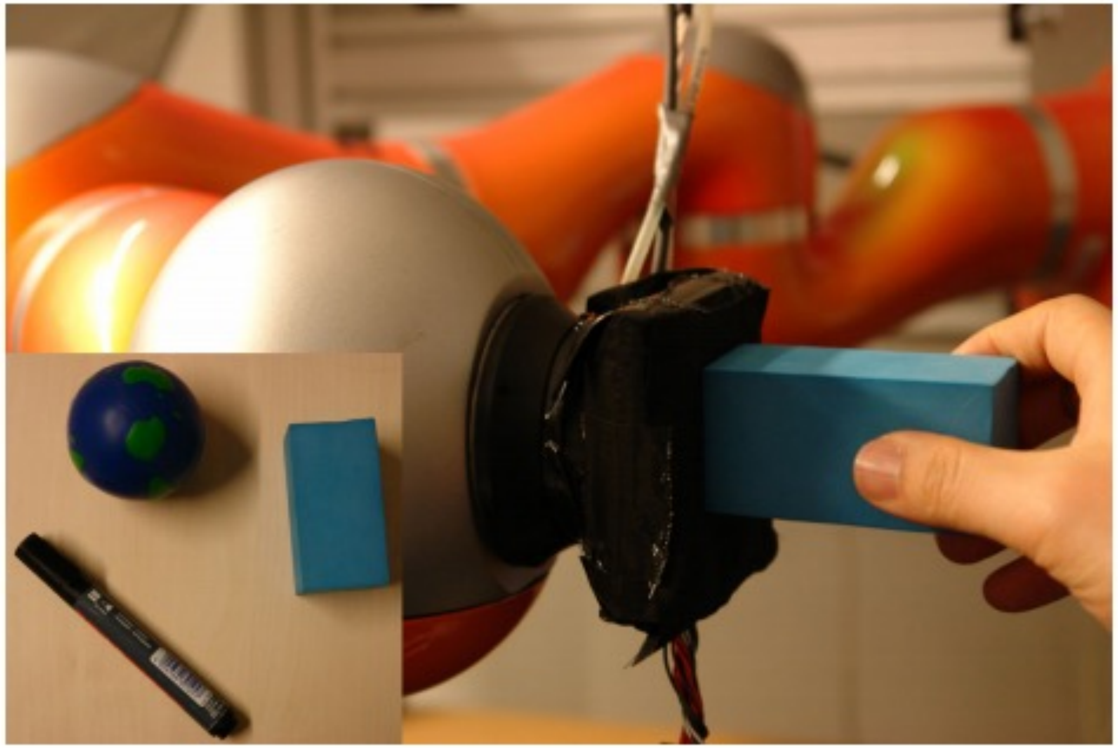

Spatial resolution: ~5mm



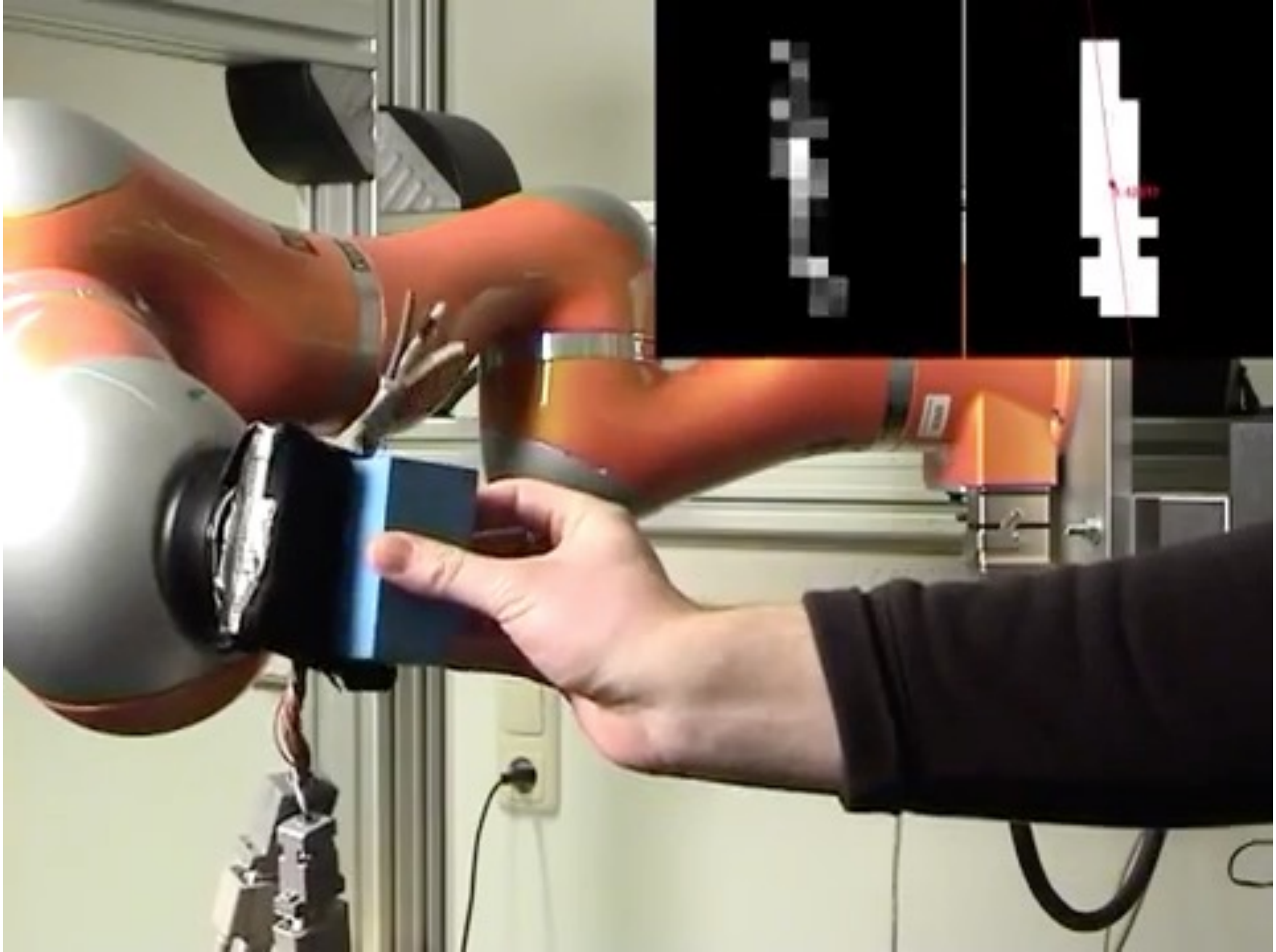
Video by Peter Kiechle https://www.youtube.com/watch?v=HxBOjJg55y4

# Tactile servoing

- System:
  - 7-DoF robot arm;
  - 16×16 tactile sensor array as the end-effecter, with 5mm spacing, 1.9kHz sampling rate
- Target: realizing a specific tactile interaction pattern
  - Tracking a touched object
  - Maintaining contact location and contact force
  - Tracking an object's pose
  - Tactile object exploration
  - Etc.

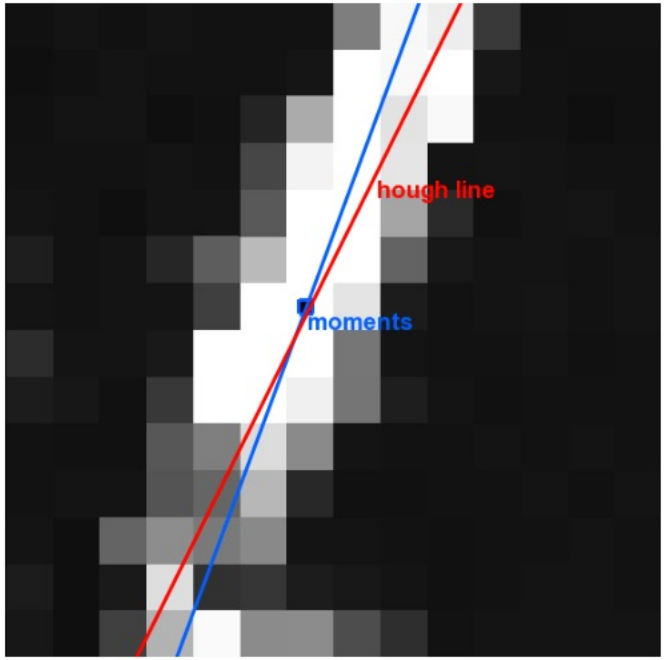


Li, Carsten, Haschke, and Ritter. "A control framework for tactile servoing." 2013

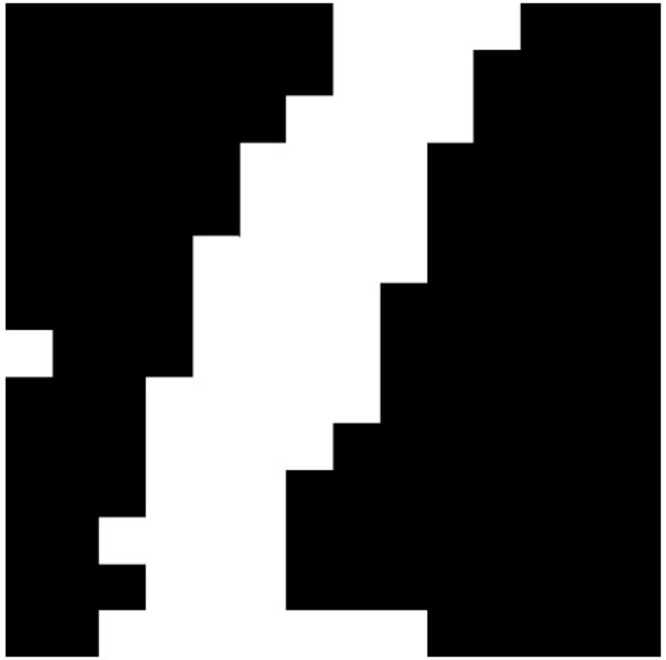


https://www.youtube.com/watch?v=TcWipks3qJ0

# Tactile features



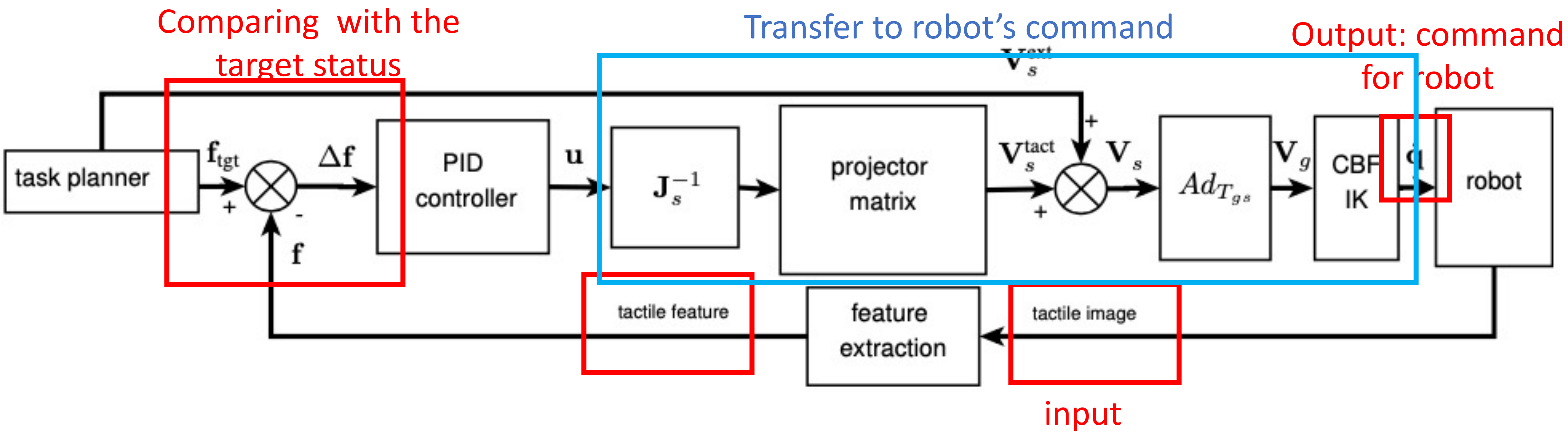

Raw tactile image



Extracted contact region

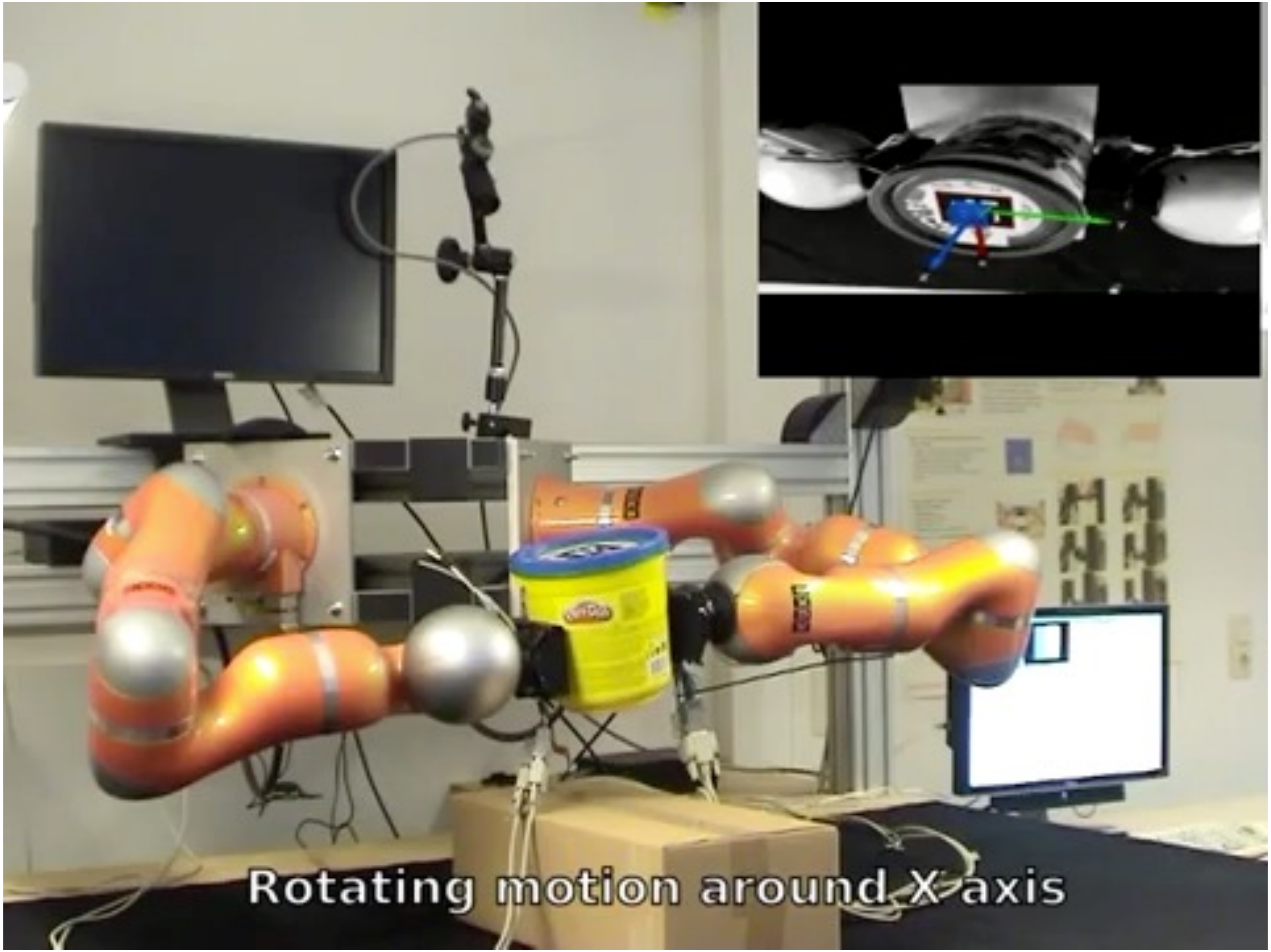
- Contact position
- Contact force
- Orientation of an object edge

# Control scheme: matching the tactile feature




$$\Delta\mathbf{f}(t) = [\Delta x_s, \Delta y_s, \Delta f, \Delta\alpha]$$

Deviation of the feature vector




https://www.youtube.com/watch?v=UgCv5ESAYfc

Karlsruhe Institute of Technology

# 3D Contour Following for a Cylindrical End-Effector Using Capacitive Proximity Sensors

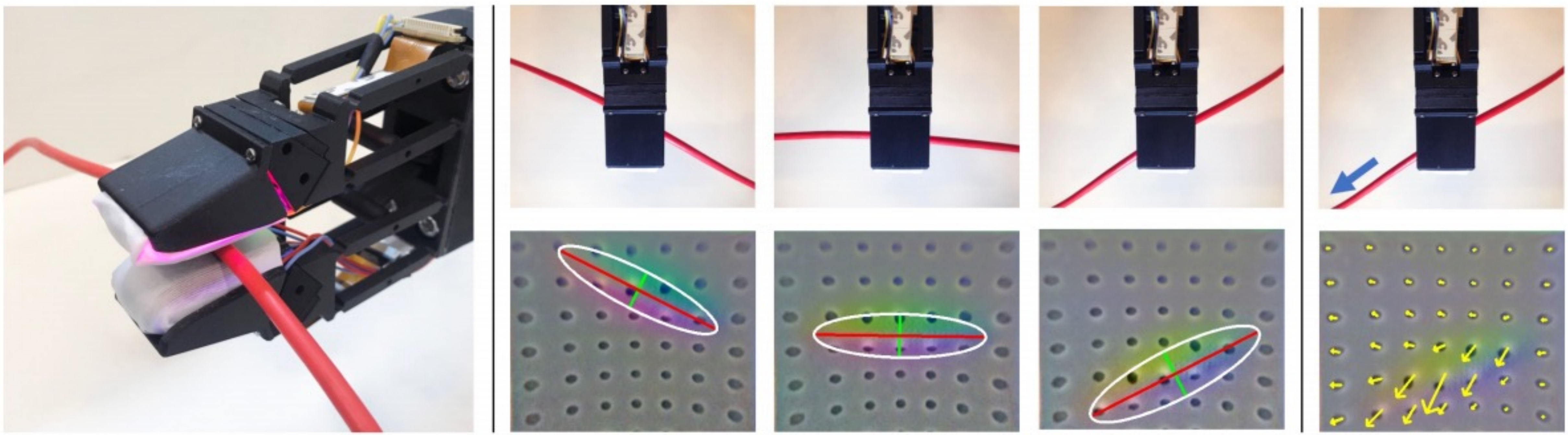
Stefan Escaida Navarro, Stefan Koch and Björn Hein

Institute for Anthropomatics and Robotics (IAR)-
Intelligent Process Control and Automation Lab (IPR)

https://www.youtube.com/watch?v=xujtV9OSknM

Navarro, Koch and Hein. 2016

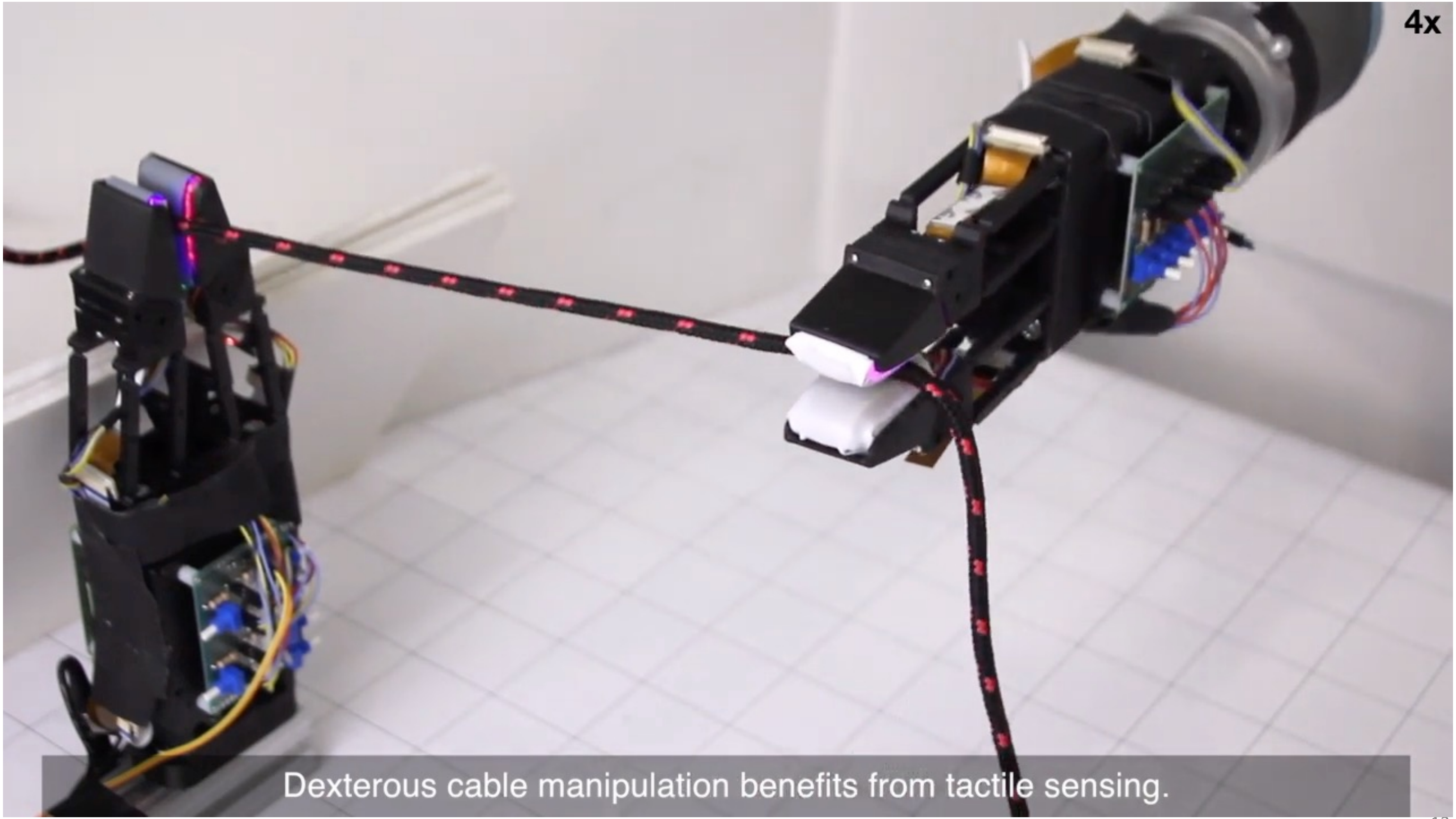
# Cable manipulation using GelSight



(a) Gripper grasping a cable (b) Cable pose estimation (c) Force estimation

- Goal: Sliding along the cable
- Using GelSight to locate the cable location/direction, and estimate shear force

She, Wang, Dong, Sunil, Rodriguez, and Adelson. "Cable Manipulation with a Tactile-Reactive Gripper." *2020.*

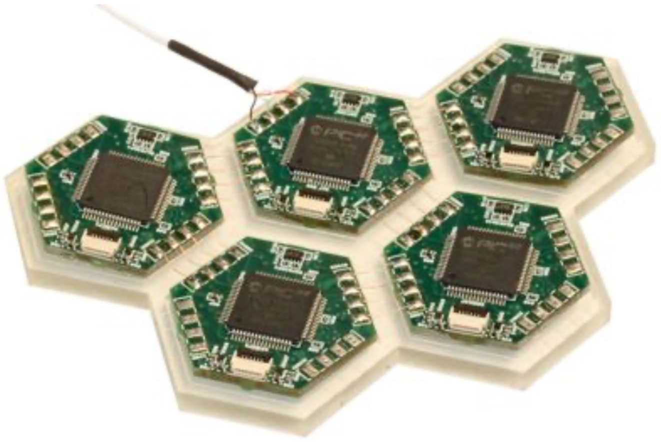




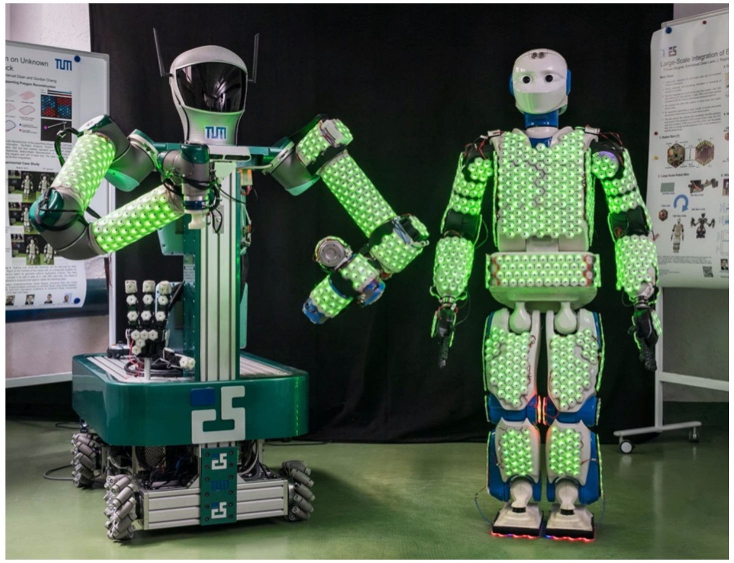

https://www.youtube.com/watch?v=-xKeWdrmuBc&t=16s

# Tactile skin HEX-O-SKIN

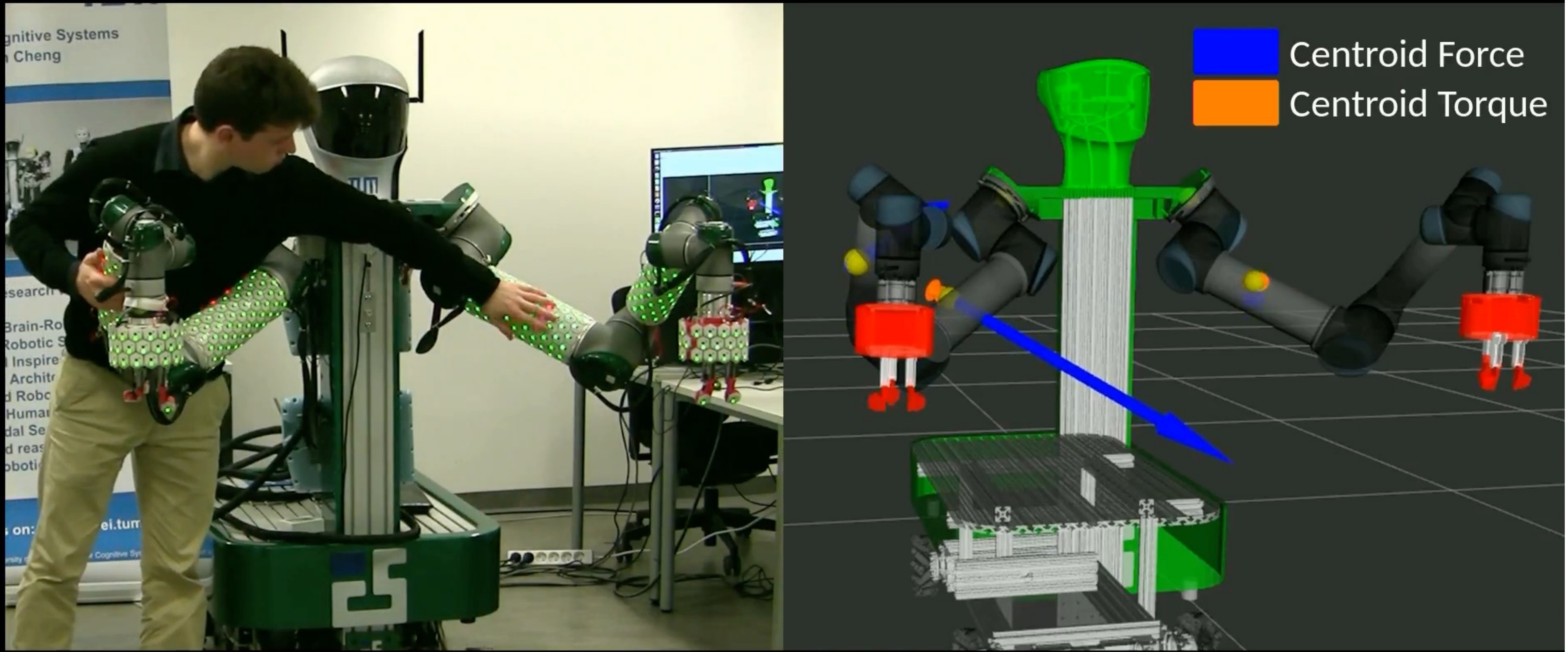
By Prof. Gordon Cheng's group at TU Munich



- Independent sensor modules
  - could be connected in arbitrary ways to cover a large area
- Multimodal sensing
  - Capacitive normal force sensor
  - Optical proximity sensor
  - 3-axis accelerometer
  - Temperature sensing
- Adaptive redundant routing algorithm



Mittendorfer and Cheng. "Humanoid Multi-Modal Tactile Sensing Modules." 2011.

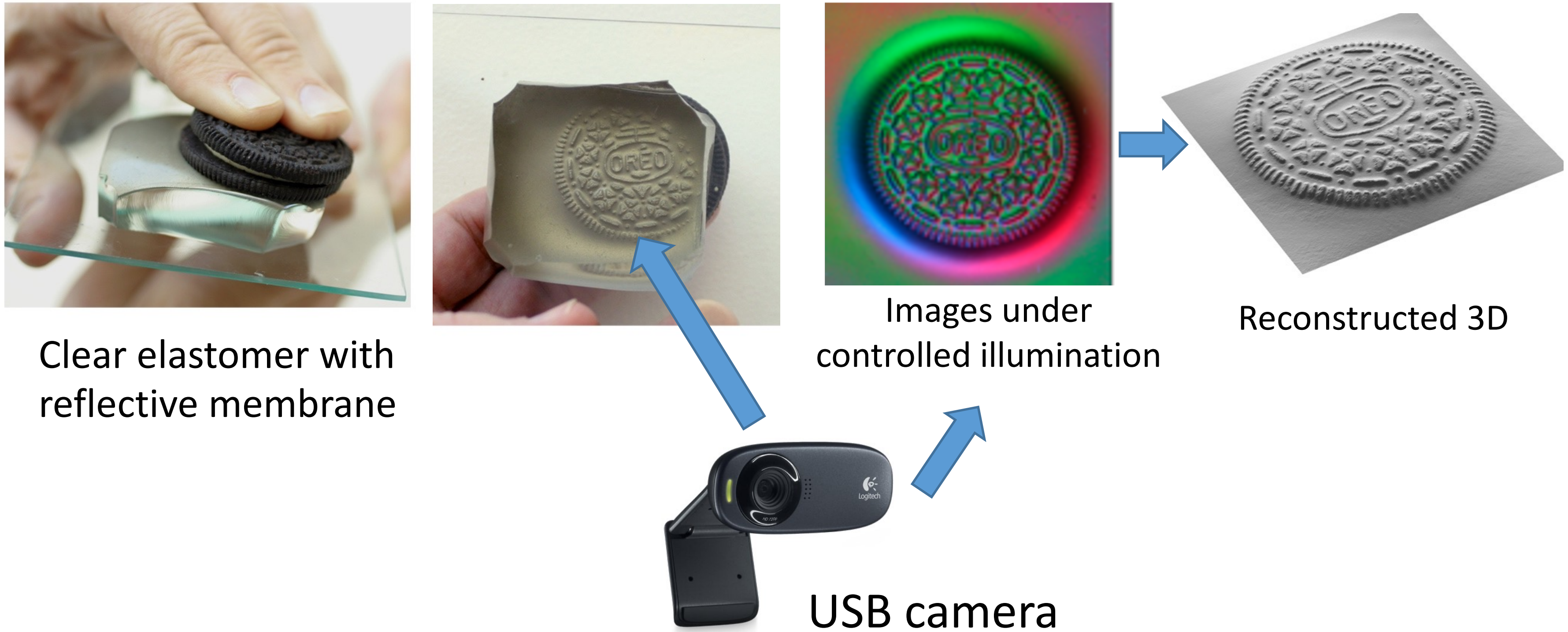


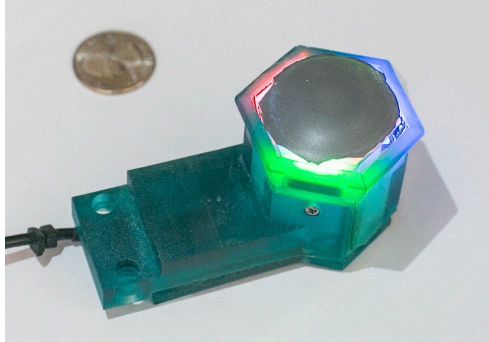

In this manner, even complex multi-contact interactions involving arbitrary numbers of skin cells, distributed in different links or limbs, can be handled efficiently.



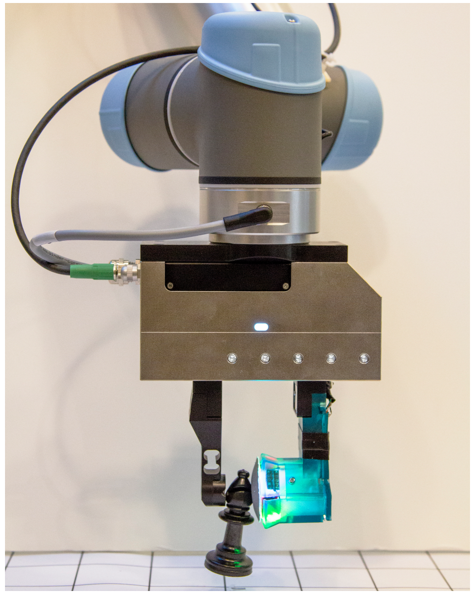
https://www.youtube.com/watch?v=teKbiiSN2K8

# GelSight: a high-resolution tactile sensor to capture the contact geometry and force



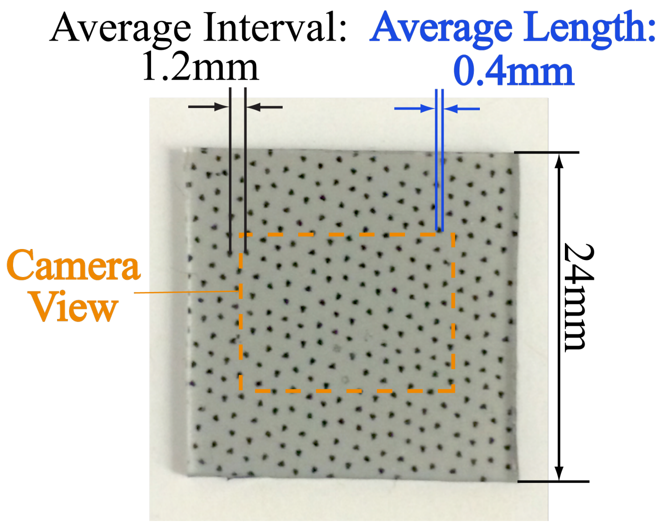
Fingertip GelSight sensor

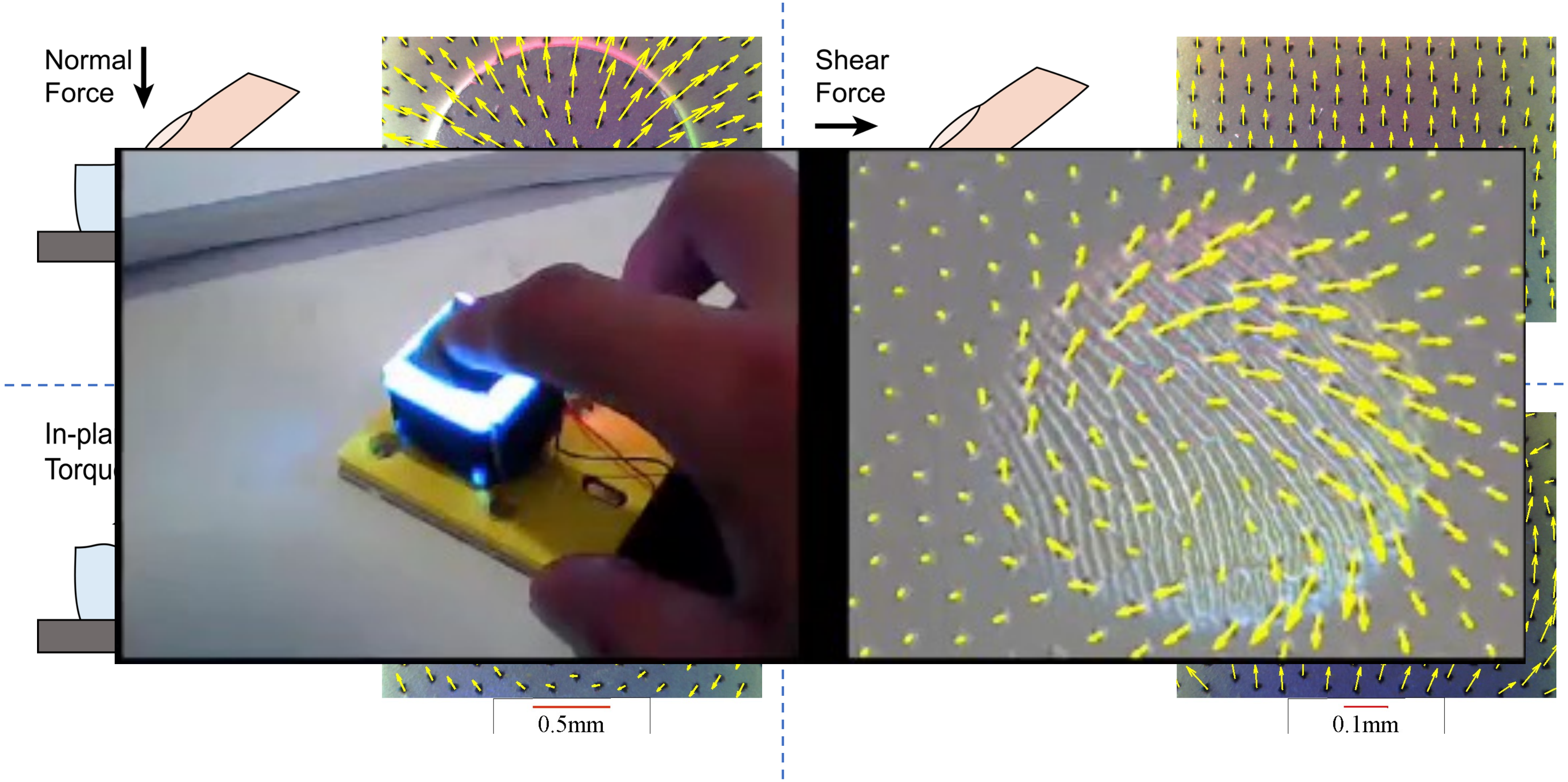


- Reflective membrane yields a shaded image
- Controlled light: different colors for light from different directions
- Photometric stereo infers surface normal of shape

Johnson, Adelson. 2009; Johnson, et al. 2011; Dong, Yuan, Adelson. 2017

# GelSight: motion of the markers indicates the force and torque

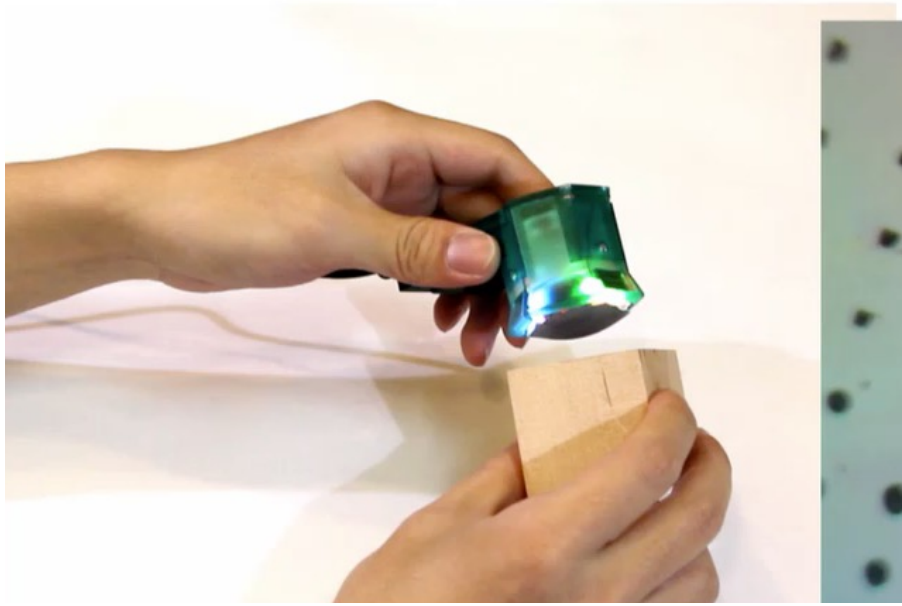


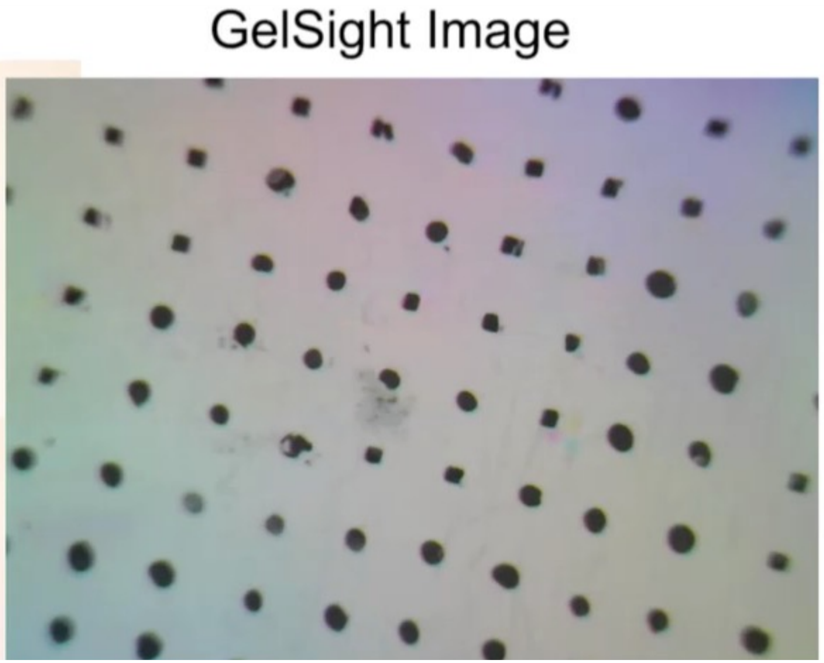



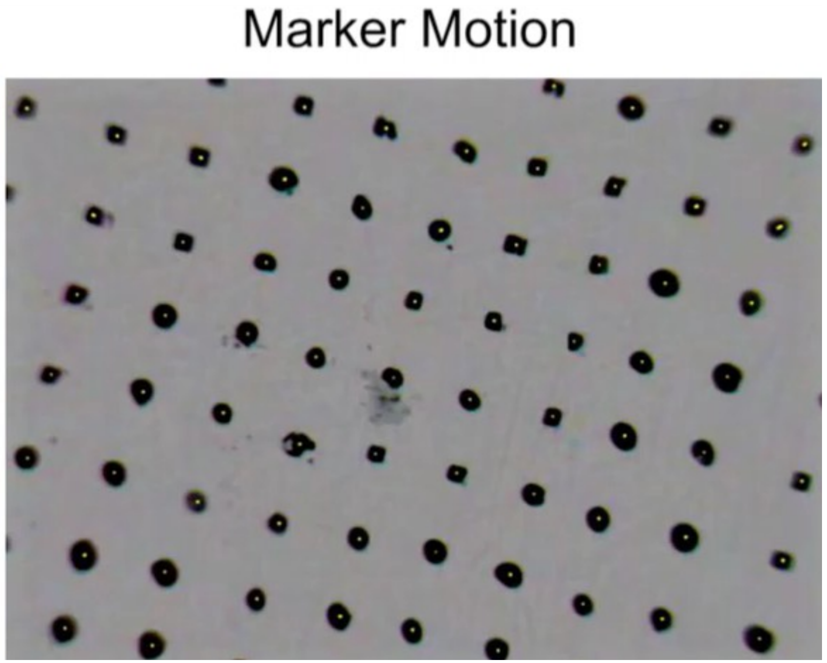

- Pattern of marker motion– type of the force / torque
- Magnitude of marker motion– magnitude of the force / torque

Yuan, Li, Srinivasan, Adelson. ICRA 2015.

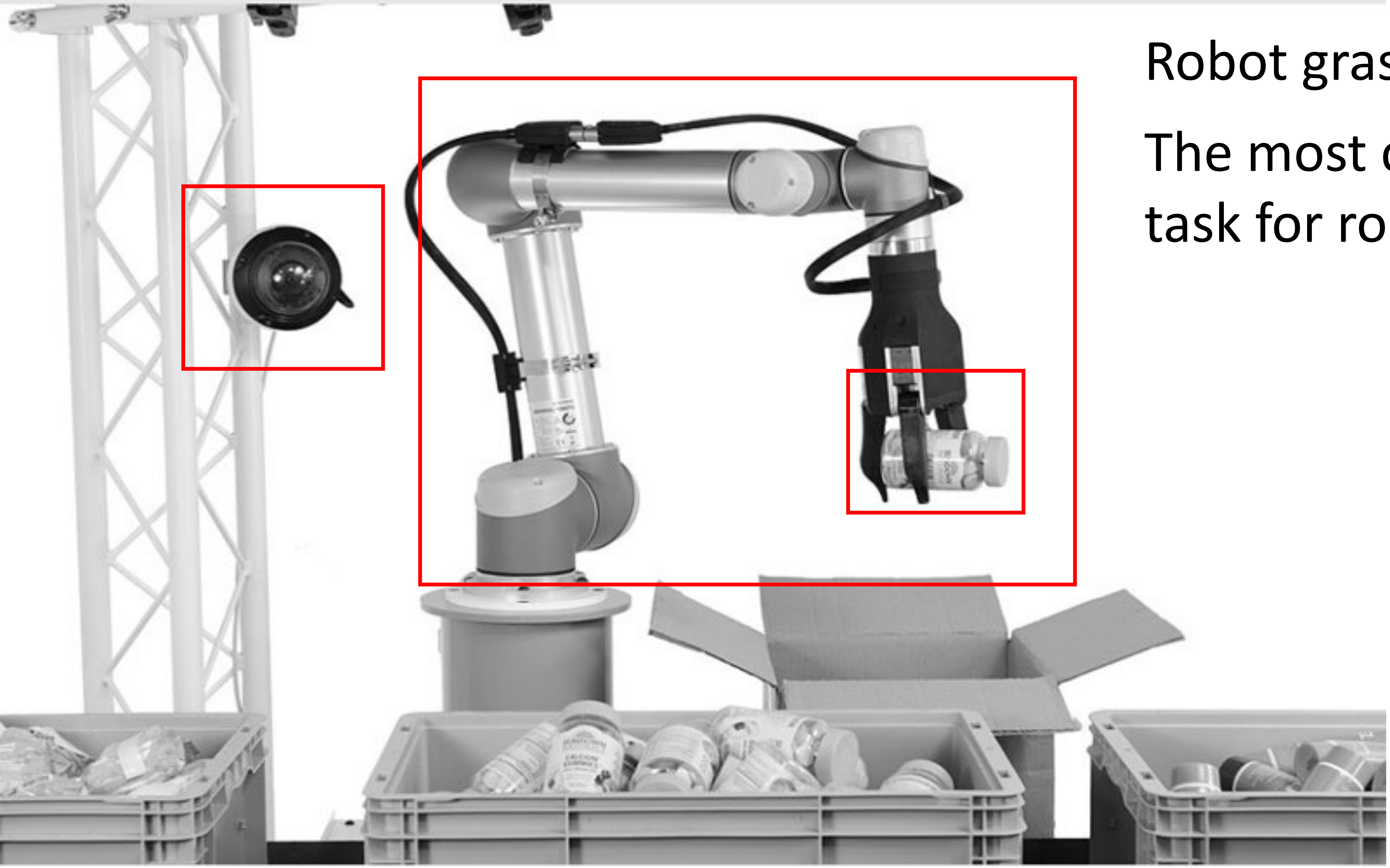
# GelSight enables robot to obtain rich information through touch






- High-resolution details of the objects’ shapes
- Soft sensor enables a larger contact surface, not point contact
- The dynamic change of the tactile image is informative

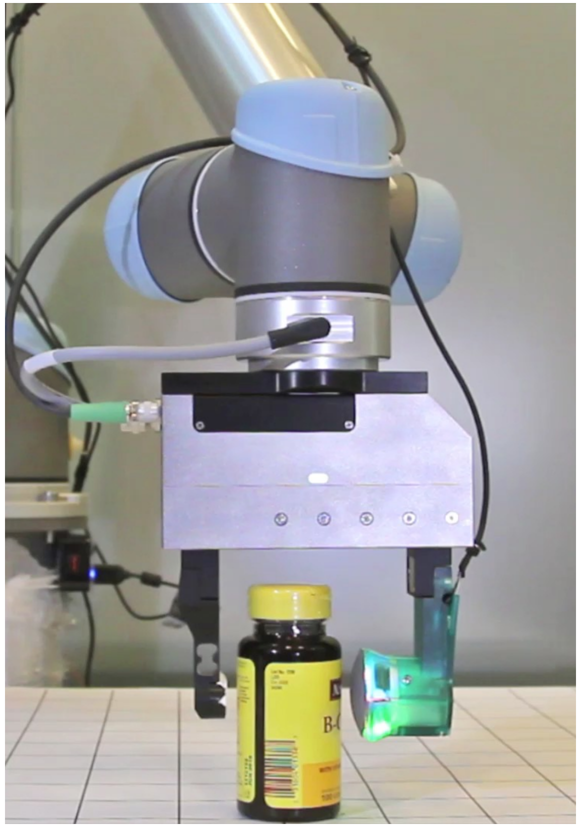


# Robot grasping

The most common task for robots

Figure from https://www.therobotreport.com/smart-grasping-demonstrated-at-automate-and-promat-trade-shows/

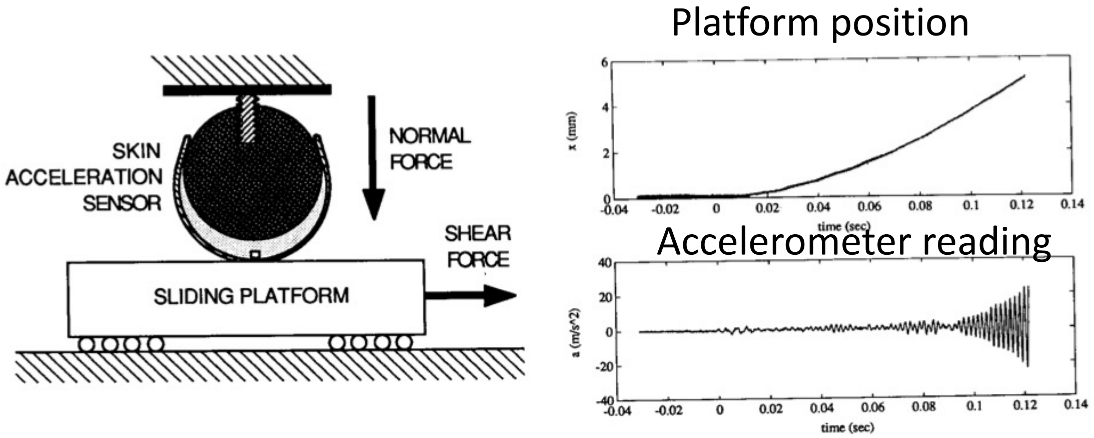
# Is the grasp successful?




daily objects with different weight and shapes

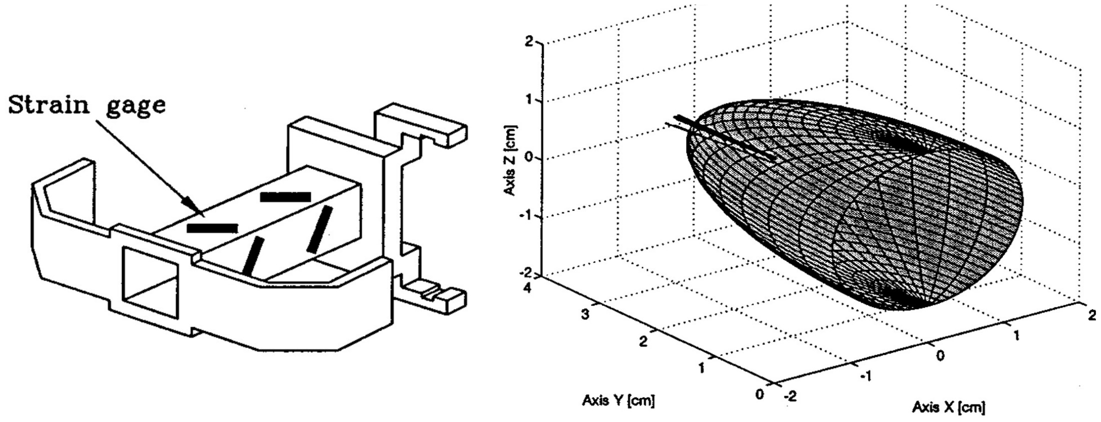
Most commonly seen grasp failure: slip

# Traditional ways to detect slip




Detecting slip from vibration detection

Howe and Cutkovsky. 1989

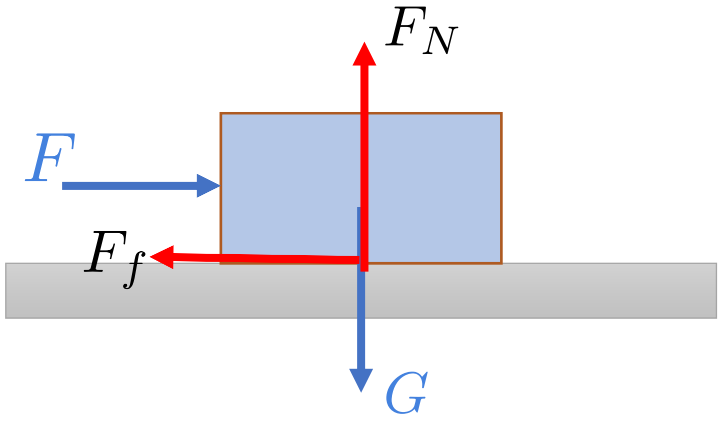



Detecting slip based on force and friction cone

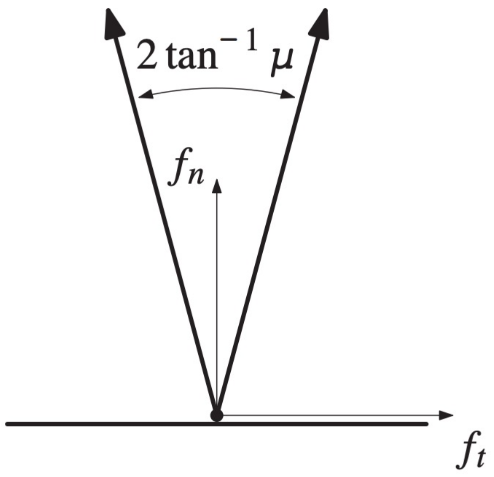
Melchiorri. 2000

# Coulomb Friction

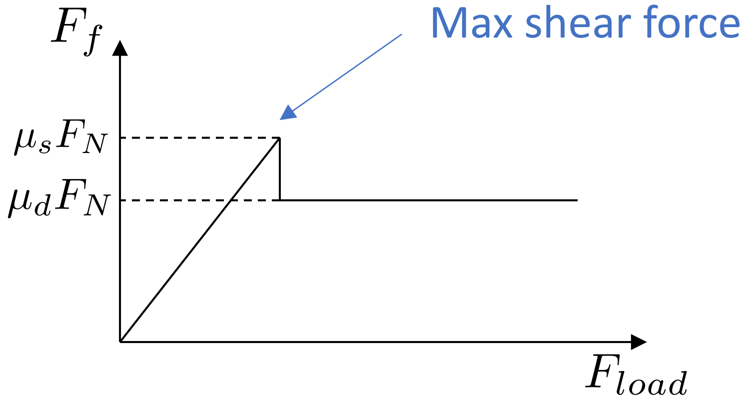
$$F_f = \mu F_N$$




- To be safe, there should be $F_f \leqslant \mu F_N$

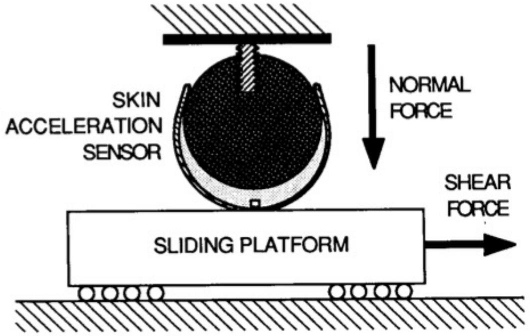



Friction cone

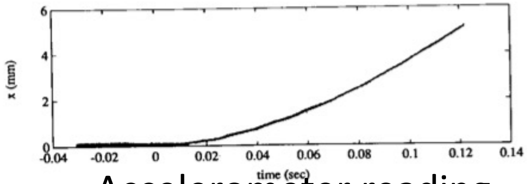



Avoid slip: measuring the normal force and shear force, and make sure the resultant is within the friction cone.

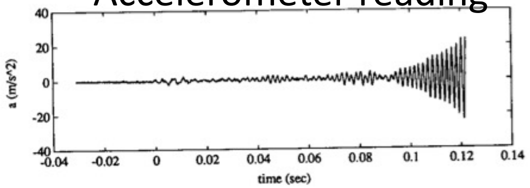
# Traditional ways to detect slip




Platform position

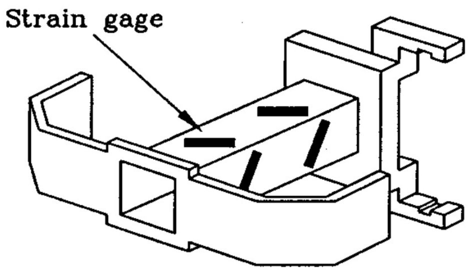


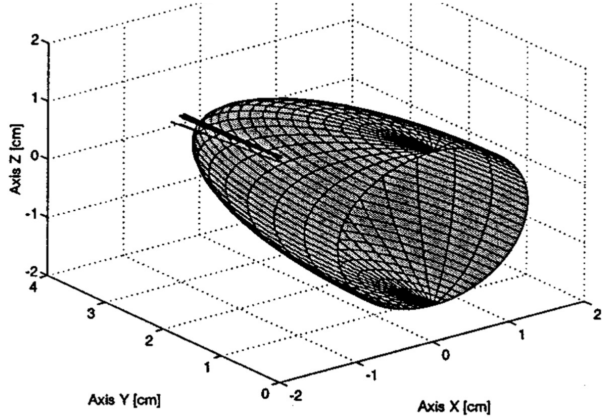

Accelerometer reading




Detecting slip from vibration detection

Howe and Cutkovsky. 1989

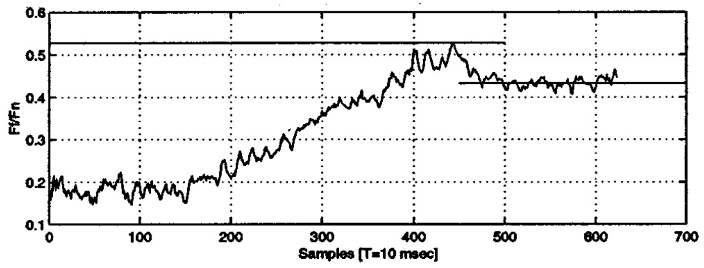



Detecting slip based on force and friction cone

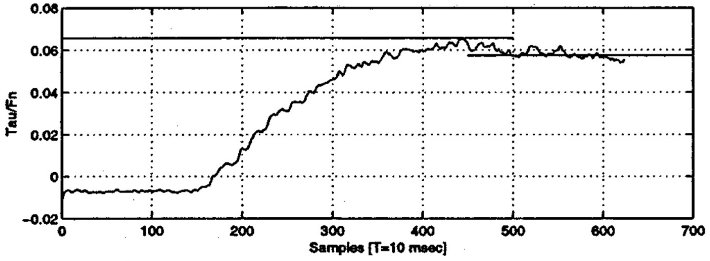
Melchiorri. 2000

Translational load




(a)

Rotational load



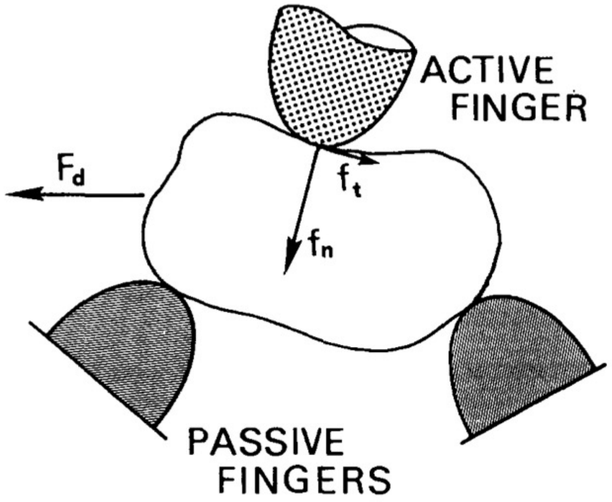

(b)

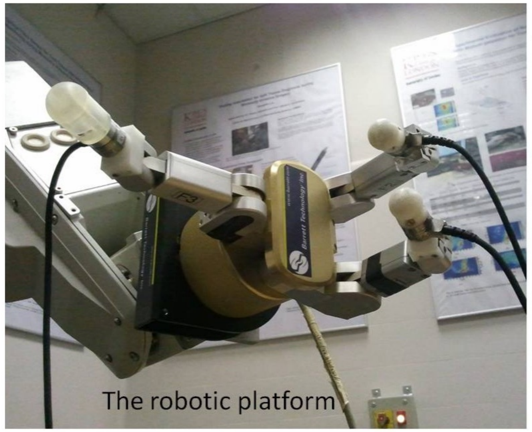
## Biggest challenge: generalization

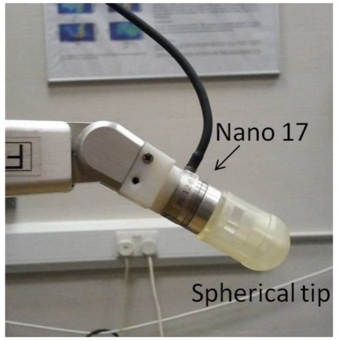
What if objects are of unknown shapes and unknown surface properties?

# Grasp based on force closure

- Multi-finger gripper
- Sensors: “intrinsic tactile” sensing
  - 6-axis force/torque sensor at the fingertips
- Based on force closure, intrinsic tactile sensing is able to completely characterize a soft-finger type contact
  - Detect the position of the contact centroid on the fingertip
  - The components of the normal and shear contact force, and the torque generated by friction
  - Based on the assumption of (almost) point contact



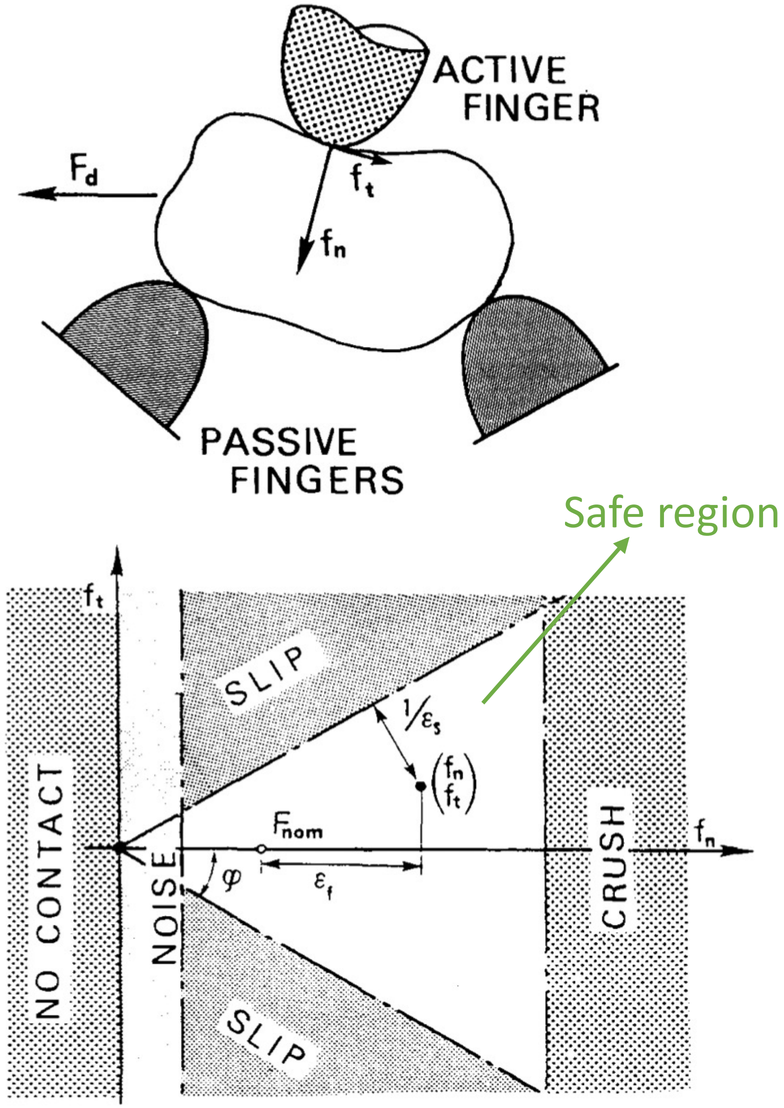




Liu, Song, Bimbo, et al. 2012

Antonio Bicchi, Kenneth Salisbury, and Paolo Dario. “Augmentation of Grasp Robustness Using Intrinsic Tactile Sensing”. 1989

# Grasp based on force closure

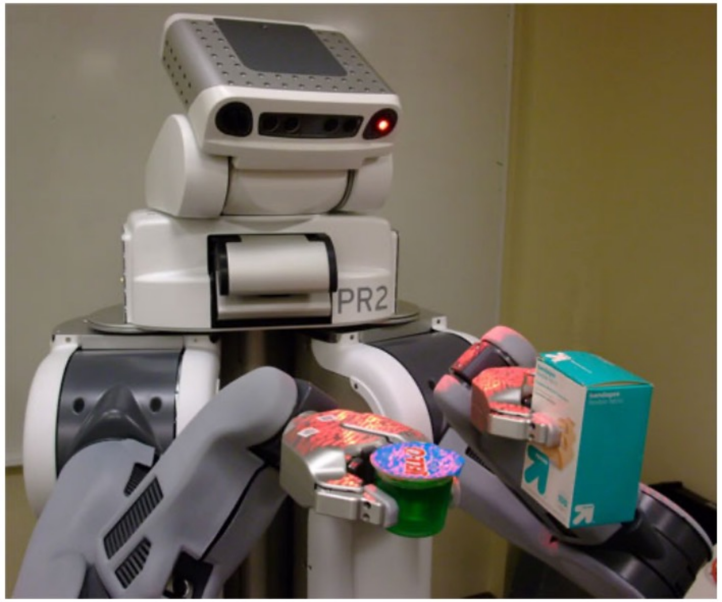
- Grasp
  - Described in terms of the number and the position of contacts between fingers and the object and the intensity and direction of forces and torques
  - Geometry & wrench
- Force-closure
  - Capable of equilibrating any external force tending to move the object
- Force should be large enough to prevent slip, and not too large to crash objects
  - Assuming the friction coefficient is known with some approximation

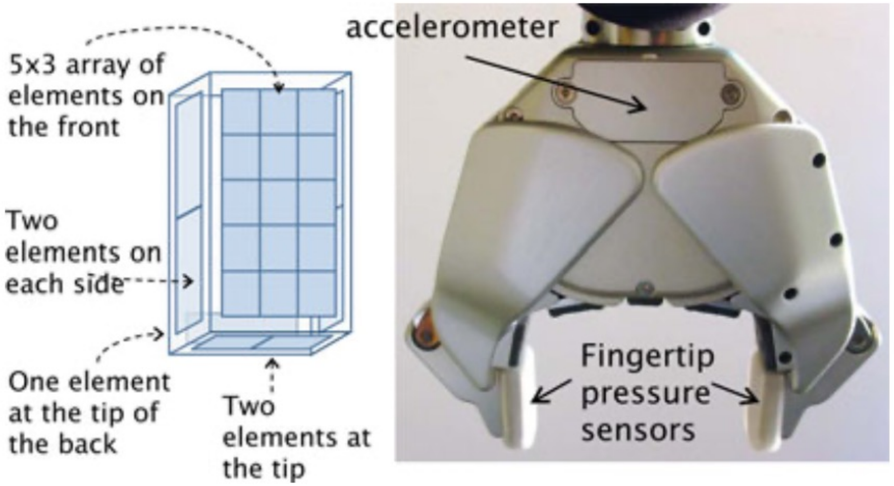



Antonio Bicchi, Kenneth Salisbury, and Paolo Dario. “Augmentation of Grasp Robustness Using Intrinsic Tactile Sensing”. 1989

# Tactile sensing for grasping

- Goal: secure grasp
  - Not too large force to crash objects
  - Not too small force to make objects slip
- Infrastructure
  - Arm + parallel gripper
  - 5x3 tactile array on the fingertip
  - Accelerometer on the fingertip




Romano, Hsiao, Niemeyer, Chitta, and Kuchenbechker. “Human-inspired robotic grasp control with tactile sensing. 2011


https://www.youtube.com/watch?v=02NNX1dGK68

# Grasping with proper force: using thresholds

Low frequency force (SAI)

High frequency force (FAI)

Detecting contact:

$$\text{LeftContact} = (F_{gl} > \text{FLIMIT}) \,\|\, (\widetilde{F}_{gl} > \text{DLIMIT})$$

$$\text{RightContact} = (F_{gr} > \text{FLIMIT}) \,\|\, (\widetilde{F}_{gr} > \text{DLIMIT}).$$

(Hand vibration is not helpful)

Hand tuned

Grasping force:

$$F_c = \max_t(F_g) \cdot \frac{\text{KHARDNESS}}{\text{VCLOSE}}$$

Slip detection:

$$\text{Slip} = (|\widetilde{F}_g| > F_g \cdot \text{SLIPTHRESH}) \;\&\&\; (F_g^{BP} < \text{FBPTHRESH})$$

Slip control:

$$F_c = F_c \cdot \text{KSLIP}.$$

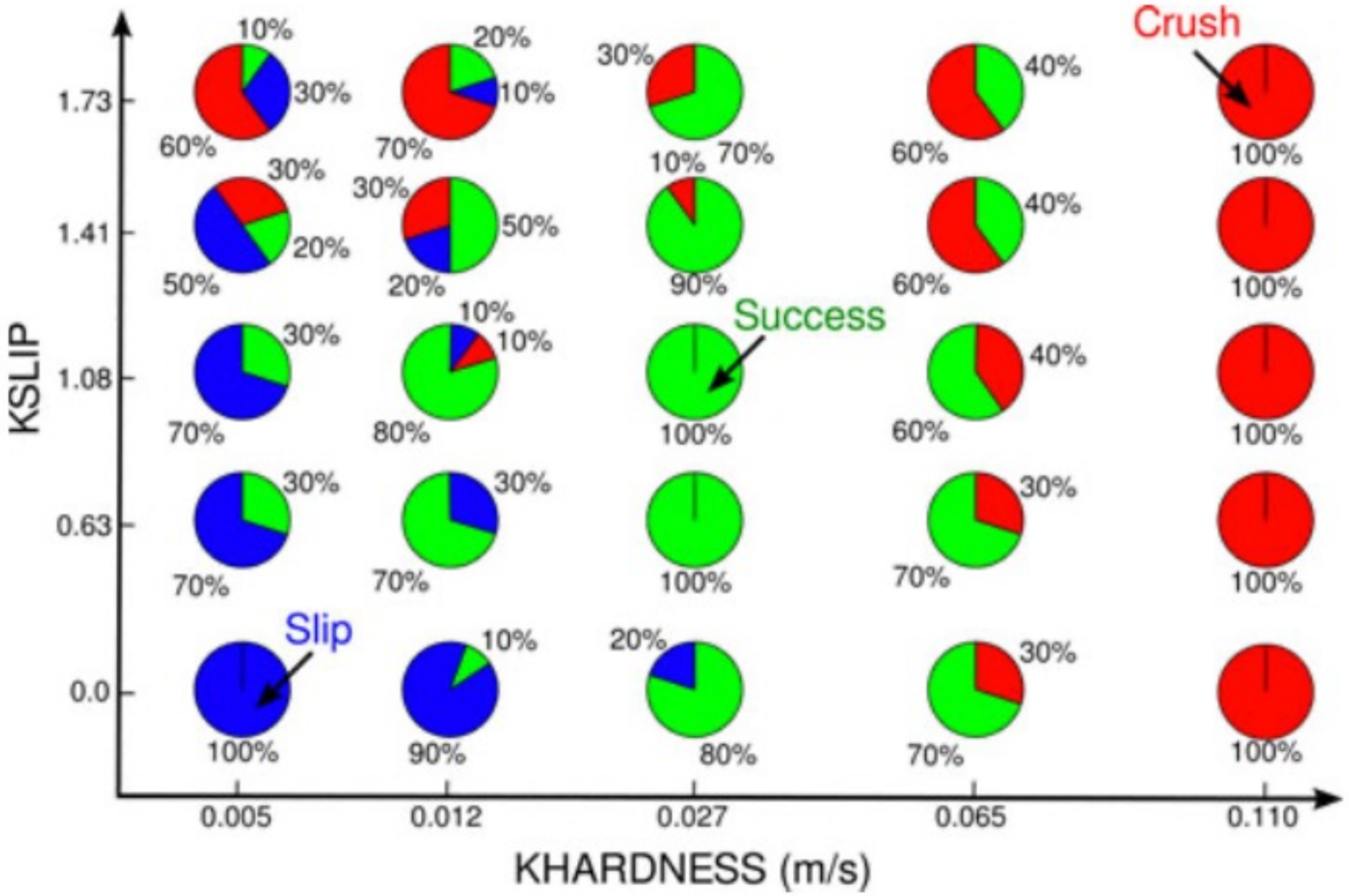
Increasing gripping force when slip is detected

# Parameter Tuning –by experiments

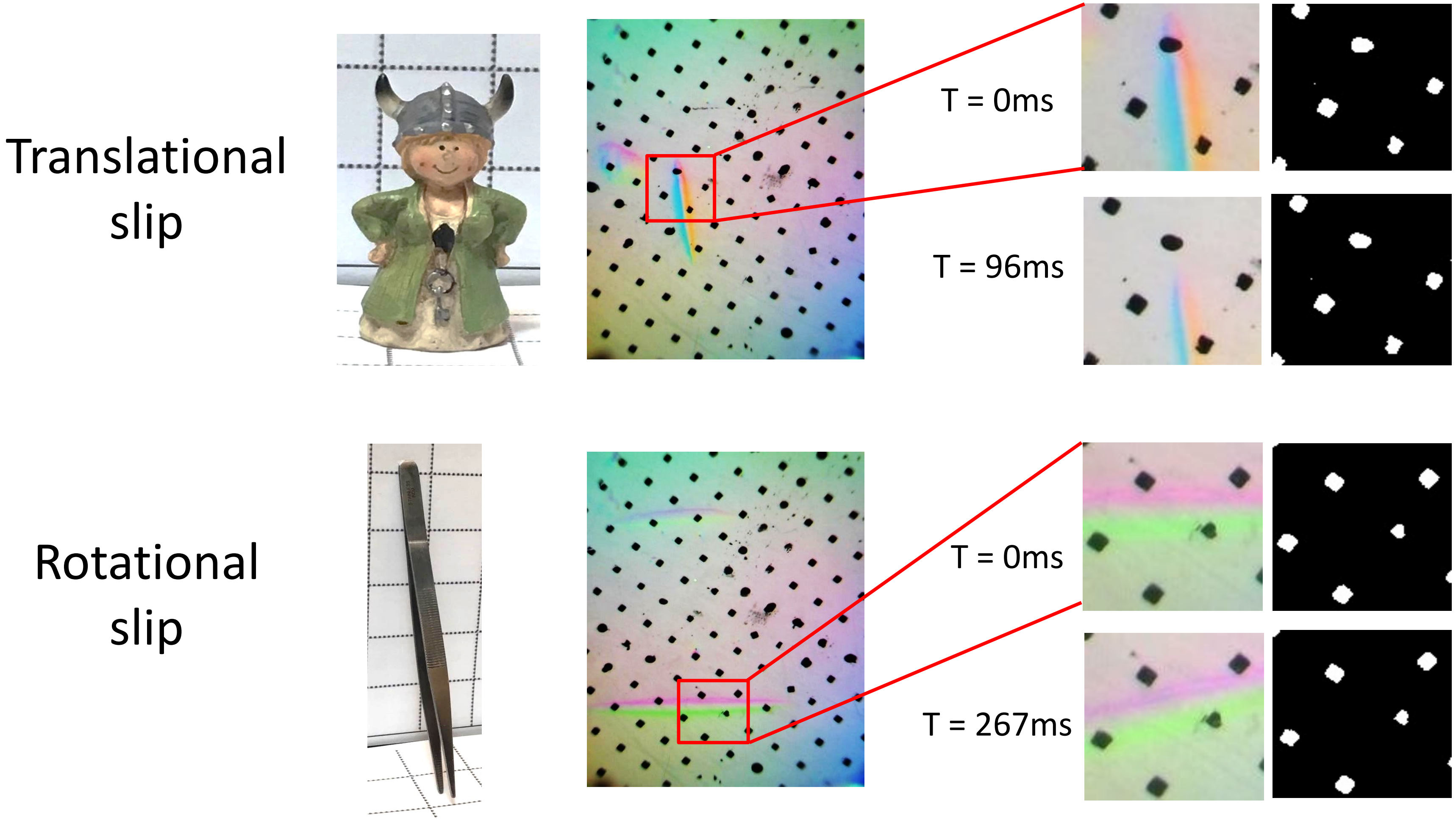
KHARDNESS, KSLIP

Prevent crushing (small KHARDNESS)
Prevent slip (large KSLIP)

Different thresholds for different objects



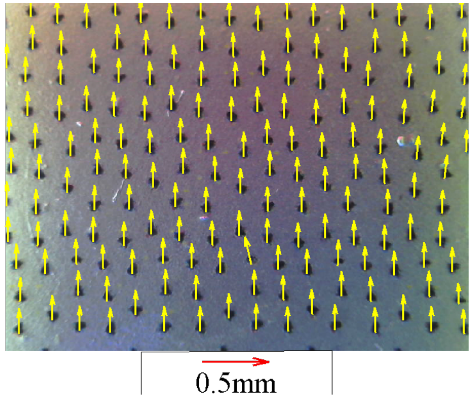
# Slip detection for objects with obvious textures: comparing the motion of the object and the sensor surface



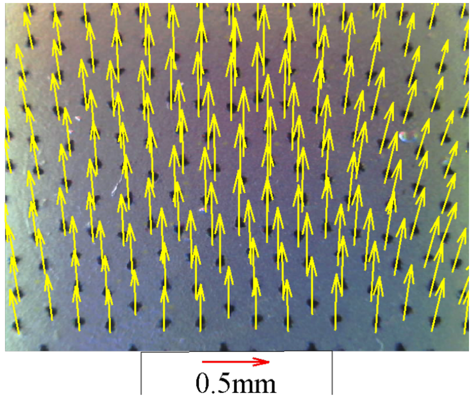

Dong, Yuan, Adelson. IROS, 2017.

# Slip detection for objects with flat surface: comparing the distortion of the marker motion field

Under small load

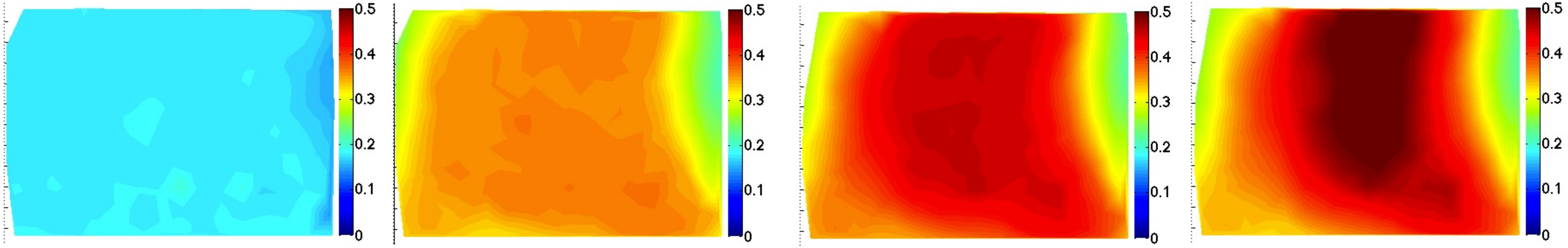



Under large load




Slip occurs from the peripheral contact area, causing an uneven distribution of the motion of the markers

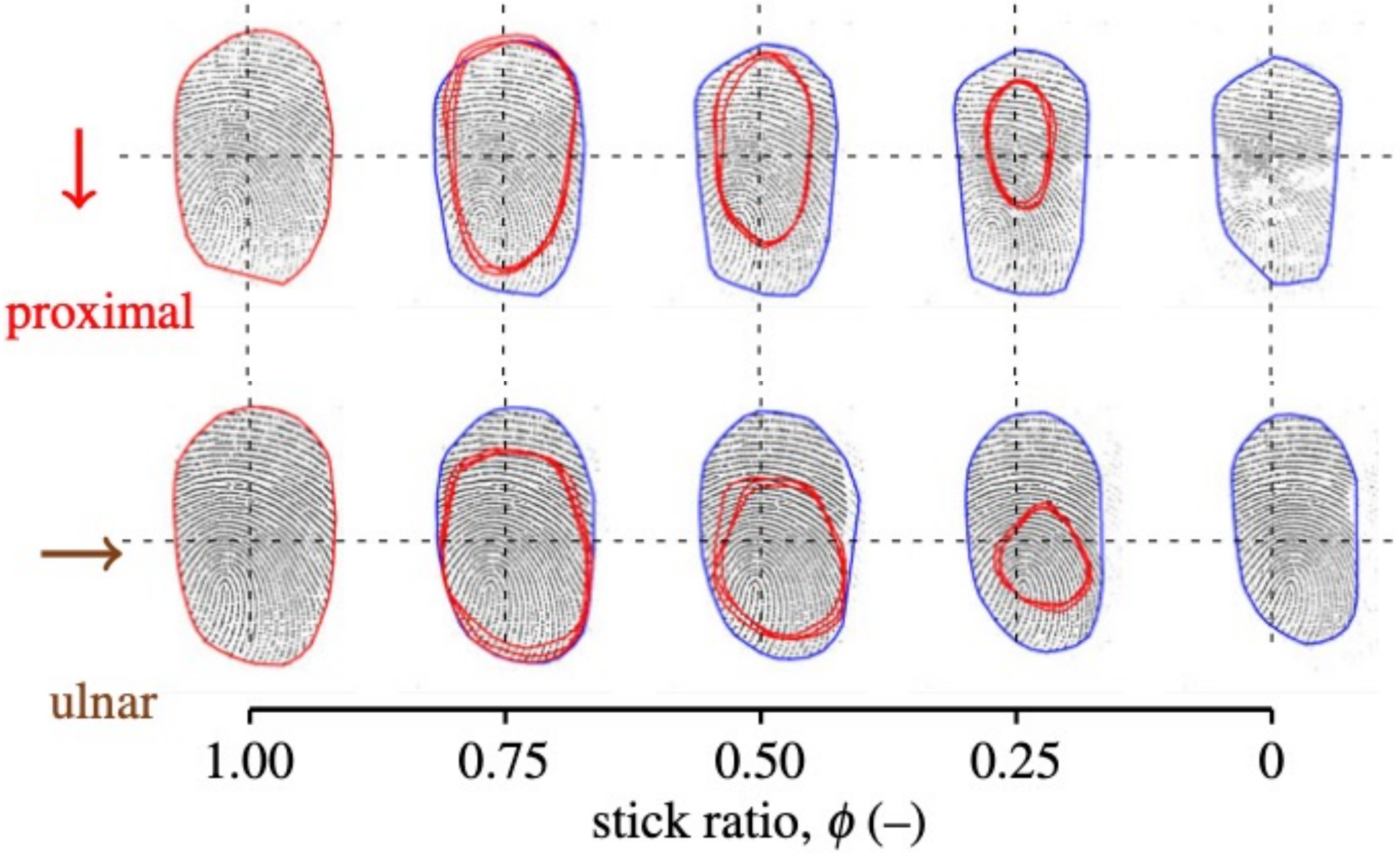
Magnitude of displacement




Load increases

Yuan, Li, Srinivasan, Adelson. “Measurement of shear and slip with a GelSight tactile sensor” 2015.

# Lessons from humans: incipient slip starts at the boundary

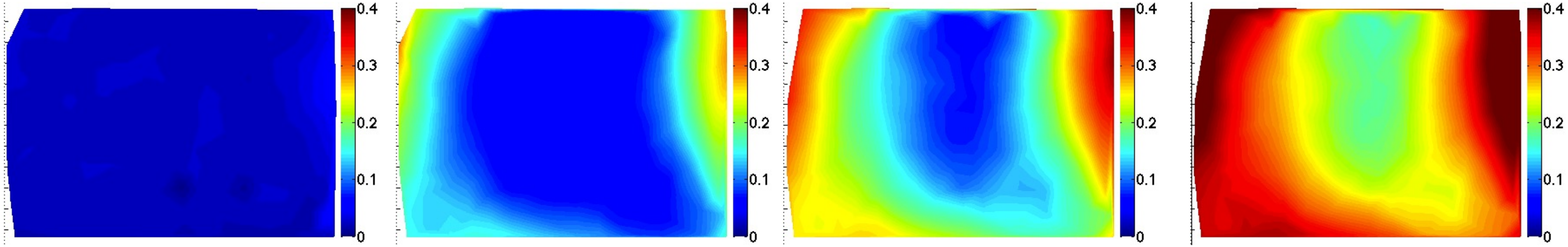



Blue contours: contact area
Red contour: stuck area

Delhaye, Lefevre, and Thonnard. "Dynamics of fingertip contact during the onset of tangential slip." 2014.

# Measuring the relative displacement

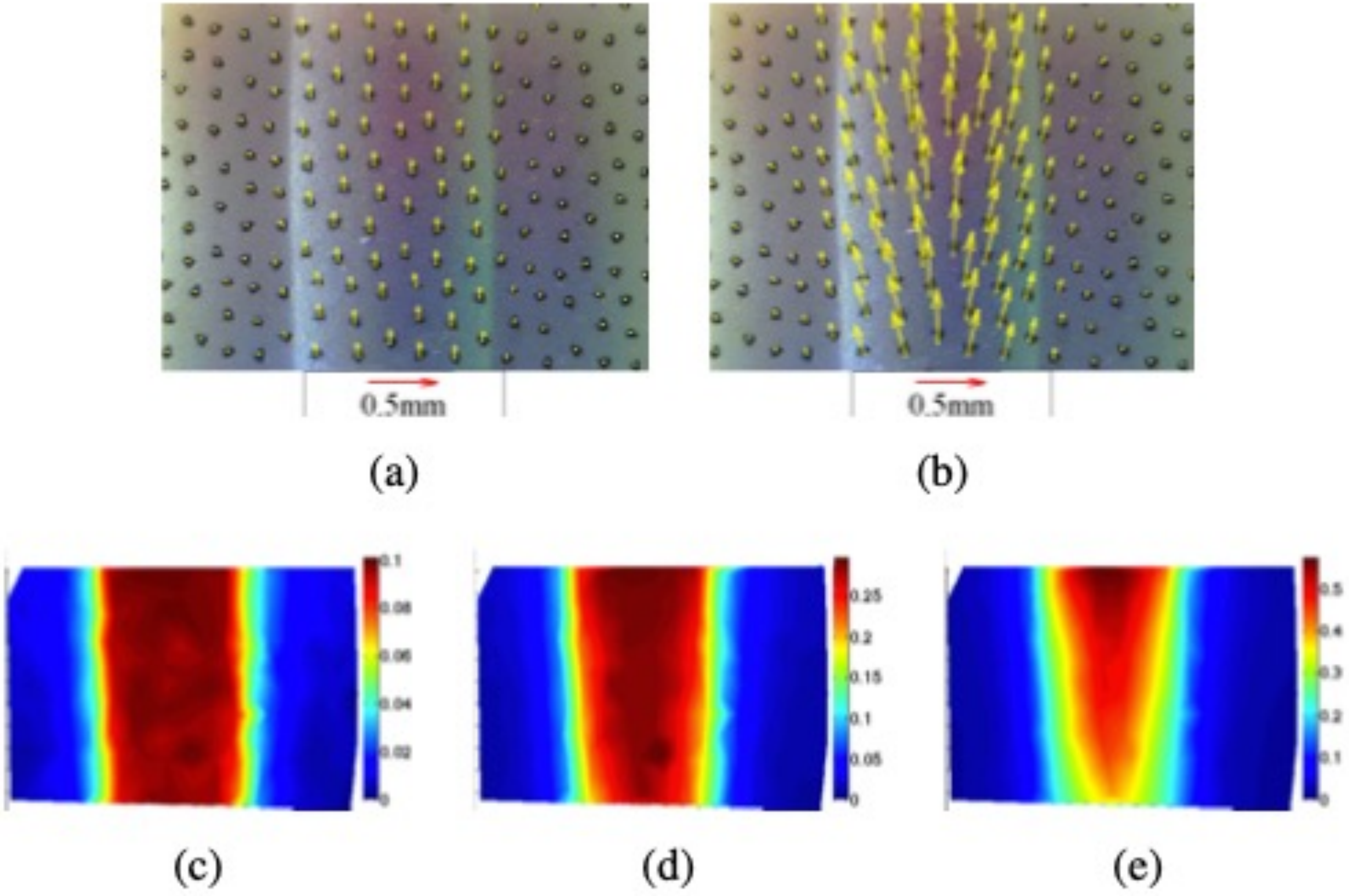
$$||\vec{d_i}|| - ||\vec{d_o}||$$




| Small load | Larger load | Large load | Very large load |
|---|---|---|---|
| Shear state | Partial Slip | Incipient slip | Slip |

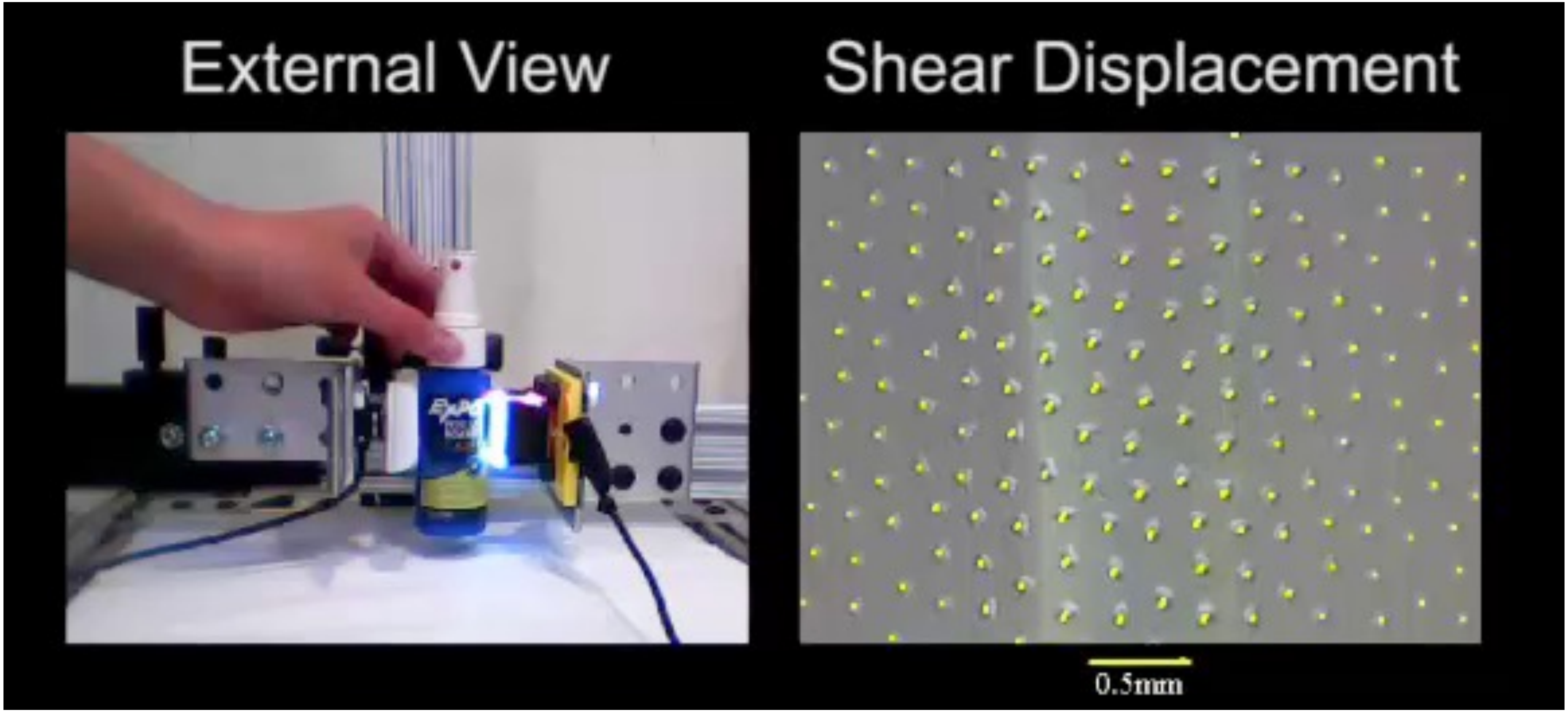
$\vec{d_i}$ : Displacement vector of a local point
$\vec{d_o}$ : Displacement vector of the indenter

# Slip detection for objects with non-flat surface

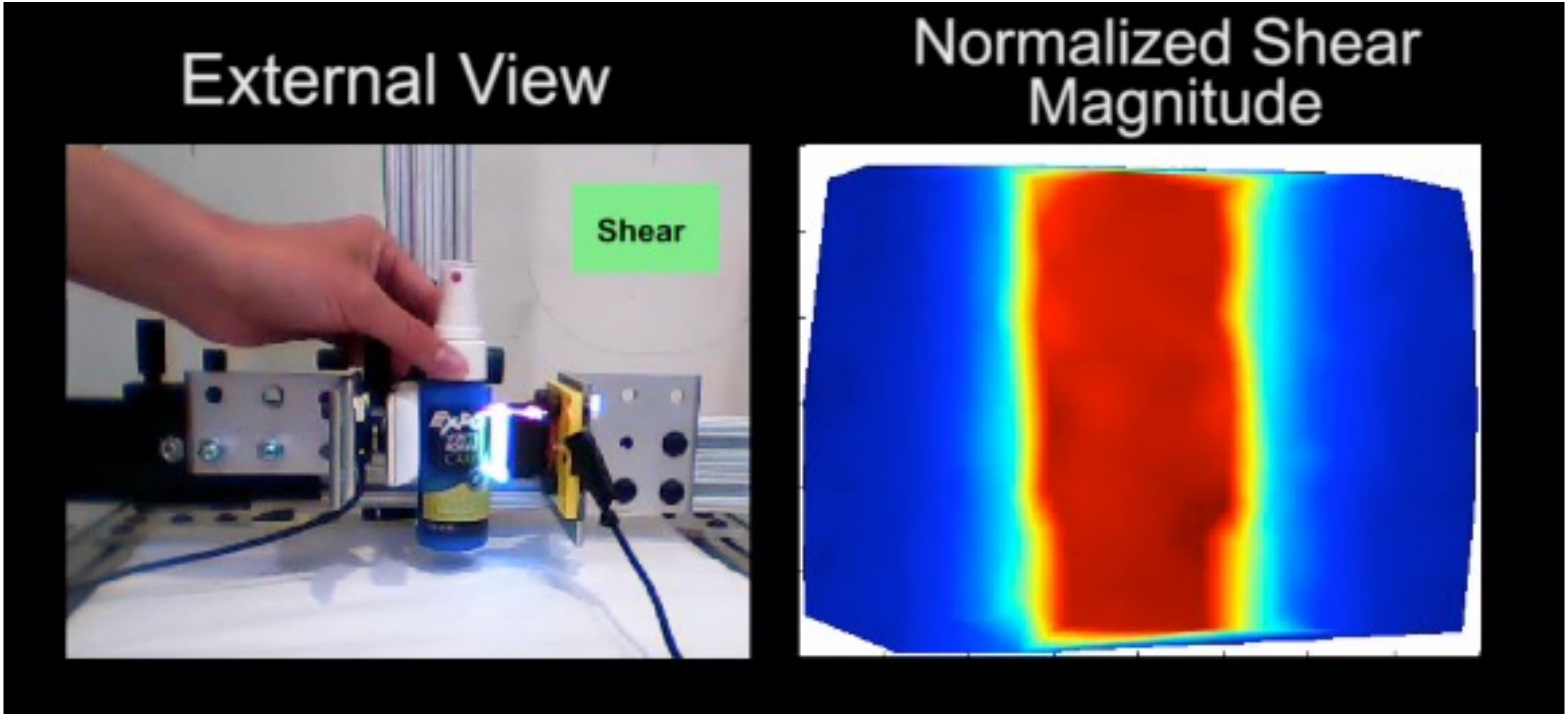



- Similar distribution patterns
- The normal pressure near the edges are usually smaller

# Slip detection for objects with flat surface: comparing the distortion of the marker motion field



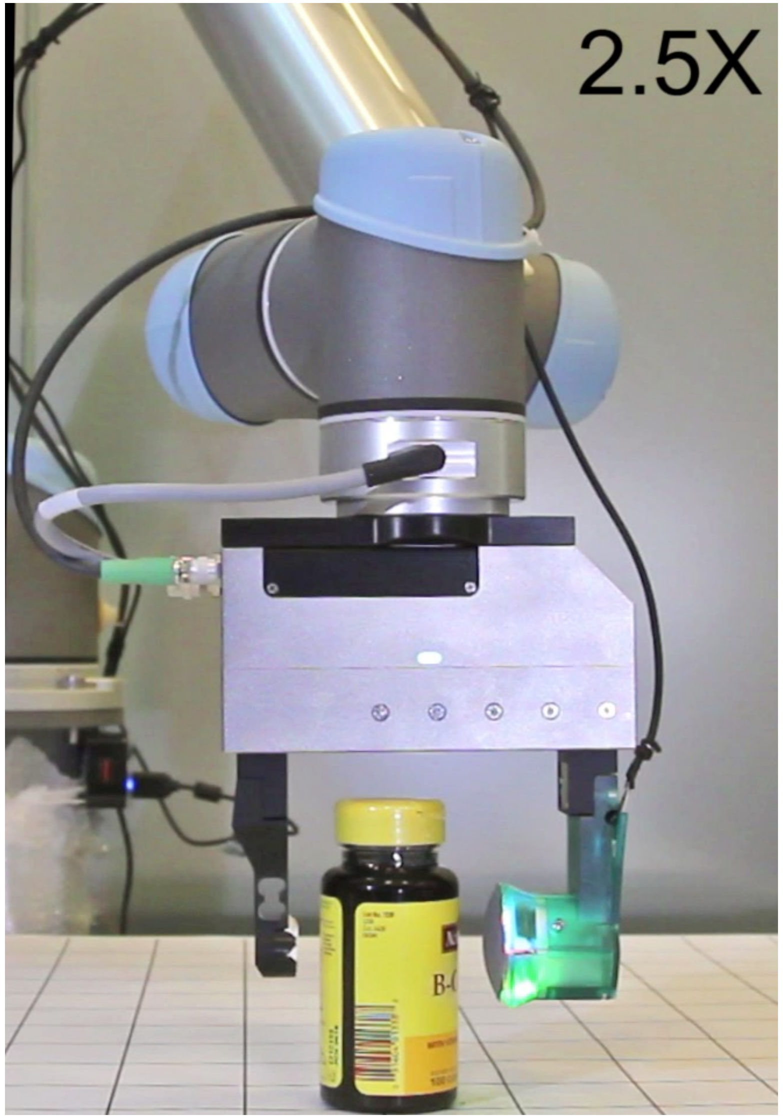
# Slip detection for objects with flat surface: comparing the distortion of the marker motion field



# Slip detection: combining two measurement for different objects

Grasp prediction result on 37 natural objects:

| | No slip | Slip |
|---|---|---|
| Test number | 147 | 116 |
| Prediction accuracy | 79% | 84% |




Closed-loop grasp control:

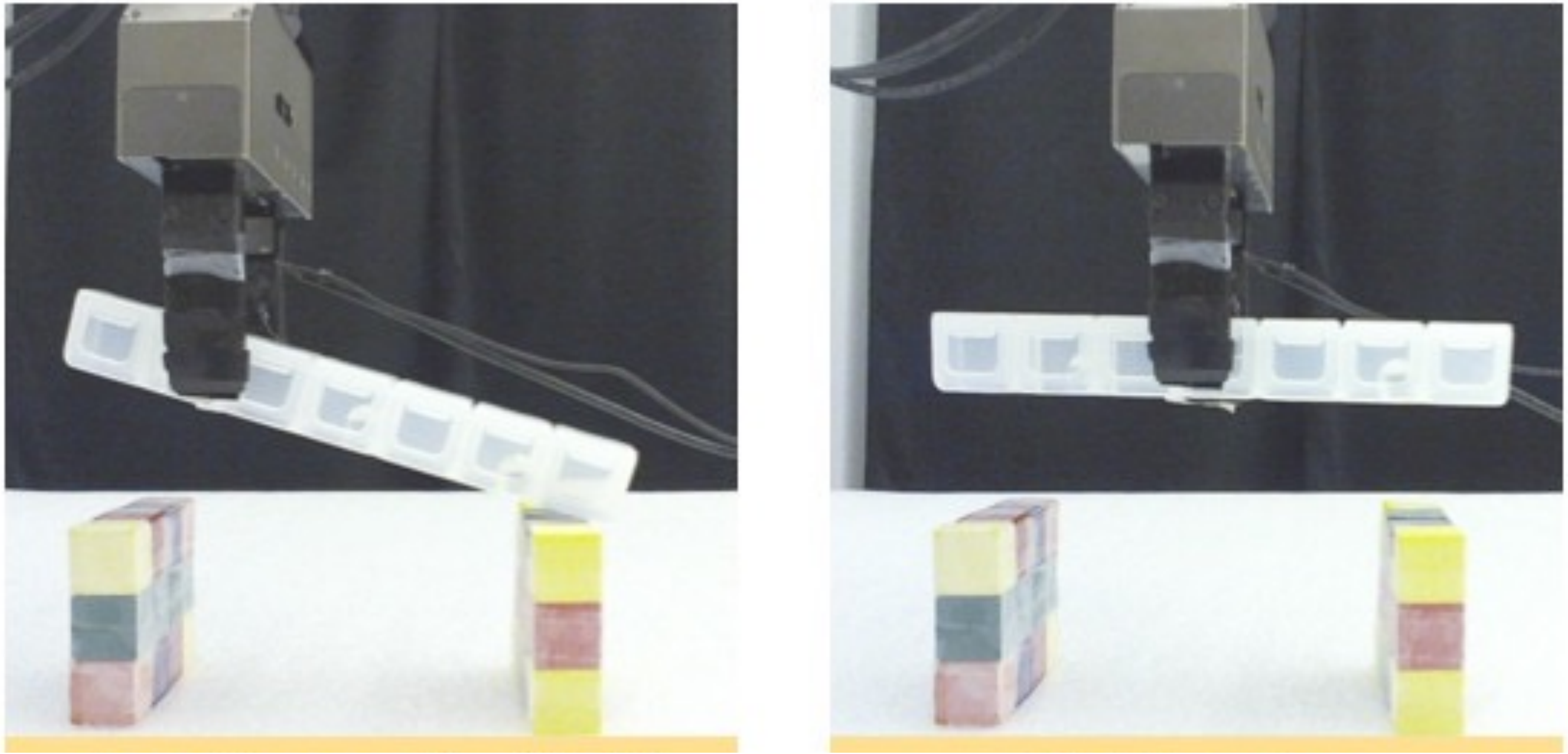
When slip is detected, release and re-grasp the object, with larger force

Result:

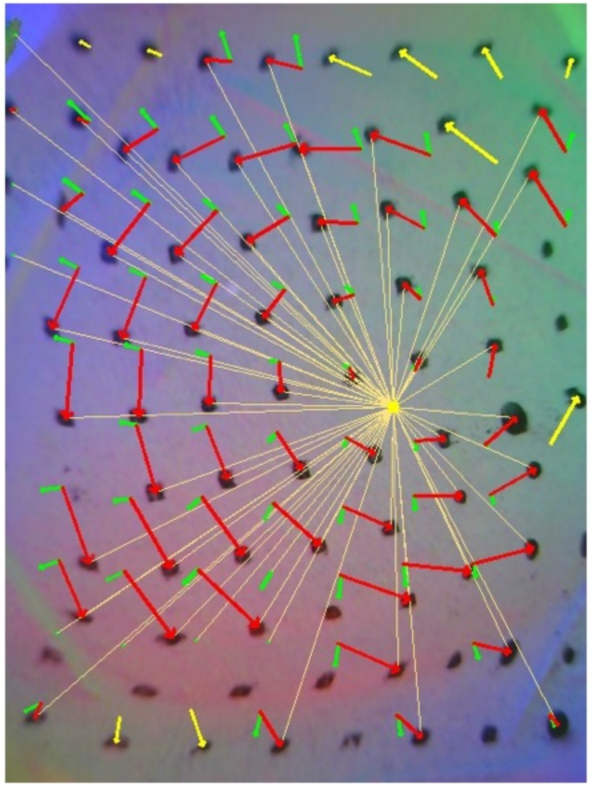
Out of 99 grasp experiments, the robot succeeded in 89% of the cases

Dong, Yuan, Adelson. IROS 2017.

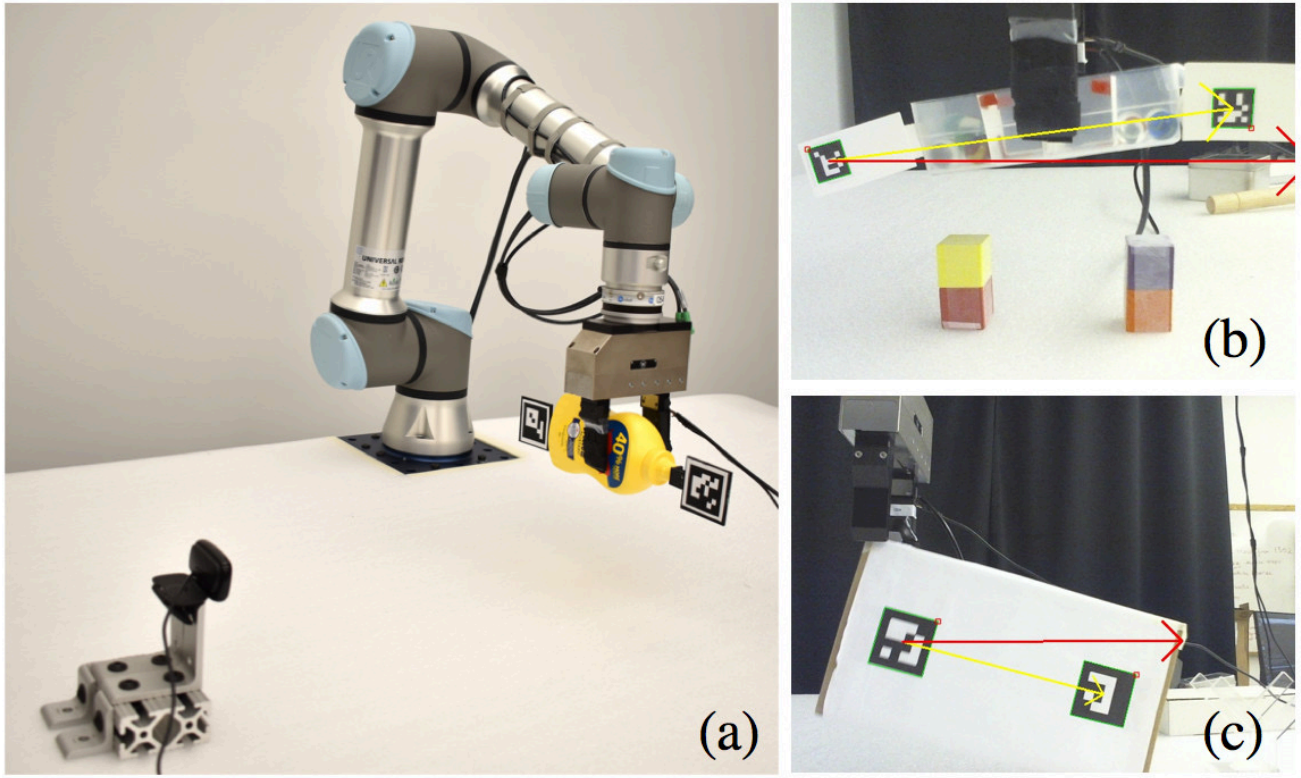
# Rotational grasp failure



# Measuring the big torque cases



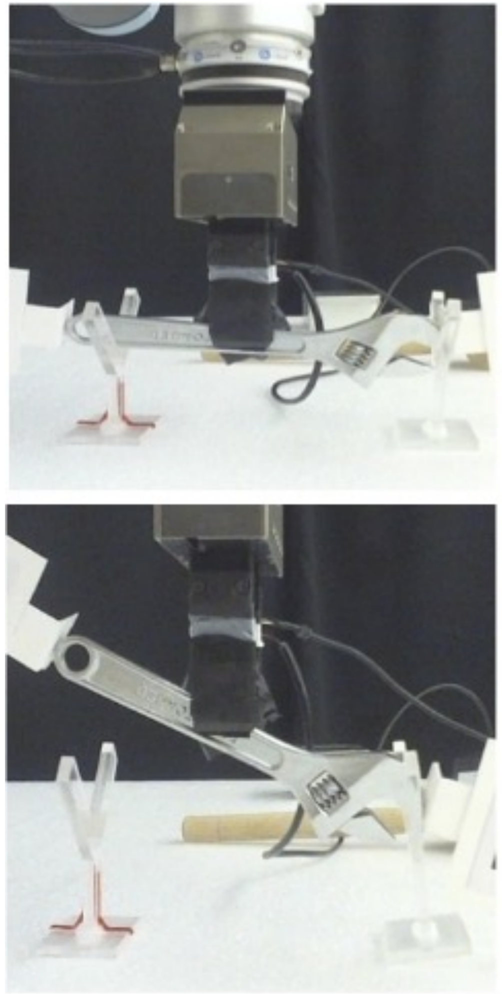
Measuring the rotation angle of markers on GelSight



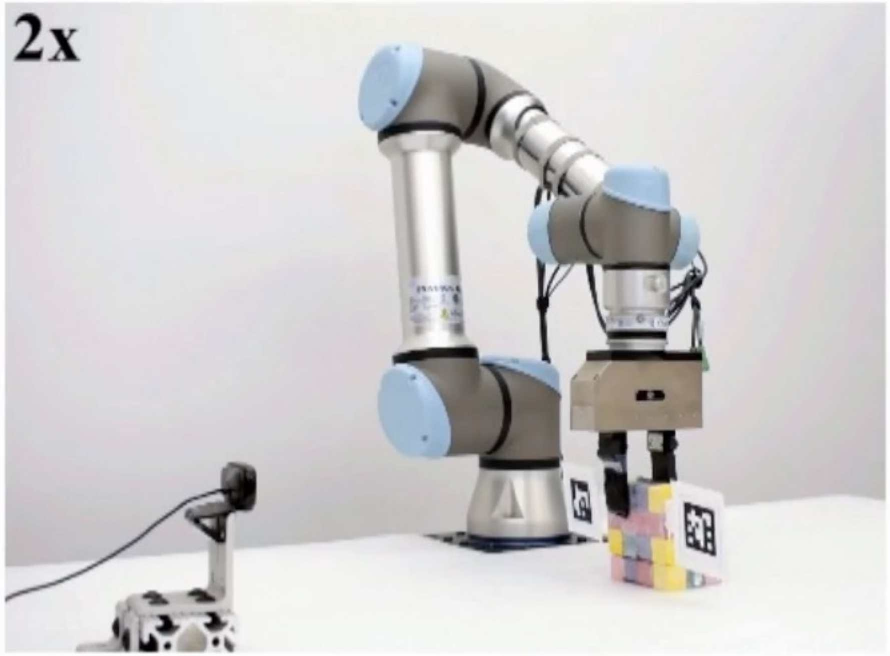

Ground-truth of object rotation from an external camera

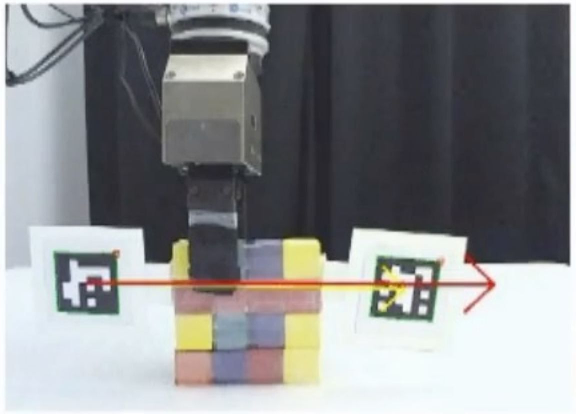
# Rotation detection with texture-rich obiects

External view

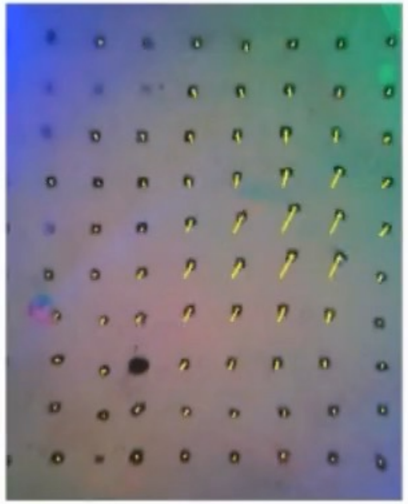


Kolamuri*, Si*, Zhang, Agarwal and Yuan. IROS 2021.

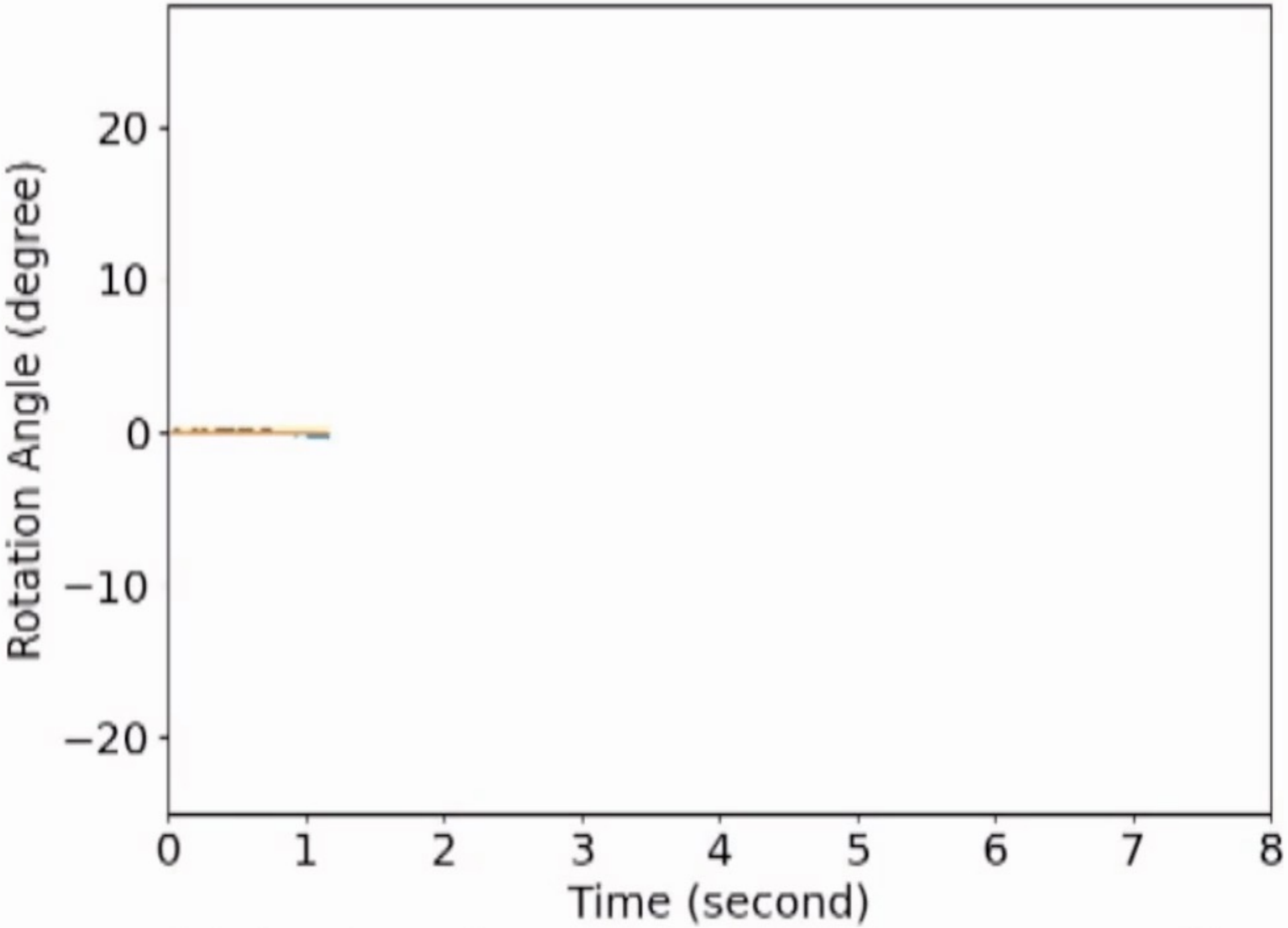


Processed Side View



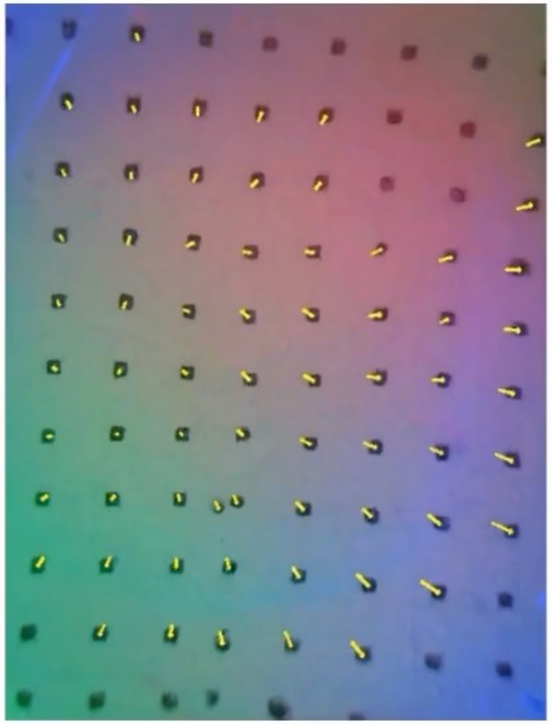
Gelsight image



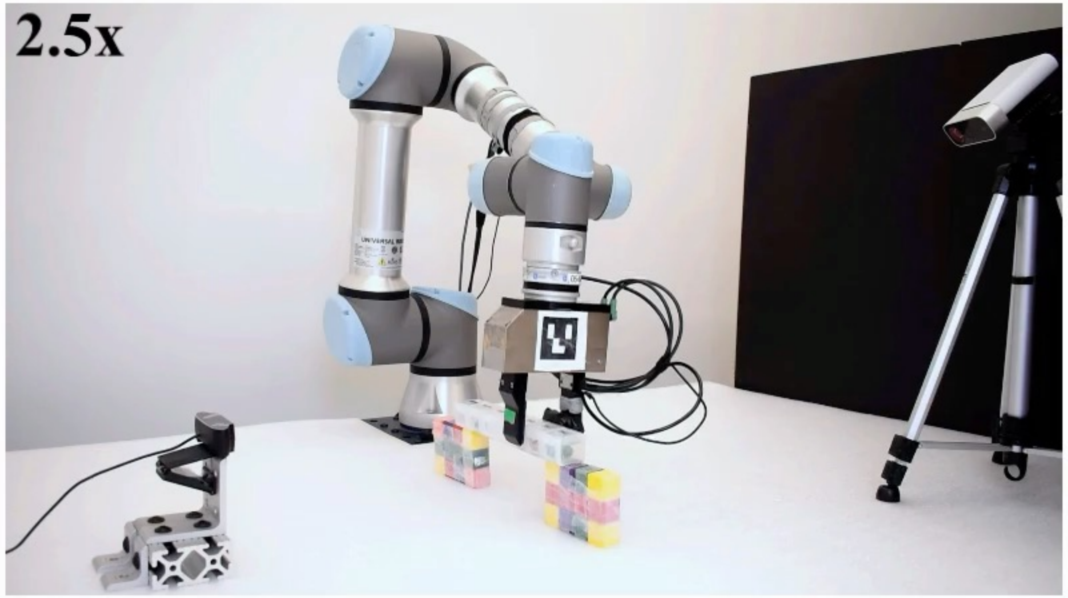

**Calculated rotation angle vs ground truth**

The rotation angles from Gelsight's images are compared with the ground truth from the processed side view.

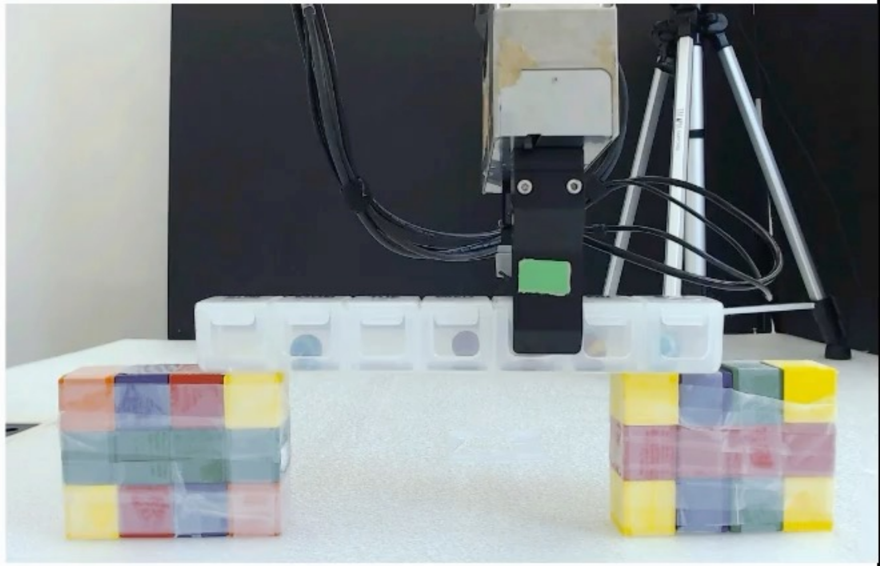
# Closed-loop re-grasping by adjusting grasping locations



Angle: −3.53
Orientation: CW




External View

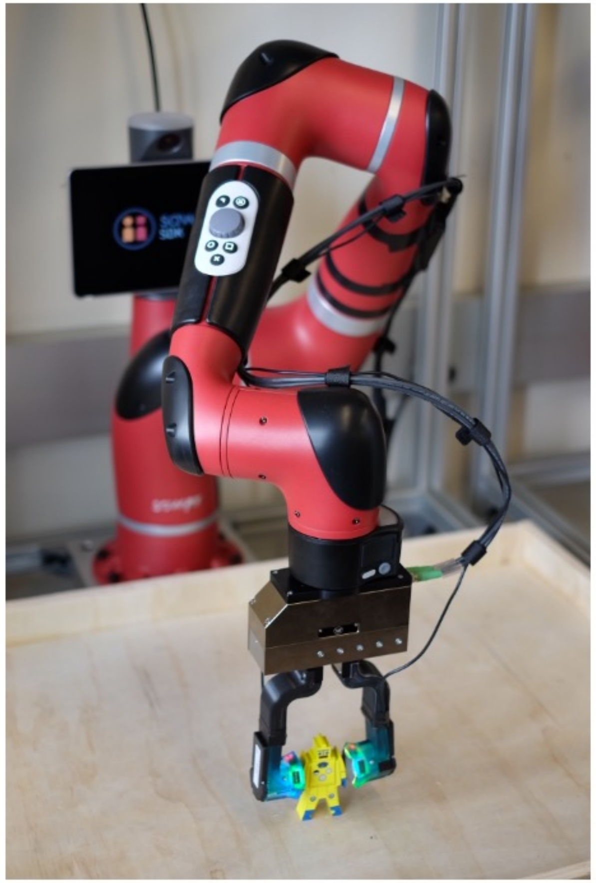


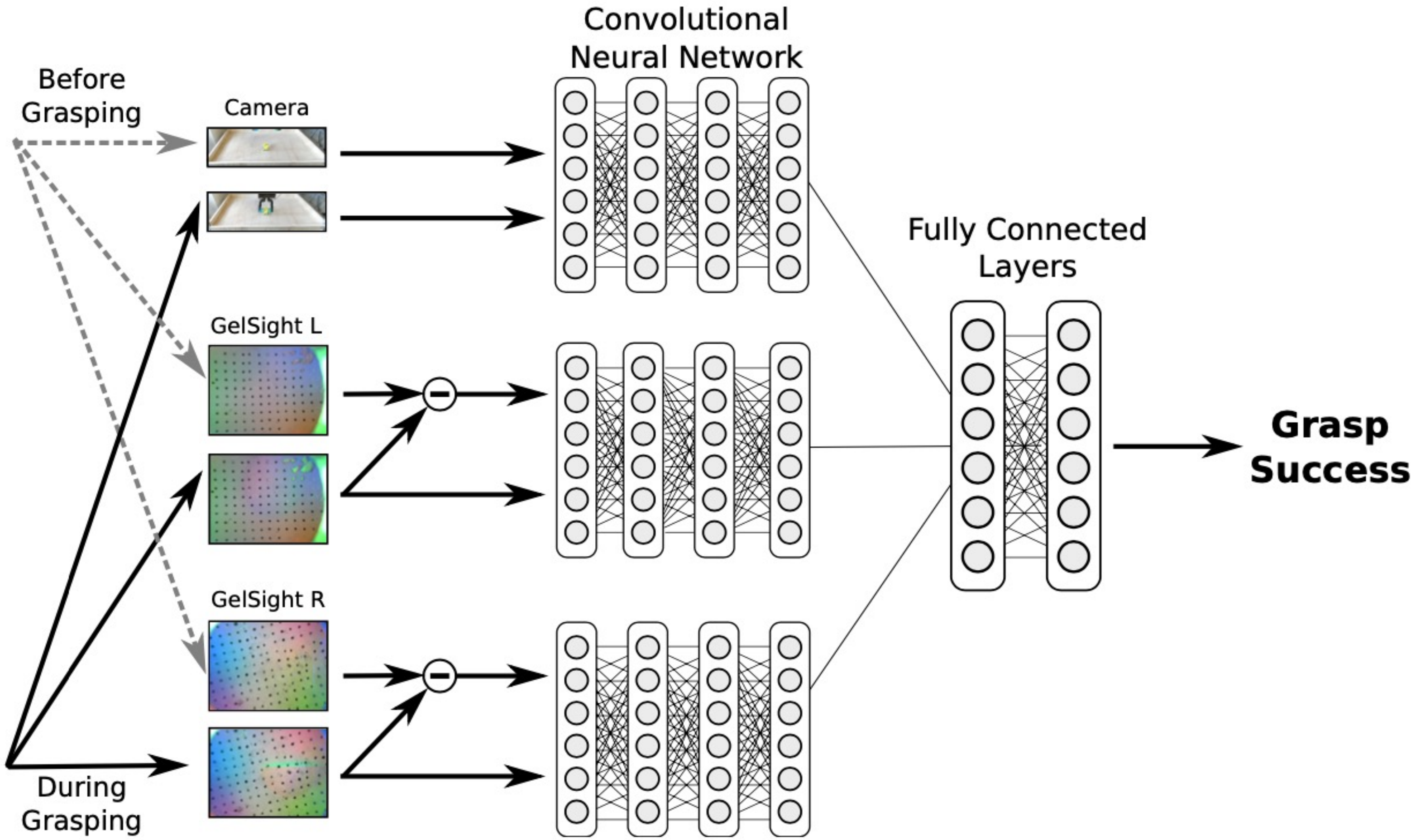
Side View



Kolamuri*, Si*, Zhang, Agarwal and Yuan. IROS 2021.

# Data-driven approach for grasping






Dataset: 9269 grasping trials from 106 unique objects

Calandra, et al. "The Feeling of Success: Does Touch Sensing Help Predict Grasp Outcomes?." 2017.