High Resolution Tactile Sensing for Robotics, Metrology, and Medicine

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brain+cognitive sciences

The inspiration.

I’m a vision guy, but my baby girls convinced me that touch is really important.

How to understand the contact interactions of a soft finger and a real world object?

- It's hidden; you can't see it.
- Solution: an artificial soft finger that is *itself* a precision measuring instrument.
- Optical approach: put a camera inside; view the skin from within.

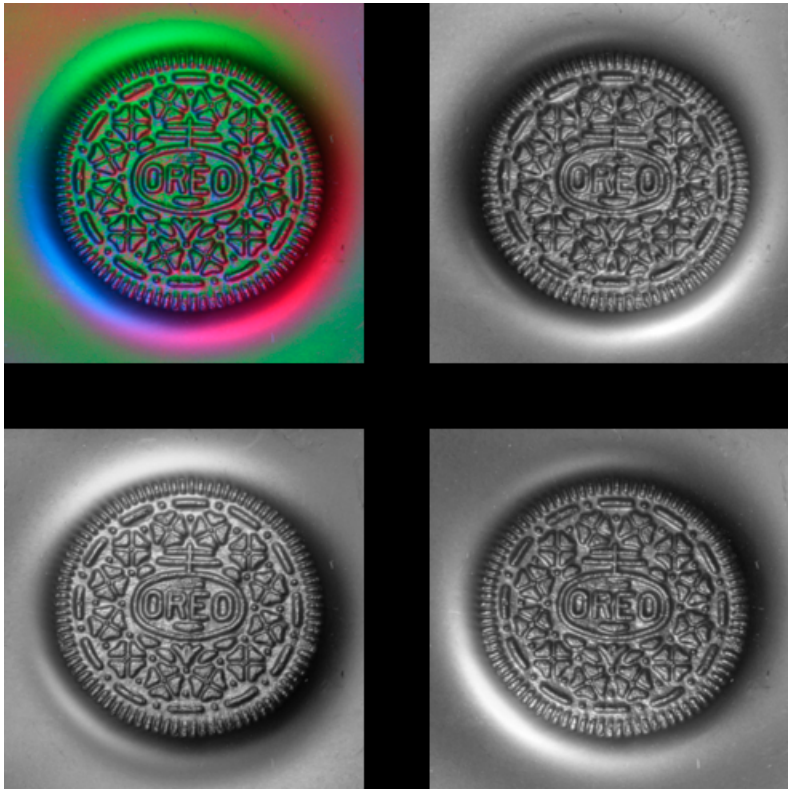
Goal: touch sensor that matches or exceeds human fingertip

- **Compliance:** to conform to objects being grasped
- **Resolution** of fine details.
- **Sensitivity** to small forces.
- **Tangential** as well as normal force

Basic approach:
Convert pressure patterns to images

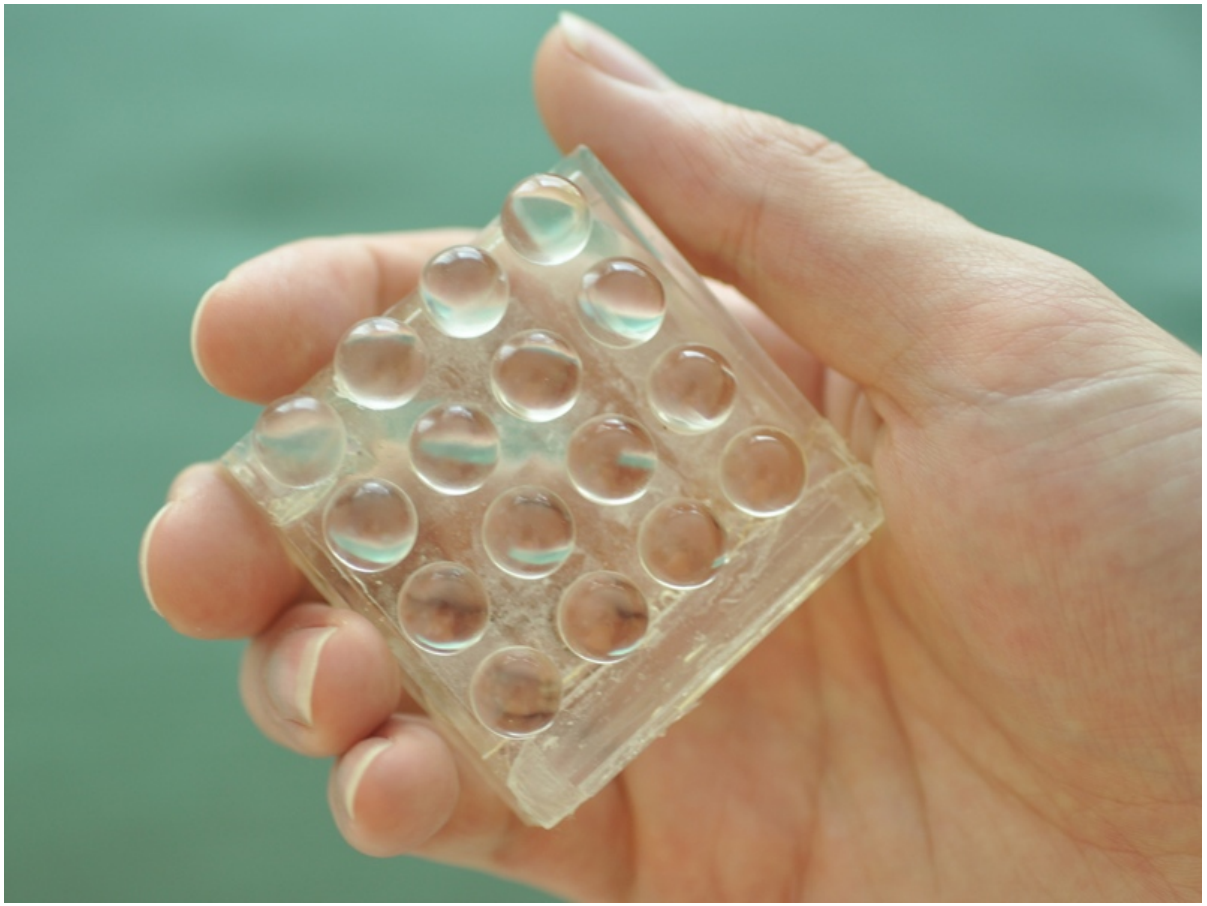
- Slab of clear elastomer
- Reflective “skin” (membrane)
- Membrane deformation yields a shaded image
- Computer vision infers shape, pressure, etc.

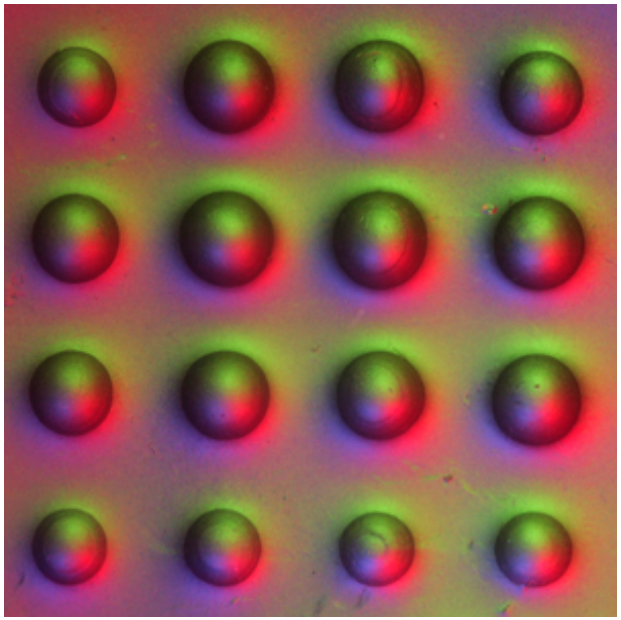
Use GelSight with computer vision to get height map, using photometric stereo.



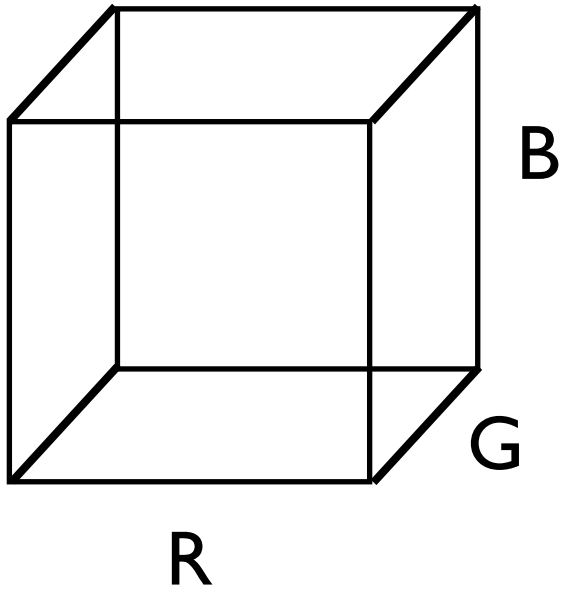
(Johnson & Adelson, CVPR 2009;
Johnson et al SIGGRAPH 2011).

Calibration





Lookup Table



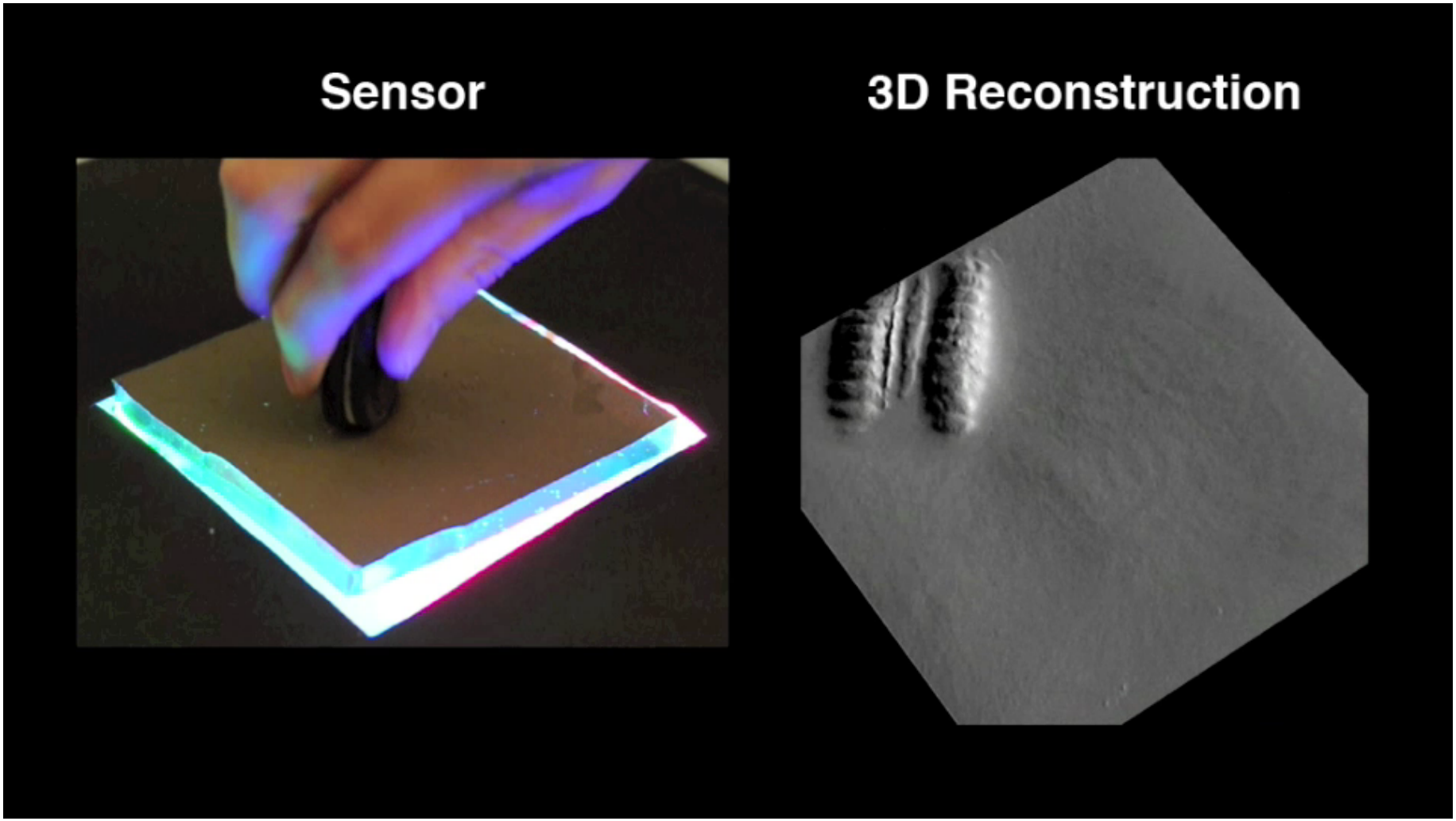
RGB color	Lookup	Gradient
(10,200,3)	→	(0,-0.3)
(200,10,3)	→	(0.2, 0.2)

Surface reconstruction:
Solve Poisson's equation by standard methods.

$$z = f(x, y)$$

$$E(z) = \sum_{x,y} \left(\frac{\partial f}{\partial x} - p \right)^2 + \left(\frac{\partial f}{\partial y} - q \right)^2$$

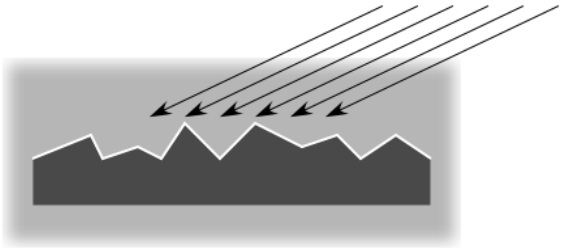
“Feel” the 3D shape in realtime

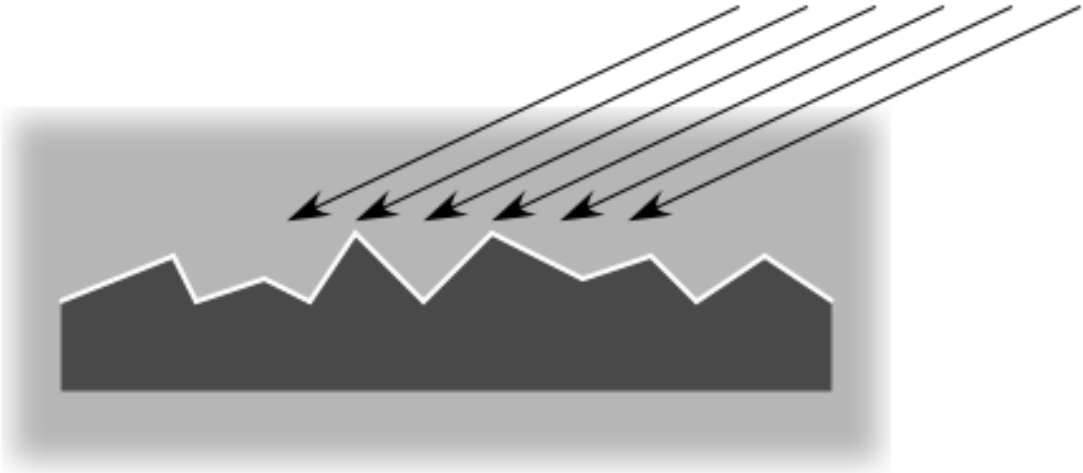


Optical methods for getting depth

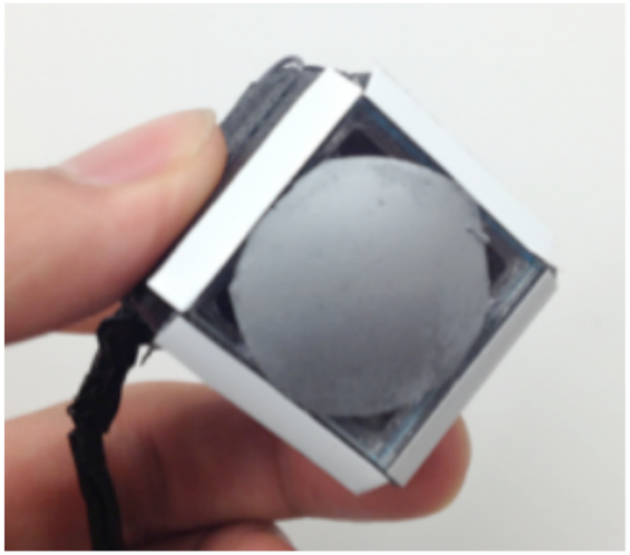
- **Triangulation** (including stereo, structured light, focus). Problems with specular, translucent, or transparent materials; i.e., everything interesting like metal, glass, skin, marble.
- **Interferometry.** Expensive, cumbersome.
- **Time of flight.** Not good for micro-scale.
- **Shading? (e.g., photometric stereo)** Nobody uses shading. It needs controlled BRDF and lighting.
- We use shading (mostly).

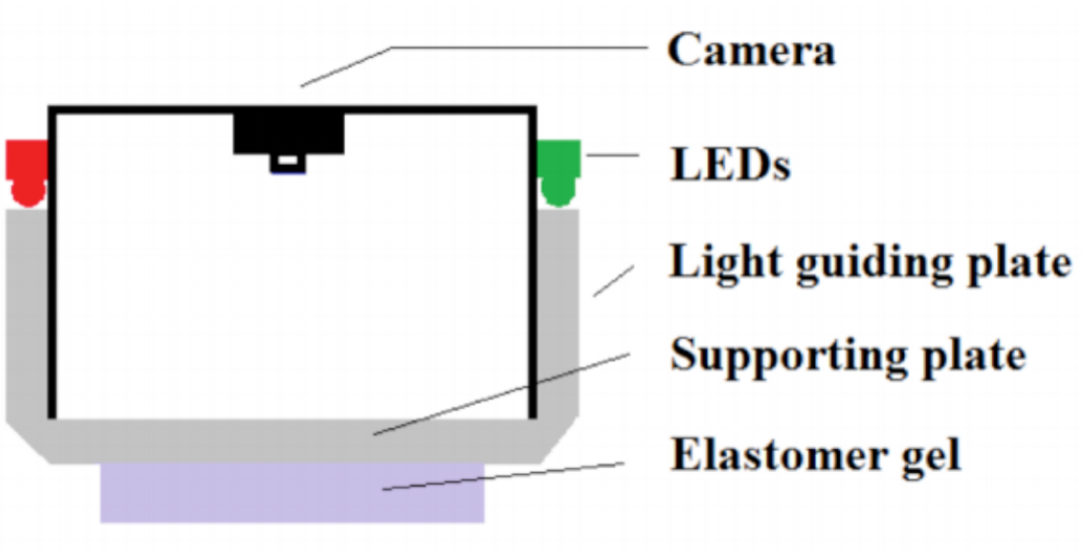
Shading signal is nice. Based on surface slope; accentuates fine detail. Amplitude is scale invariant.



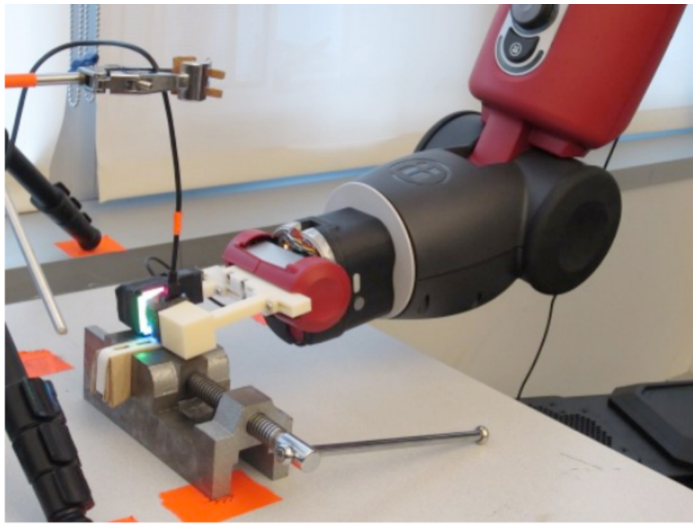


Compact device for robot fingers





Mounted on a robot gripper. Robot can tell exact pose of object from touch.



When Baxter robot grasps USB cable, position/pose is uncertain.

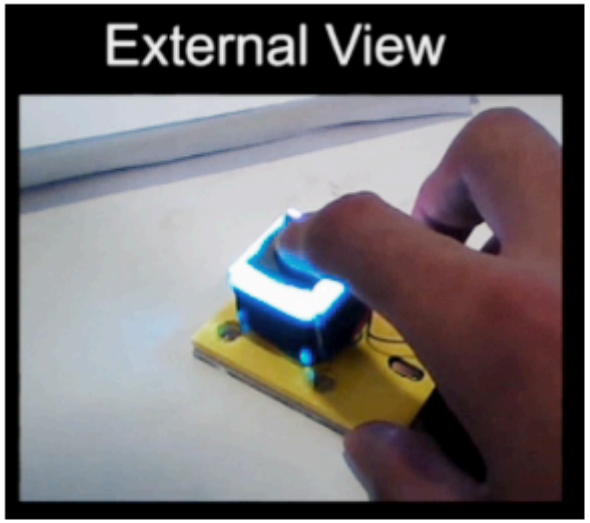
Tactile image is matched to known template.

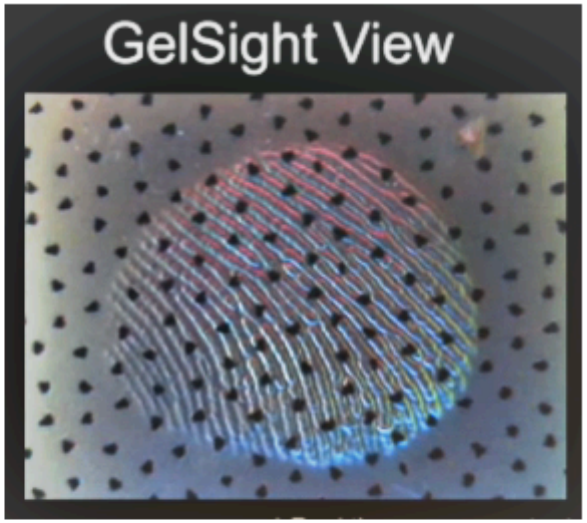
Trajectory for insertion task can now be calculated.

Collaboration with Robert Platt

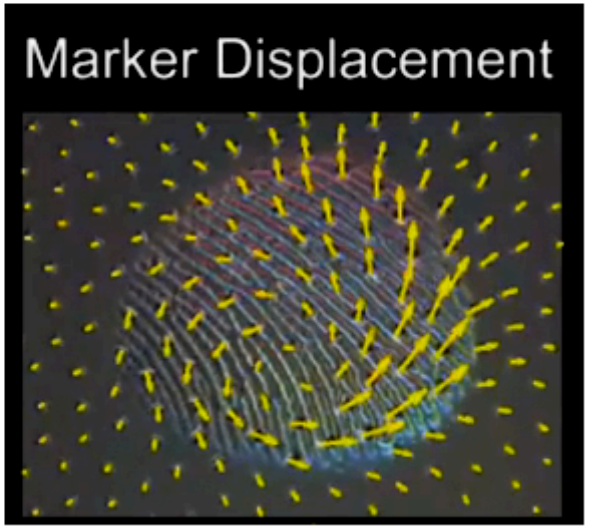
Li et al, IROS 2014

Another version:
Sensing both normal force and tangential force.

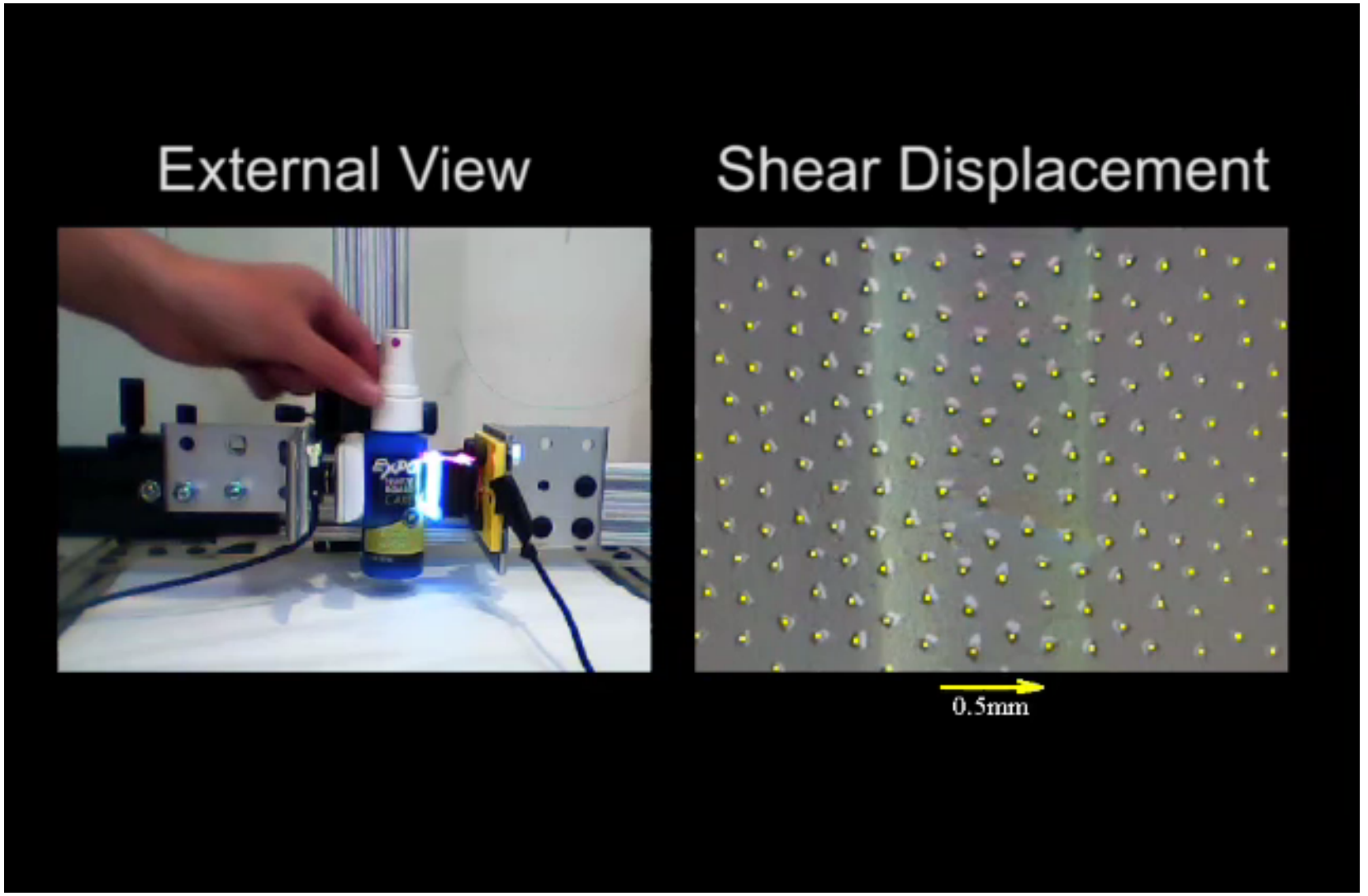




Add markers to membrane.
Track markers to get shear.



Measuring shear while someone wiggles the grasped object (a spray bottle).



Tangential measurements (shear, slip) are critical.

- Friction is a tangential force!
- Slip is critical to manipulation.
- Commercial touch sensors measure normal force but not shear or slip.

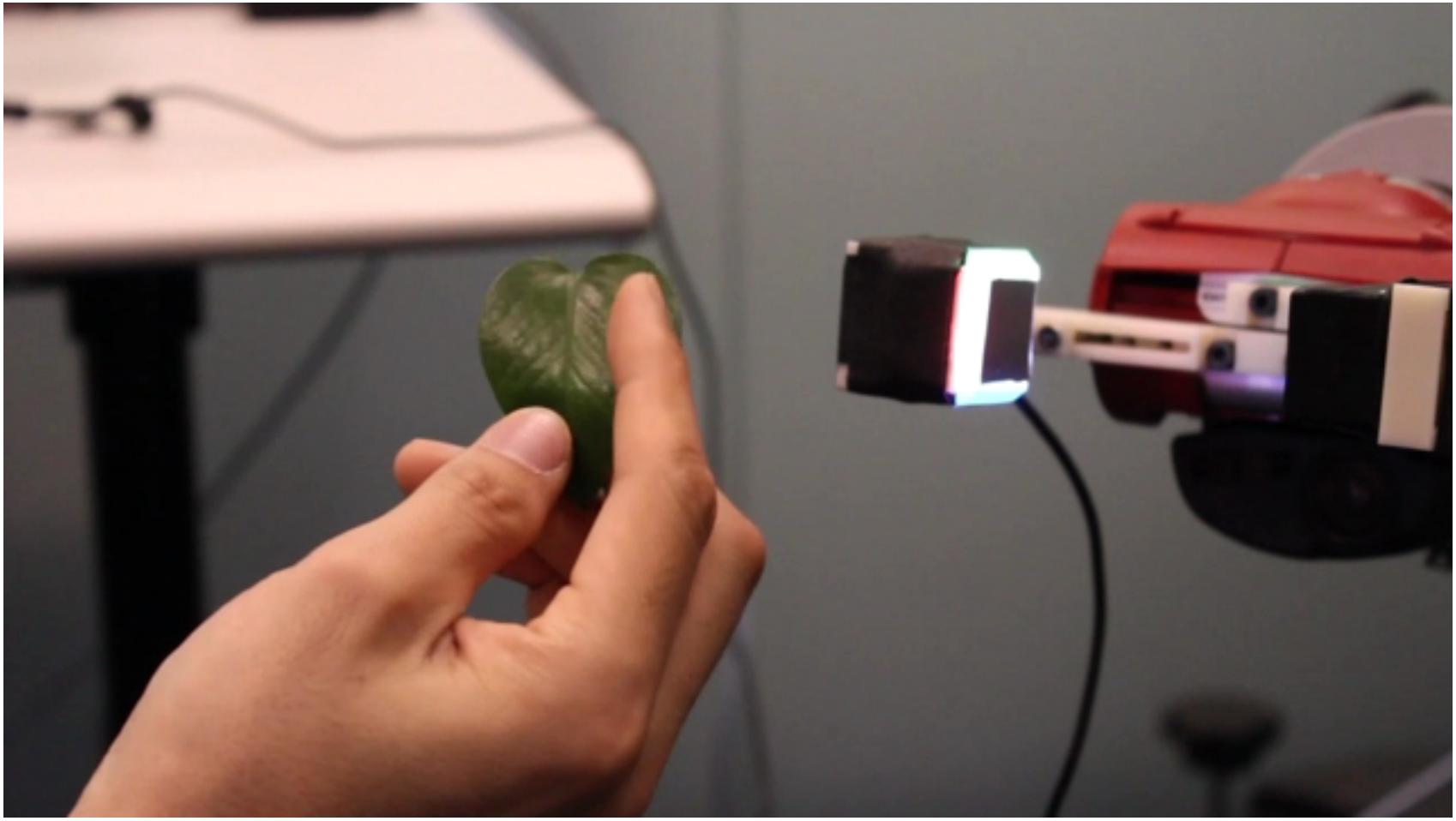
Grip, then lift Red Bull can

(program runs with fixed parameters)

Normal force (grip) must adjust during lifting to prevent slip.

Delicately holding a leaf with GelSight

(running with same fixed parameters)

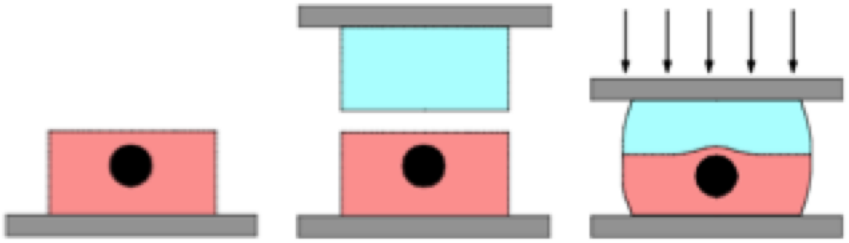


Leaf is flexible, but Gelsight senses light touch and grips just hard enough to prevent slip.

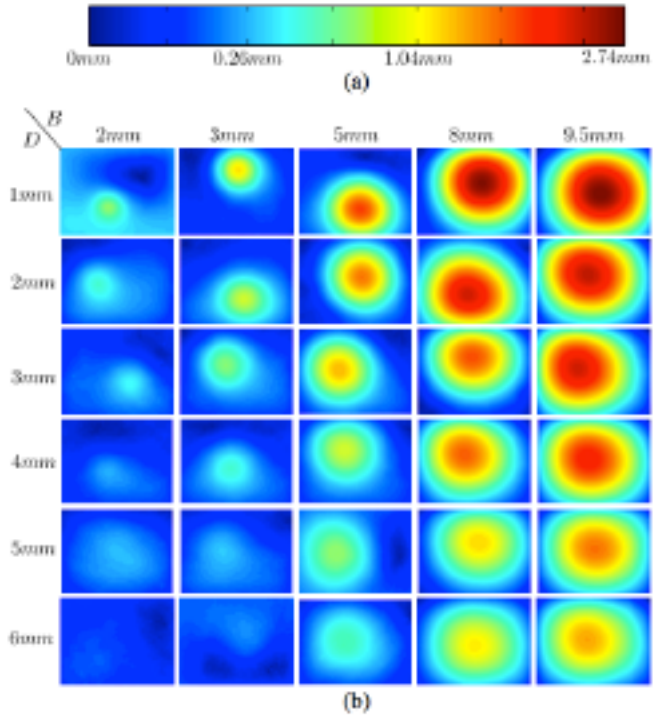
Exploring medical applications

- Lump detection
- Dermatology
- Blood pressure
- Etc.

Cancer diagnosis:
Measure hardness map,
for lump detection

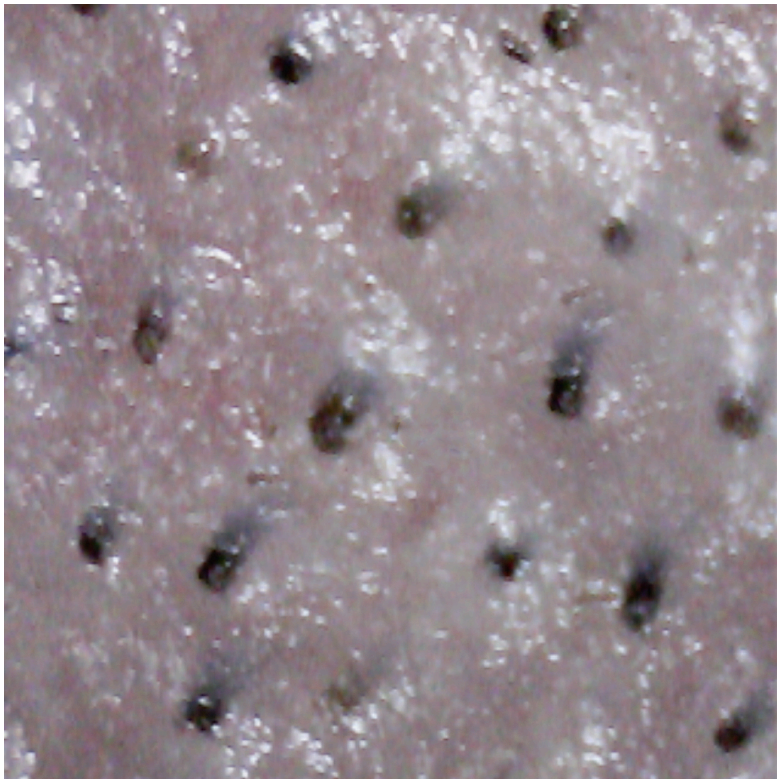


Hard object (black) embedded in soft matter (pink) resists deformation when gel sensor (blue) presses against it.

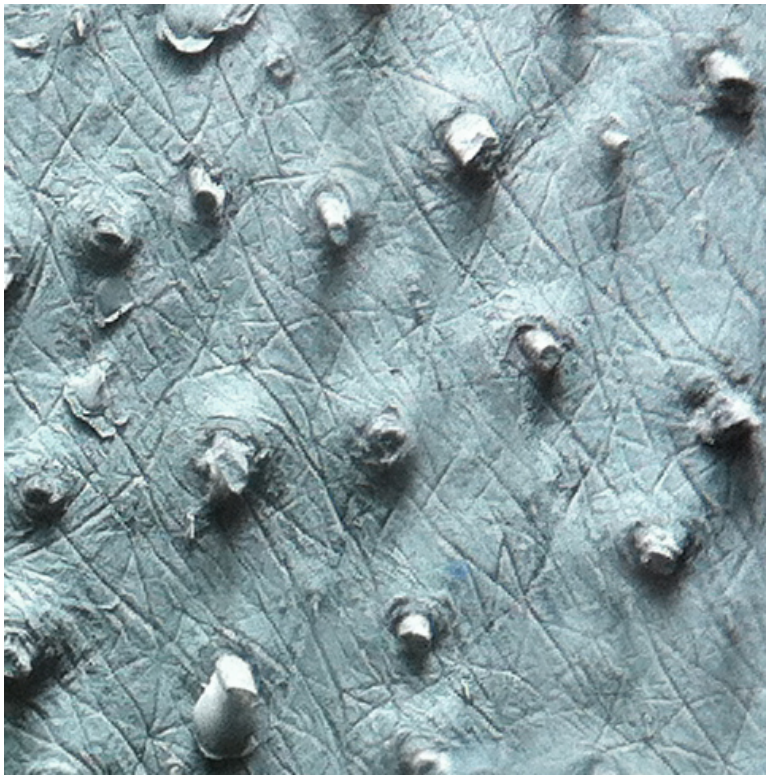


Sensitivity for small and/or deep lumps is better than human finger (as tested on non-experts).

Skin is translucent.
You normally can't see the detailed topography.
GelSight makes everything opaque.



Skin and stubble
without GelSight

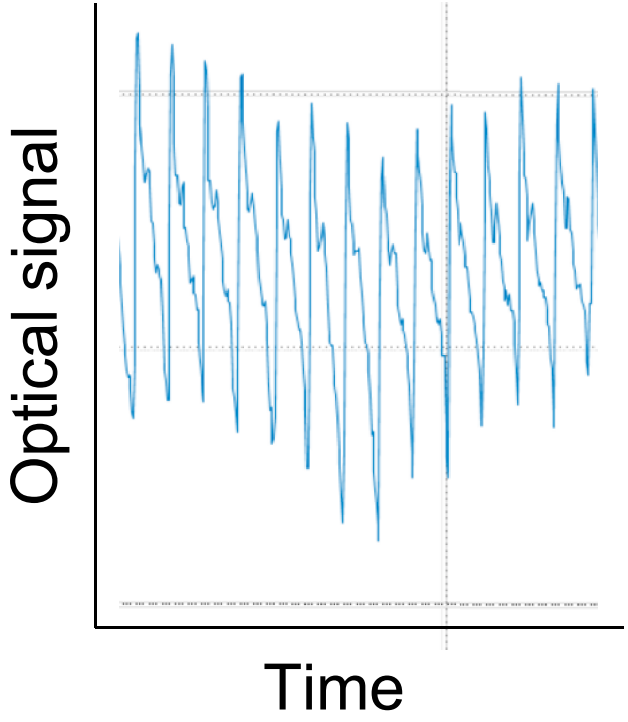


Skin and stubble
with GelSight

Blood pressure: visualizing pulse on wrist. (Pressing softly at first, then pressing harder)

Non-invasive continuous blood pressure

- You want to know your BP throughout the day (not at doctor's office).
- Goal: wearable sensor. No one can do it (with sufficient accuracy) despite years of effort and $millions.
- Can GelSight do it? We'll find out. NIH-funded project with Mohan Thanikachalam (Tufts) and Mandayam Srinivasan (MIT)



It's easy to get a pulse signal. The challenge is to convert it to systolic and diastolic pressure reliably on all users.

We have a spin-off company, GelSight Inc.

- It does NOT measure blood pressure.
- It does NOT make robot fingers.
- It does NOT find lumps.
- It sells instruments for micro-scale 3D surface metrology. (Also known as profilometry)
- Company launched due to overwhelming interest in a YouTube video.

Sensing Surfaces with
GelSight

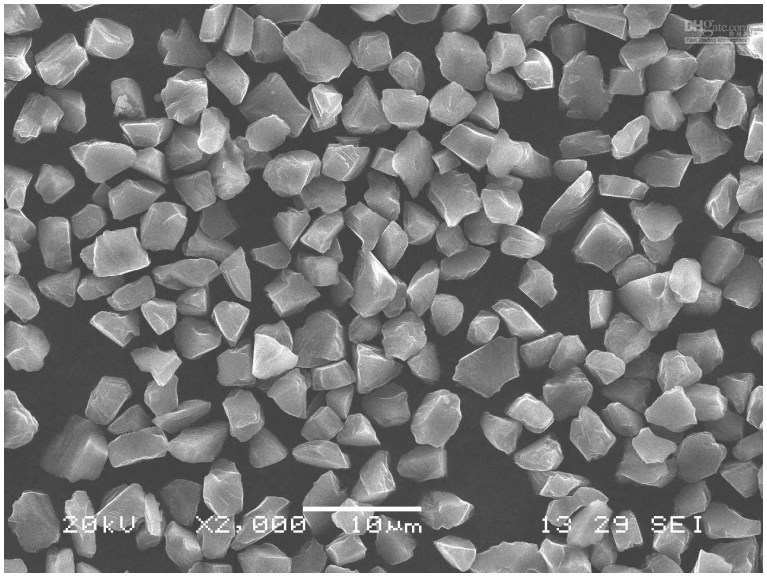
Micah K. Johnson and Edward H. Adelson

MIT Computer Science and Artificial Intelligence Lab

Massachusetts
Institute of
Technology

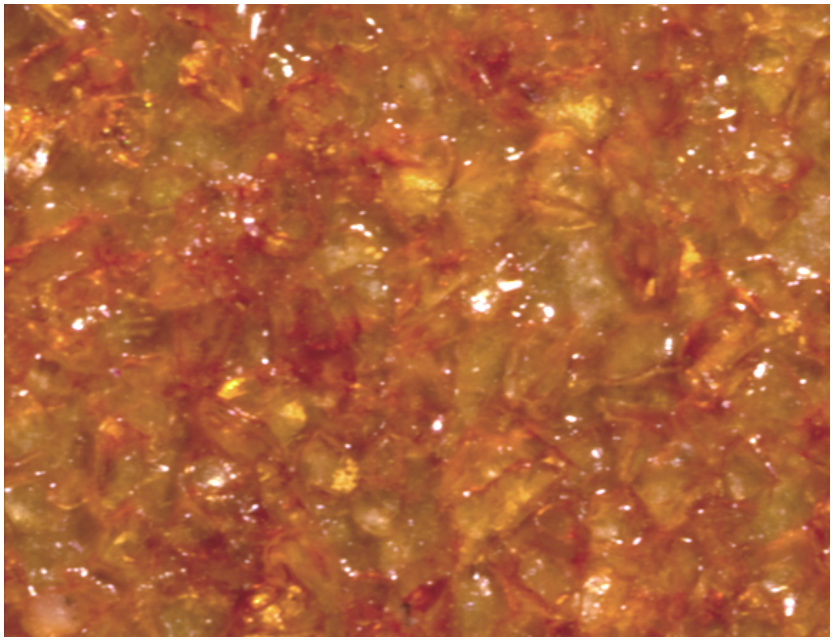
Suppose your company uses abrasives: transparent crystals – hard to measure optically. You buy an SEM (scanning electron microscope) to look at them.

JSM-7600F SEM from JEOL

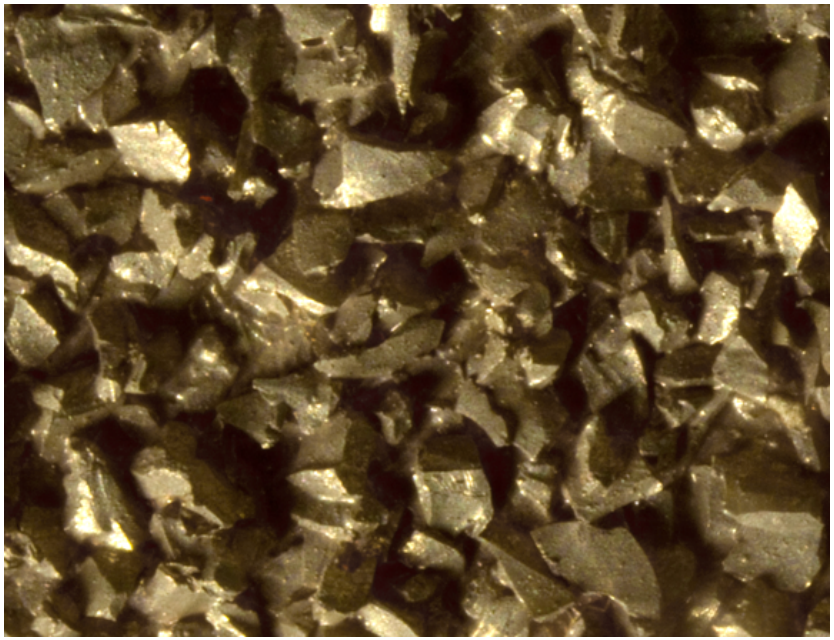


But SEM is expensive and complex.

GelSight lets you look at optically challenging materials like abrasives.

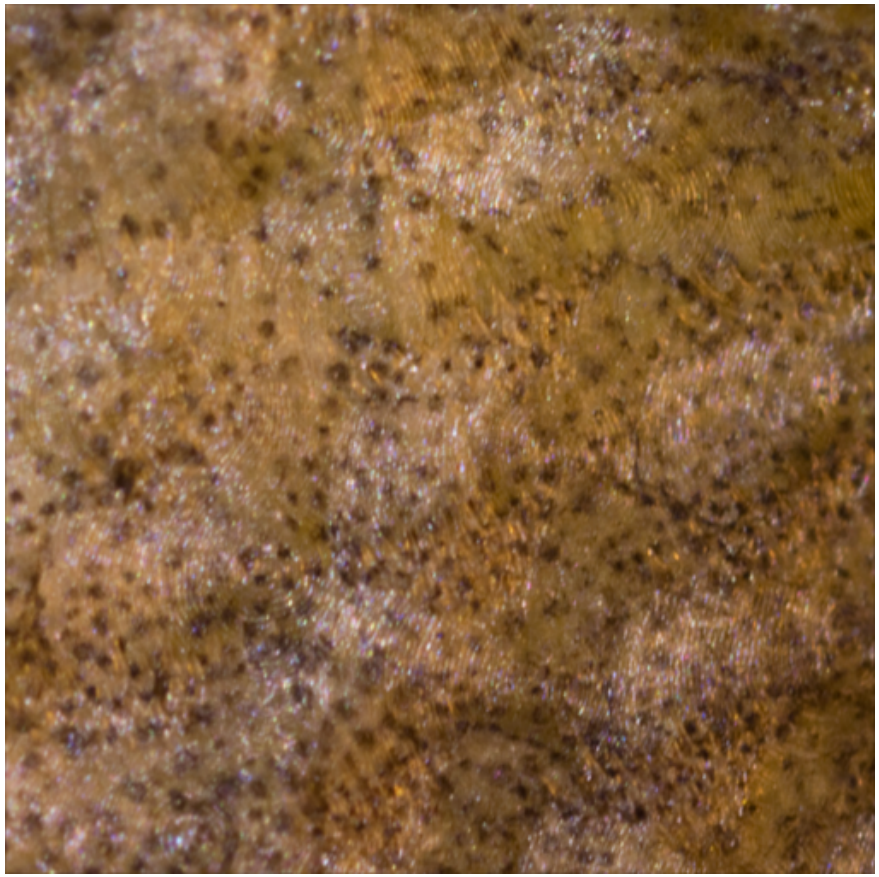


Direct view

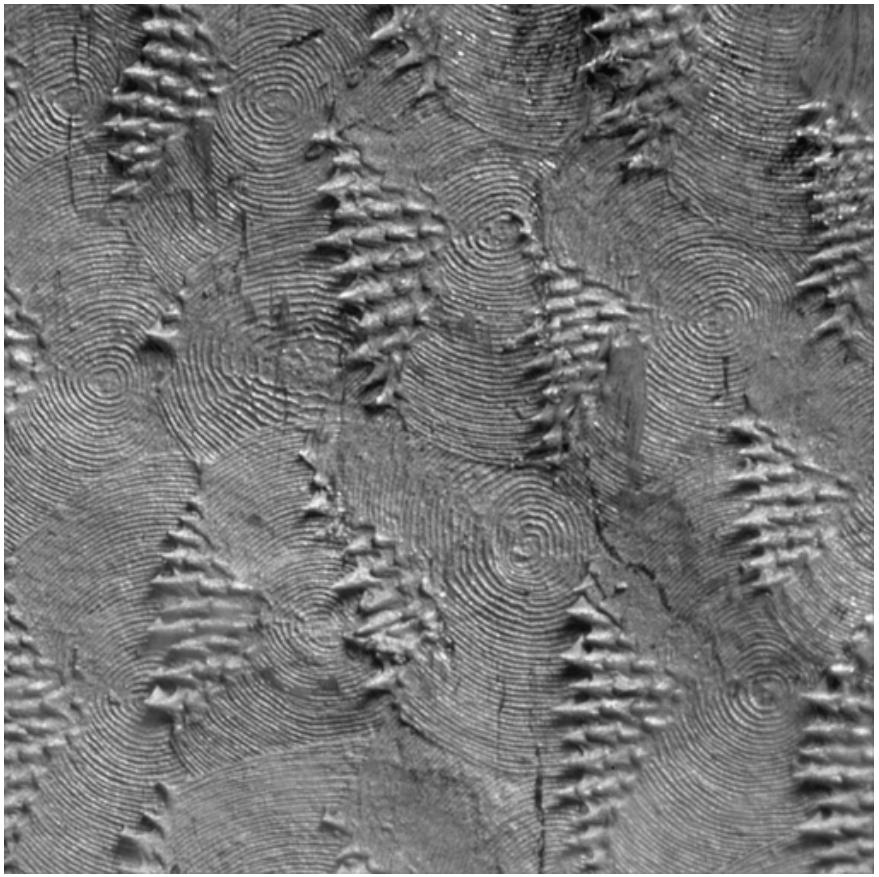


GelSight view

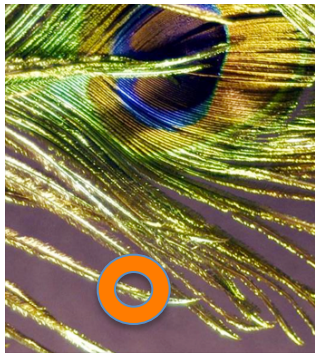
Fish scales:
GelSight reveals the geometry.



Direct view



GelSight view



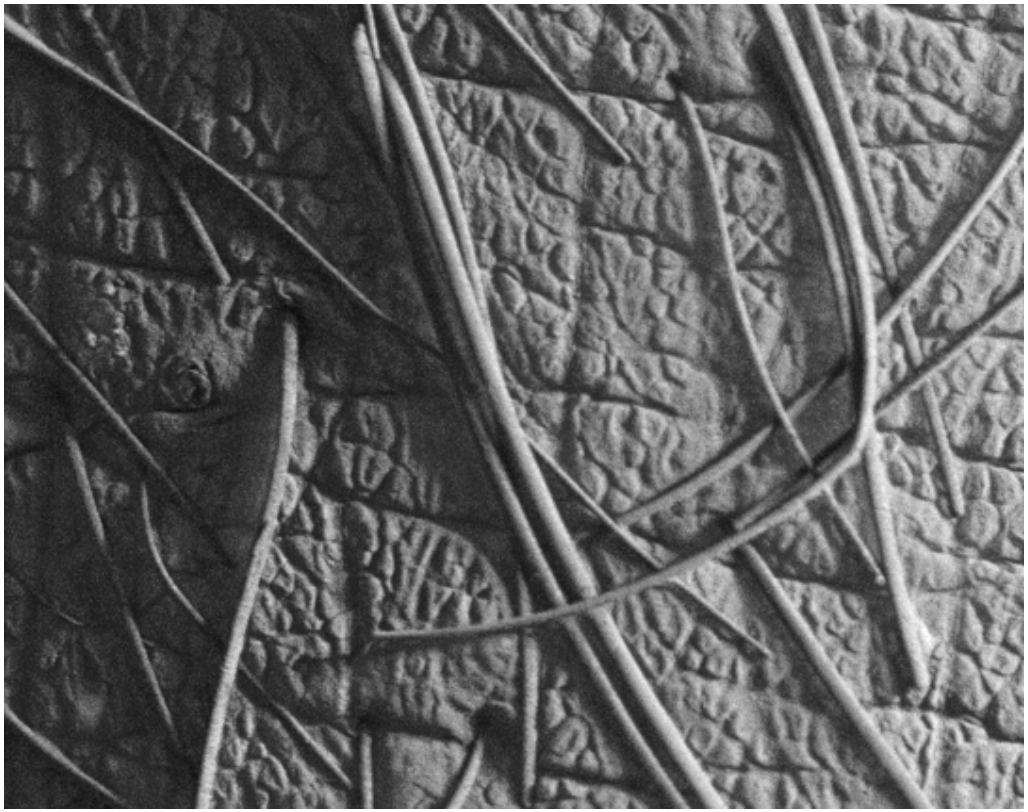
Peacock feather

GelSight removes optical complexity.

Direct view

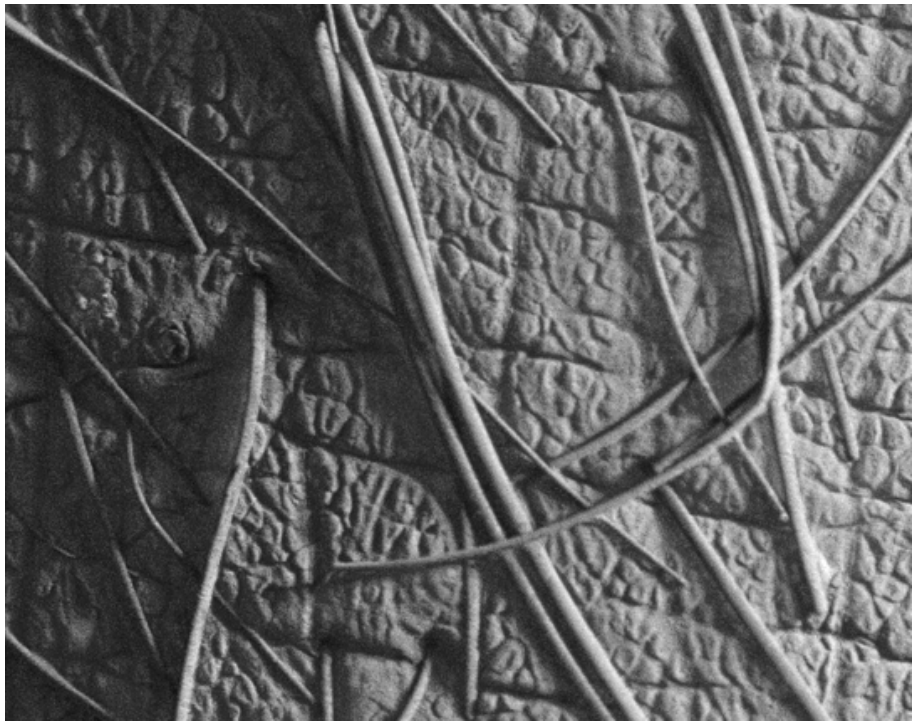
GelSight view

Striking detail can be seen in skin.



This has the “look” of SEM,
but it is done on living skin.

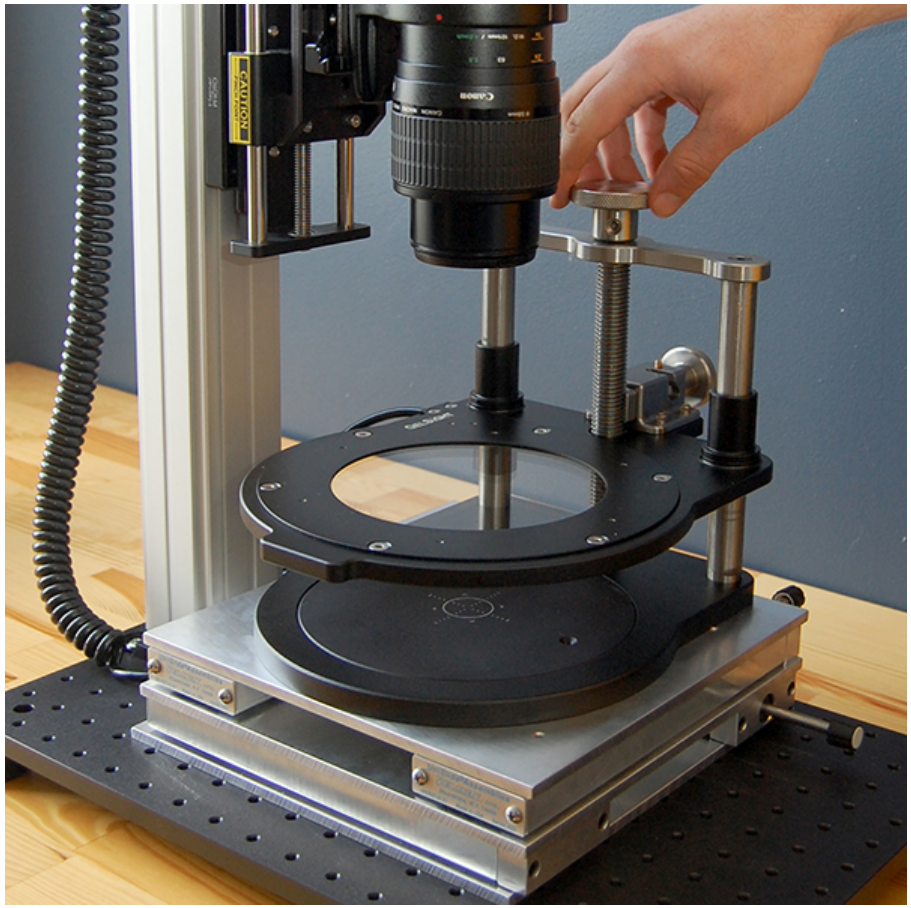
Wait! It looks like the “paint” is wrapping around the hairs. How can that be?



- In this example we use a supersoft gel elastomer, which is visco-elastic.

- It flows like liquid under pressure, filling crevices, wrapping around hairs.

GelSight Inc. will sell you a benchtop scanner for both visualization and measurement.



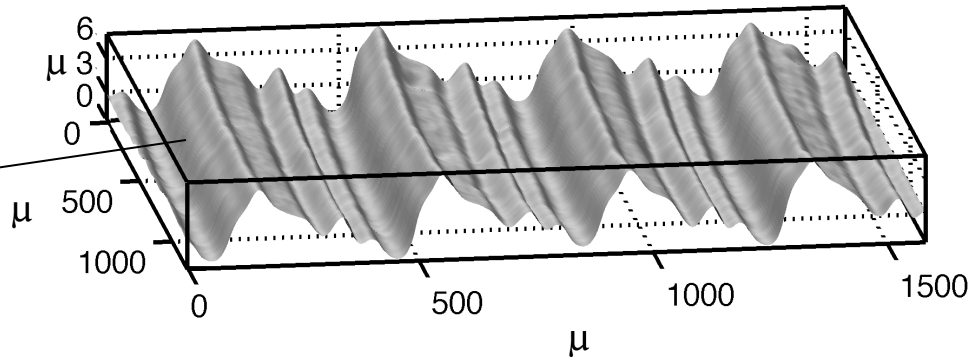
GELSIGHT

www.gelsight.com

Roughness

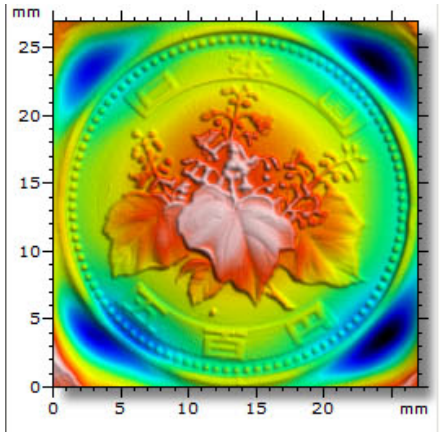
Surface roughness standards

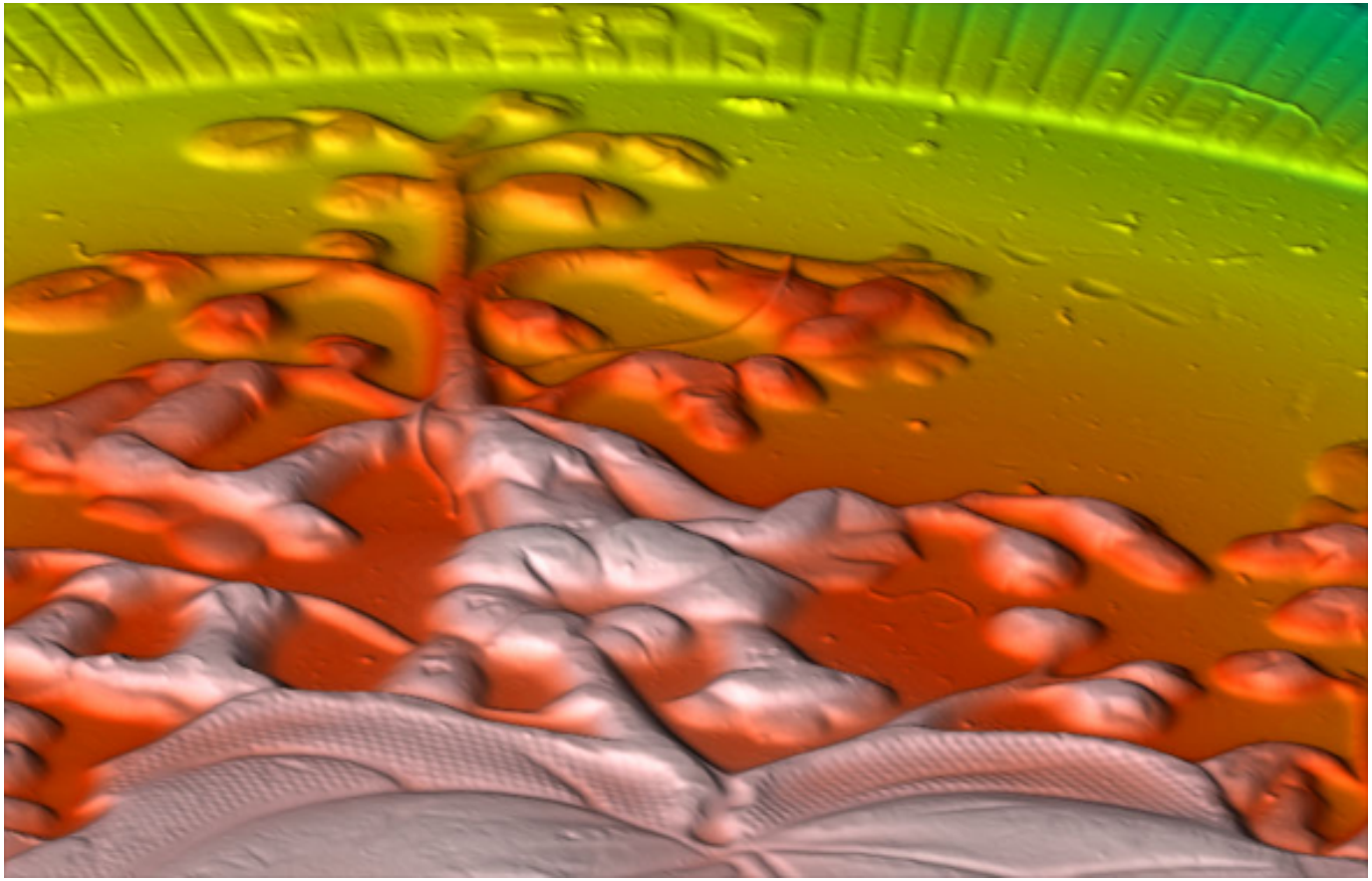
GelSight measurement:



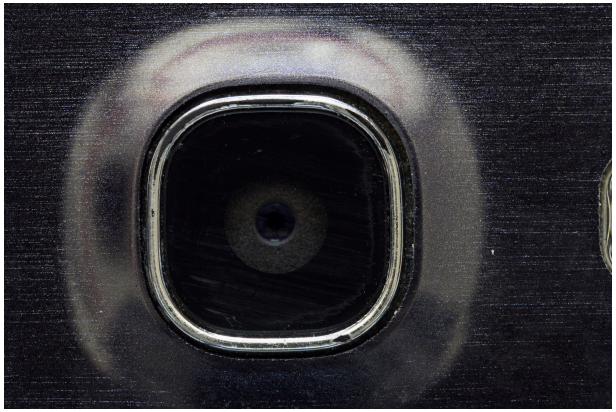
1.6 micron height variation
(63 microinch vertical milling)

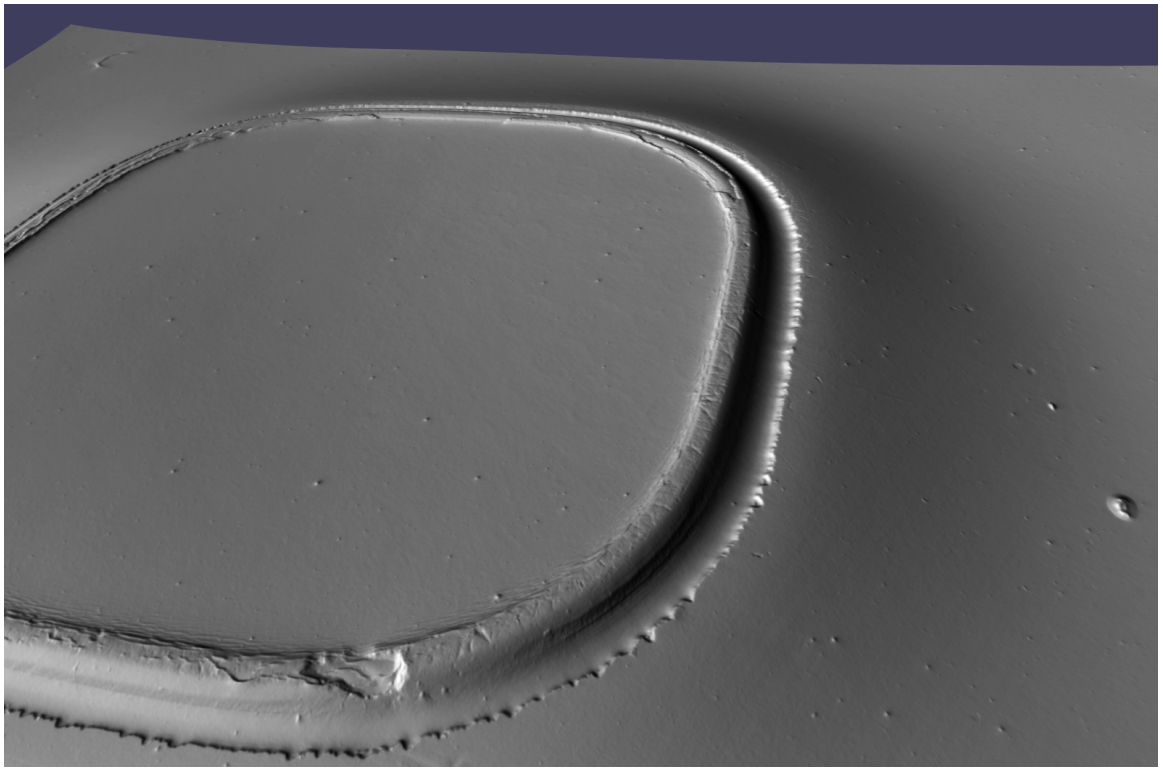
Numismatics; cultural heritage





Quality assurance in manufacturing

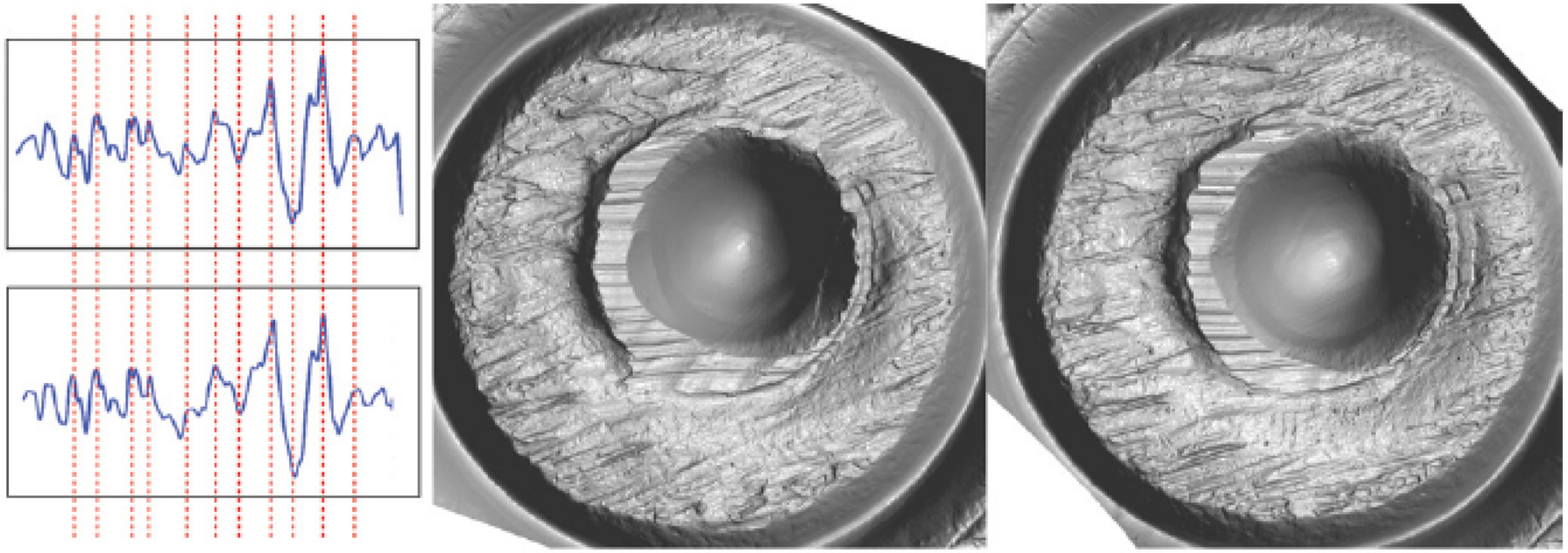




Camera lens has glass window, metal bezel, shiny plastic.
Customer comment: “Multimaterial 3D is the holy grail”

Cadre Research Labs bundles GelSight into an FBI-approved forensic system.

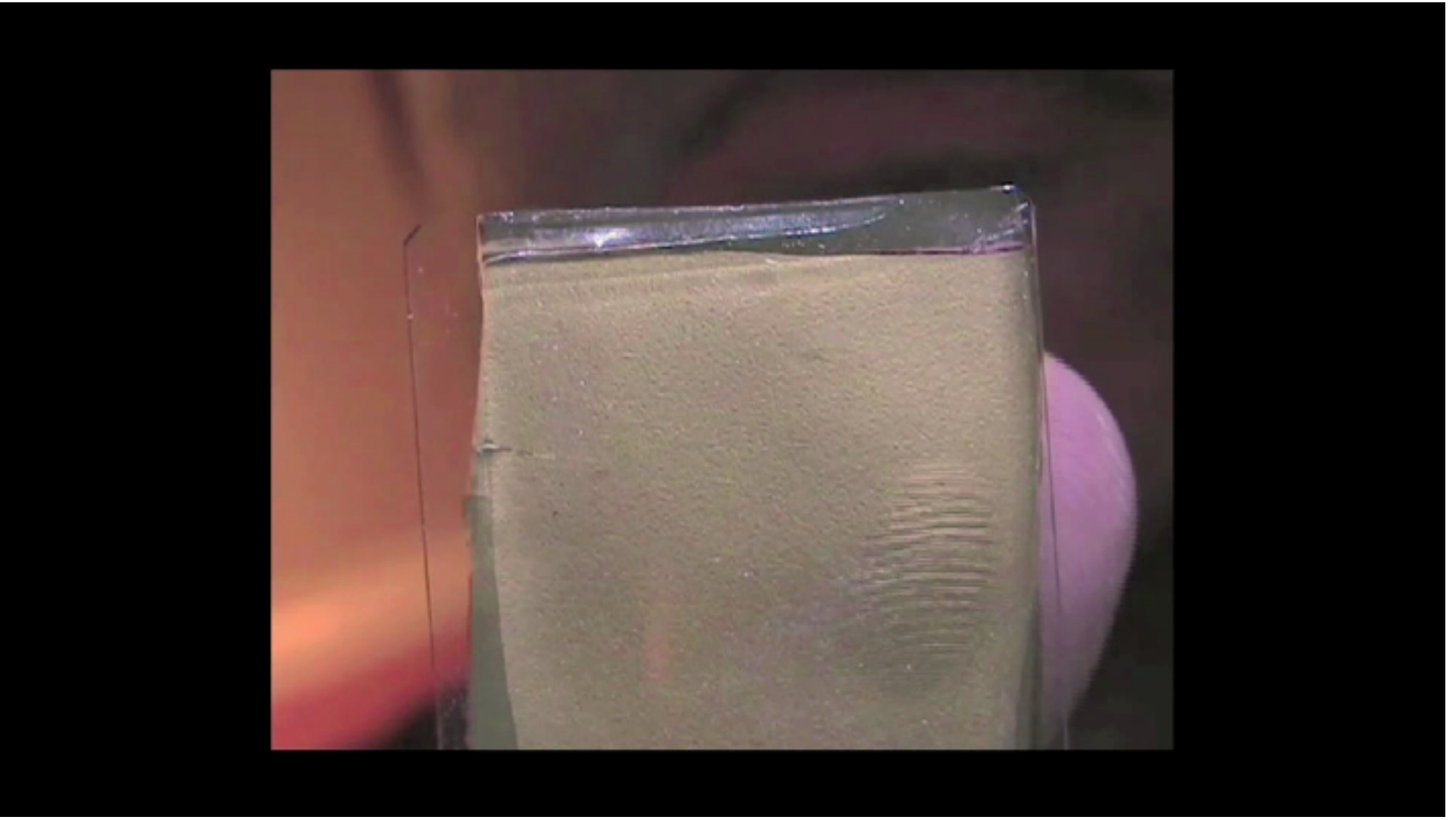
CADRE
Research Labs



Summary

- GelSight was conceived as a human-like tactile sensor.
- Converts mechanical signal to visual signal
- Robot sensors can give shape, shear, slip, hardness.
- Surprise: spatial resolution is extremely high (microns)
- GelSight Inc. devices are being used in inspection, forensics, manufacturing, 3D printing, etc.
- Many fun applications are waiting to be explored

One last demo, just for fun.



Thanks to …

- Micah Kimo Johnson
- Mandayam Srinivasan
- Mohan Thanikachalam
- Robert Platt
- Stella Jia
- Rui Li
- Wenzhen Yuan
- Janos Rohaly
- Bill Yost
- Ryan Lilien
- Funding from the NSF, NIH, Toyota, Plato

Why does it look like SEM?

- Well, why does SEM look like SEM?
- SEM provides a pseudo-shaded image due to the “diffuse” scattering of electrons from surface.
- GelSight gets diffuse scattering with photons

Measuring fish scales

Contents lists available at ScienceDirect

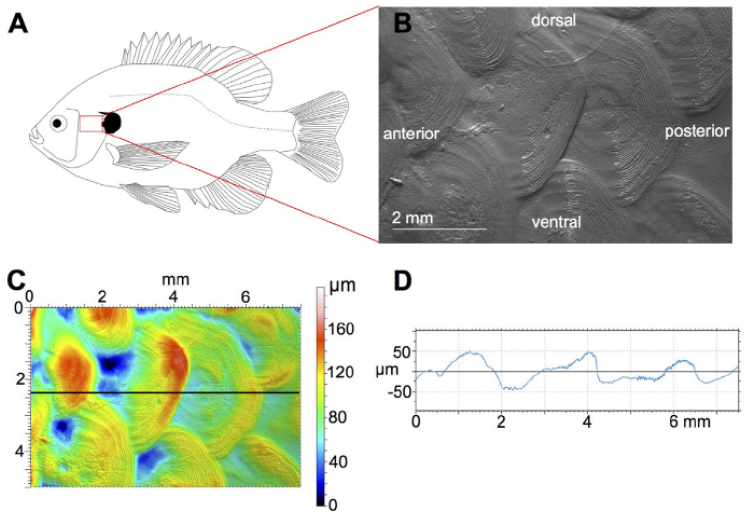
Zoology

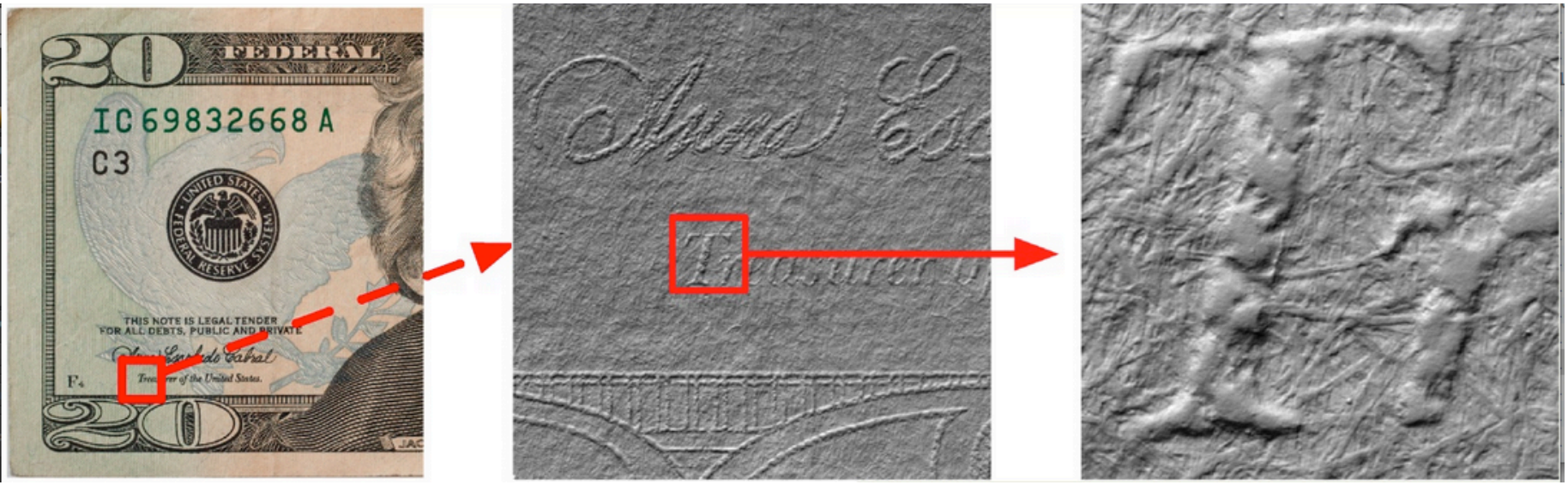
journal homepage: www.elsevier.com/locate/zool

Three-dimensional analysis of scale morphology in bluegill sunfish, *Lepomis macrochirus*

Dylan K. Wainwright*, George V. Lauder

Museum of Comparative Zoology, Harvard University, 26 Oxford Street, Cambridge, MA 02138, USA

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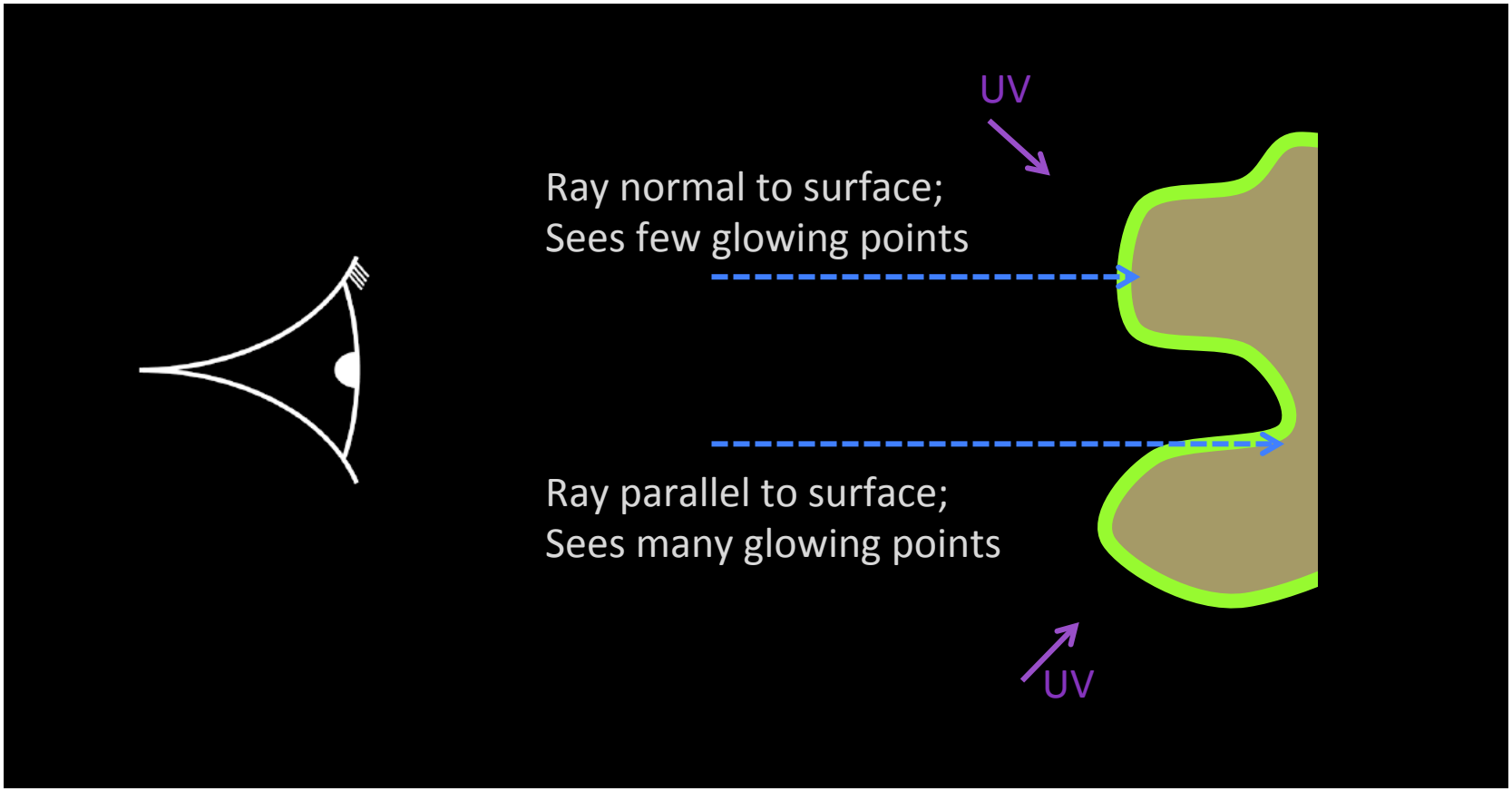
Glowing edges with fluorescent membrane



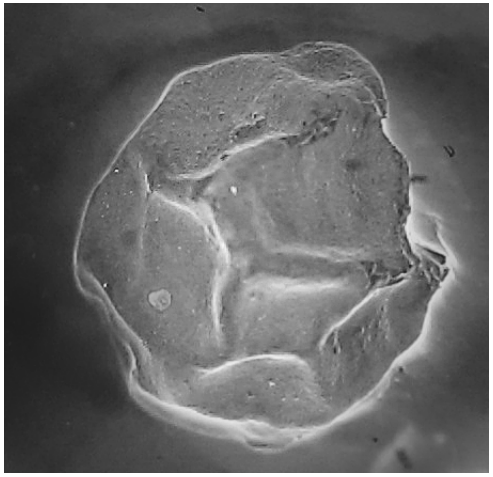
For highest resolution we use a membrane that is:

- Fine grained (to avoid granular noise)
- Lambertian
- Opaque (so we ONLY see the shading signal)
- Very thin (to avoid mechanical low-pass filter)
- Dark gray (to prevent interreflections)

Hard to achieve all at once. We mainly use submicron particles of metal or metal oxides.

Fluorescent membrane gives strong glow on receding edges.

Normal appearance



Fluorescent membrane:
Steep slopes glow brightly.

Even at low magnifications, SEM is popular because it gives 3D shaded appearance.

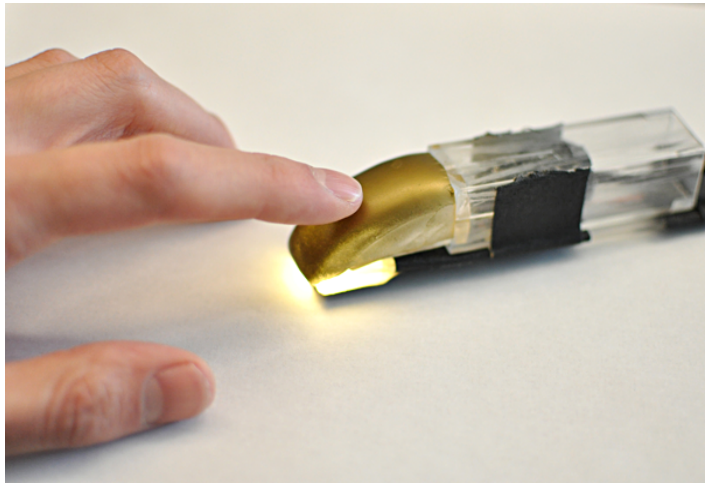
Optical microscope

SEM

C. Elegans

Artificial skin for robotic or prosthetic fingers.

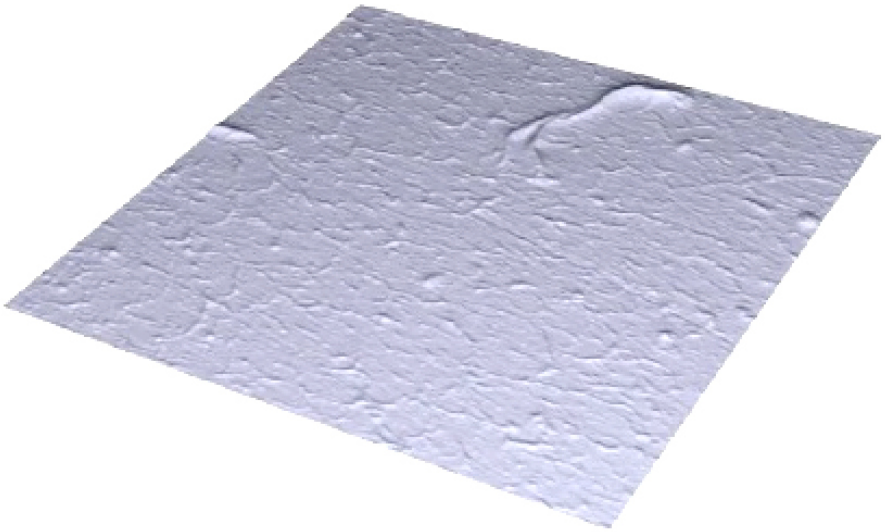
- Can match the softness, resilience of human skin.
- Can exceed the tactile sensitivity of human skin.
- Potential uses: robotic manipulators, minimally invasive (robotic) surgery, prosthetic hands for amputees.



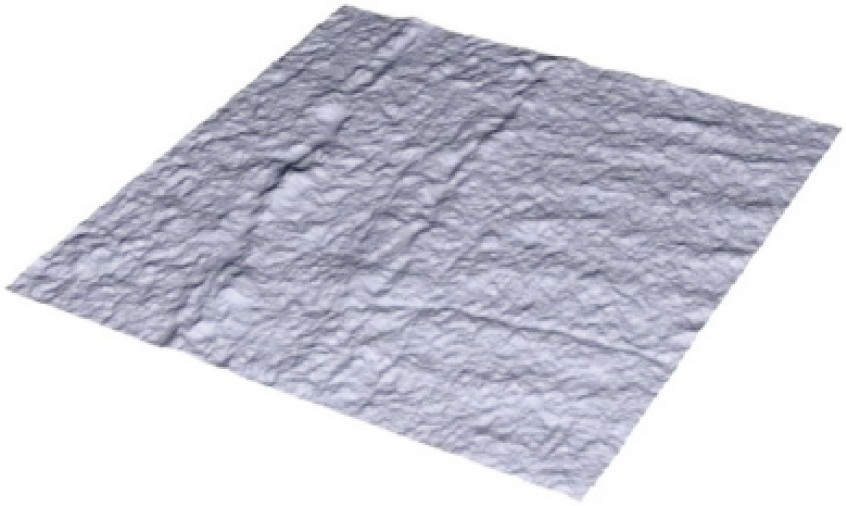
Light source and camera are inside the “fingertip.”

Tactile image: Human finger touching robot finger.

Dental surface metrology



Normal Enamel



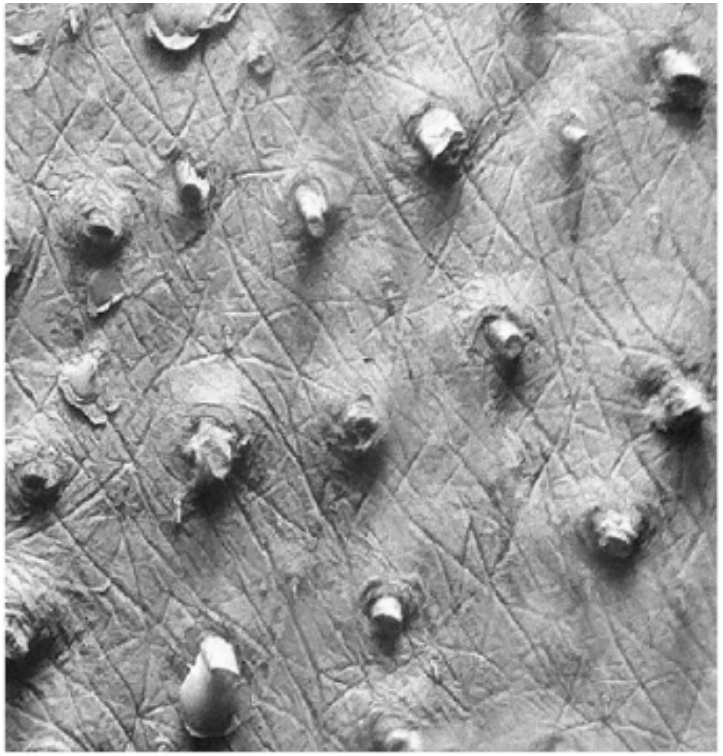
Demineralized Enamel

"Microabrasion Techniques for Removal of in vitro Enamel Demineralization"
S.A. BRUE, M. FINKELMAN, M. HARSONO, and G. KUGEL, School of Dental Medicine, Tufts University, Boston, MA
International Association for Dental Research, 2013.

GelSight can do much more.

- Sensitivity >10x human skin
- Resolution ~1000x human skin
- Can be soft (like Jello) or hard (like car tires)
- Can be arbitrary shapes & sizes

GelSight vs. SEM



GelSight:
It’s alive!

SEM:
It’s dead!

To add

- Ryan's bullets
- Chicken meat
- Wojciech (testing 3D printing)
- Fish scales (vs. micro-CT)
- BP trace (Siyuan)

There's plenty of room in the middle

- GelSight works in the 1 micron to 1 mm range.
- Boring! Not atomic scale, not cosmic scale.
- Is there a need for new imaging technology in the middle range?
- There's SEM, AFM, interferometry, optical coherence tomography (OCT).

Most optical techniques are non-contact and proud of it.

- GelSight is contact based.
- Is that good or bad? It depends.

Photometric Stereo.
Textbook technique, rarely used.

Assume:

- Specific surface reflectance
- Three lights at known positions.

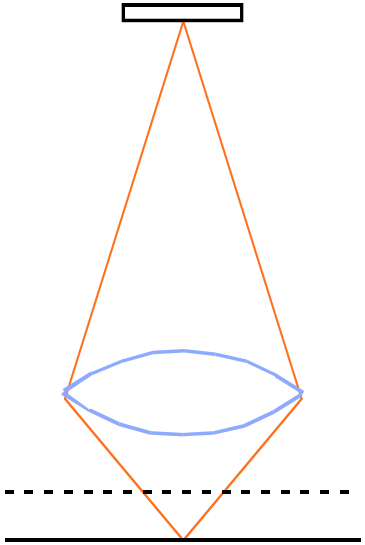
That never happens in real life!

But we can make it happen in a GelSight sensor

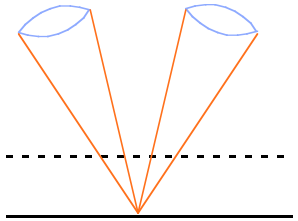
Most optical 3D systems use triangulation.

Small depth variation yields small signals.

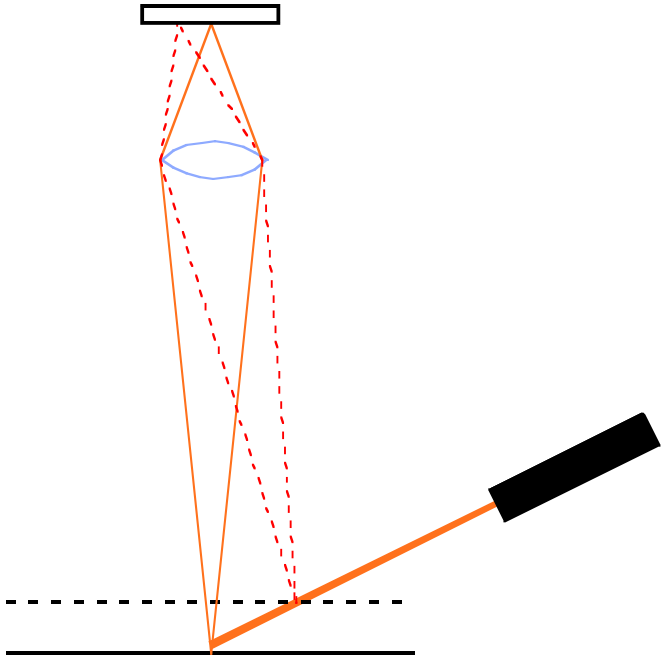
Depth from defocus
(or confocal imaging)



Stereopsis



Structured light
(incl. laser scan)



With GelSight we can use the **shading signal** instead.

Grip, then lift potato chip.

(program runs with fixed parameters)

Normal force (grip) must increase during lifting to prevent slip.

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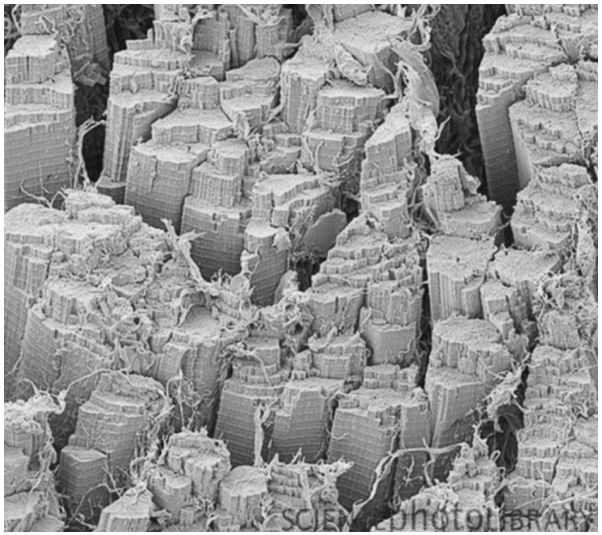
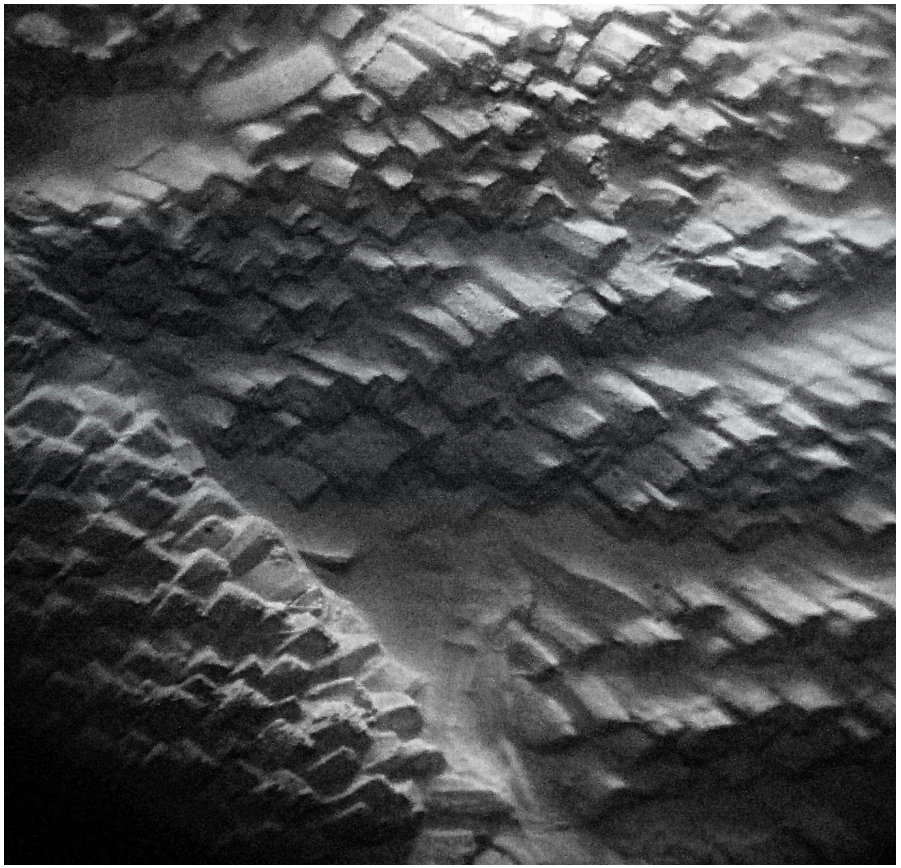
Muscle fibers (chicken)



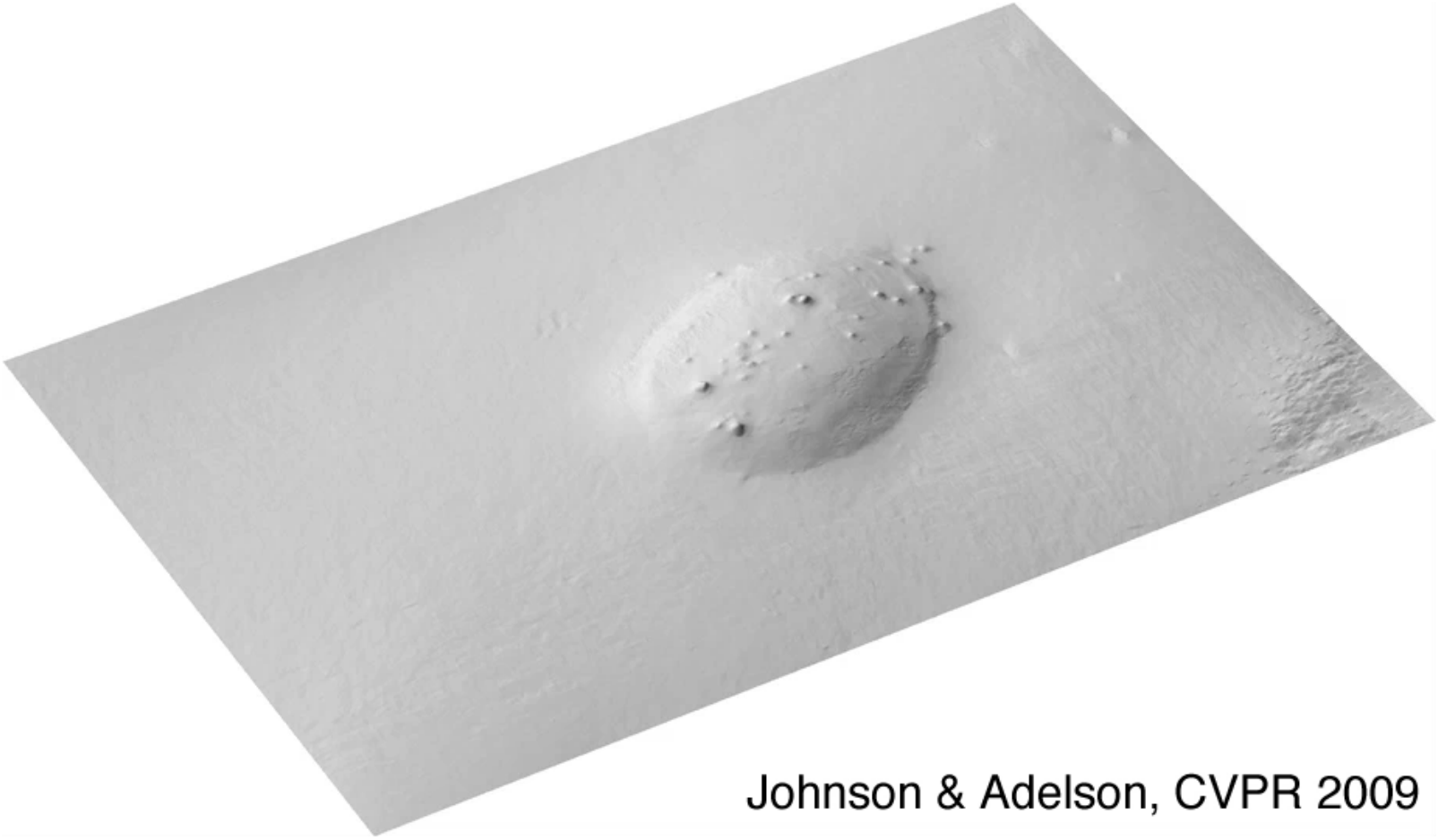


Other directions…

- Real time interactive visualization
- Some examples follow.

For optical measurements of shiny or transparent objects, people sometimes spray opaque powder on the surfaces.

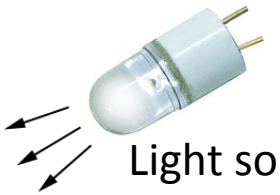
- Used with laser scanners with shiny objects
- Used in dentistry because teeth are translucent.
- Problems: Messy, uneven, loss of detail, need for removal.



Johnson & Adelson, CVPR 2009

Submicron spherical metal particles: thin, opaque, gray, matte membrane.

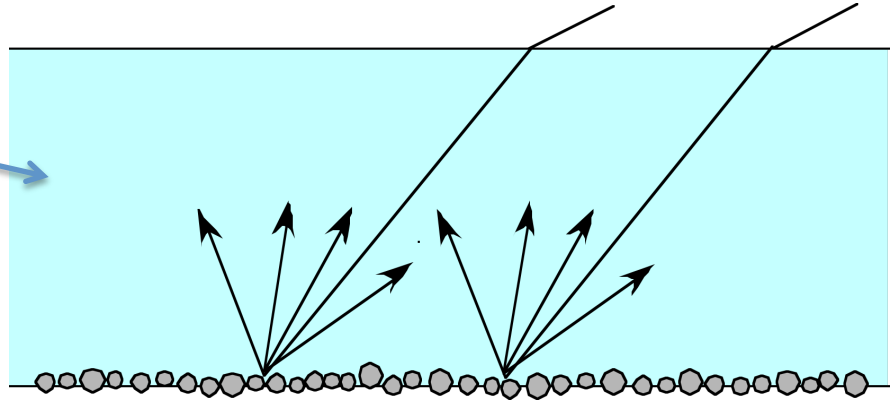
Camera



Light source

Clear elastomer

Metal particles



Specimen

What pressure patterns is the skin experiencing while lotions are applied?

GelSight can be used to examine surface detail in two ways

- **Visualization** (showing a shaded image to a human to provide a sense of 3D shape)
- **Measurement** (calculating 3D using photometric stereo or other optical technique)

Note: for high resolution, we usually use a Lambertian (matte) membrane.

GelSight overcomes surface optics; it coats the specimen with an opaque membrane.

- Specular materials (e.g., metals)
- Transparent materials (e.g., glass)
- Translucent materials (e.g., human skin)
- Albedo variation (e.g., from pigment)