Microgeometry Capture using an Elastomeric Sensor

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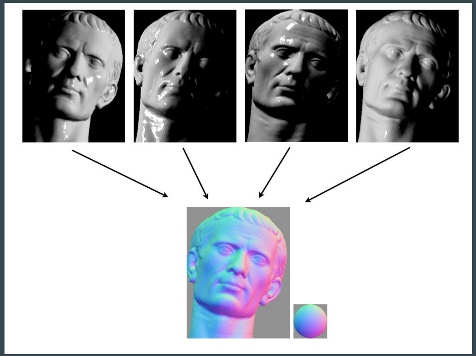
Problem

How do we find the microscopic surface geometry of an object with unknown optical properties?

- Active light scanning (Levoy, Alexander)
  - Assumes Lambertian BRDF
  - Not suitable for microscopic reconstruction
- Photometric Stereo (Woodham, Tagare, Hernandez)
  - Can only discern sub-millimeter resolution
- Shape-from-focus (Nayar)
  - Only works with rough surfaces
- White light interferometry
  - Expensive, slow, large
- Retrographic Sensor (Johnson)



Previous Work - (Johnston, Edelson 2009)

- Retrographic sensor non-destructively paints a surface by pressing it into a painted elastomer with known optical properties
- Single frame capture using red, green, and blue lights
- Can discern macroscopic details using photometric stereo

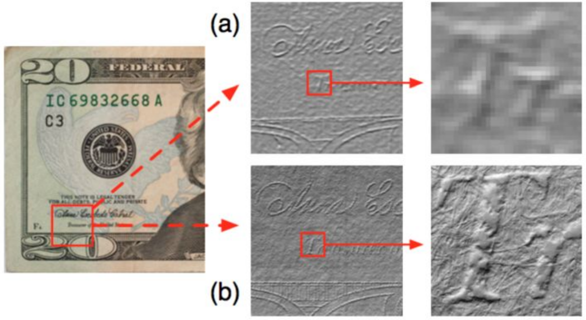
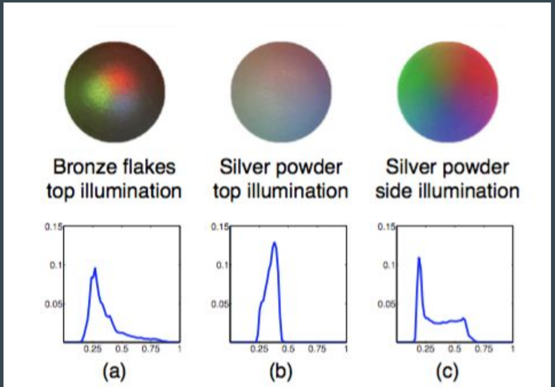


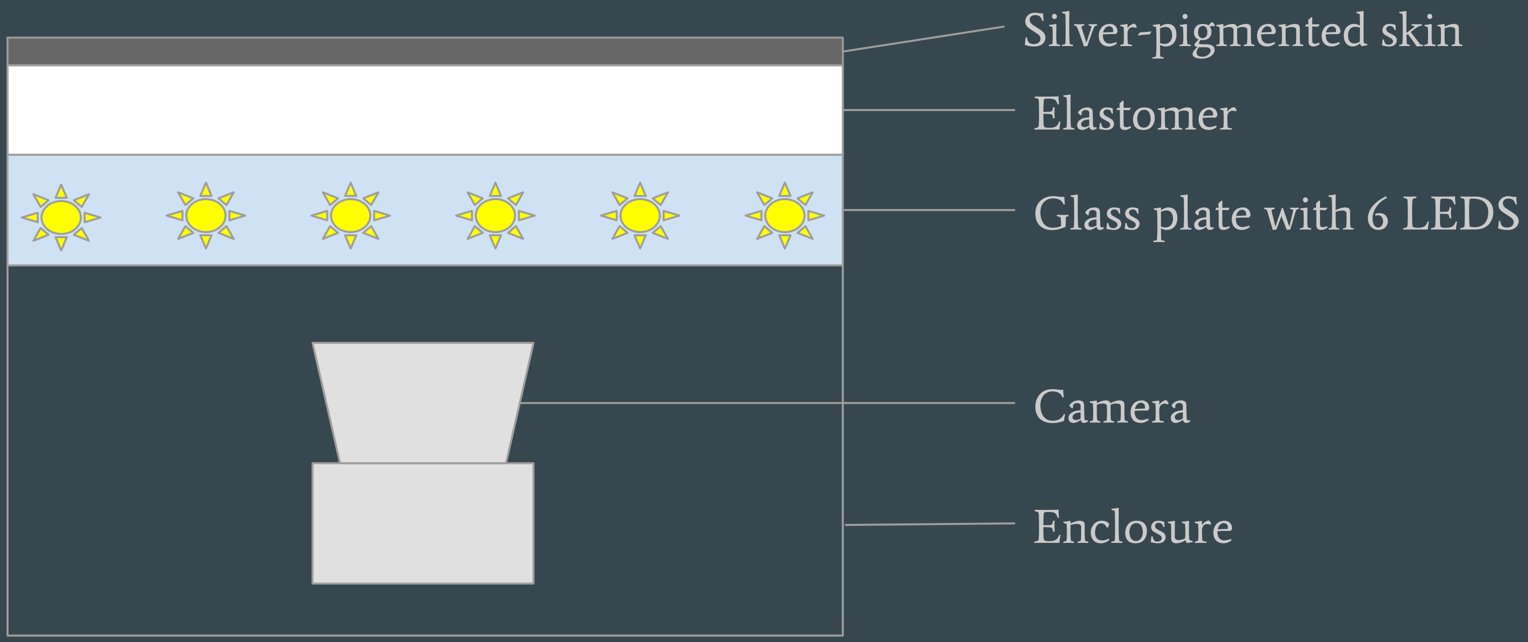
Figure 7: *Comparison with the high-resolution result from the original retrographic sensor. (a) Rendering of the high-resolution $20 bill example from the original retrographic sensor with a close-up view. (b) Rendering of the captured geometry using our method.*

Improvements to Previous Work

- Improved pigment - spherical silver (< 1 micron) instead of metal flake pigment
    - Spherical shape reduces noise
    - More diffuse - increased range of surface angles allowable for a bright image to be captured
    - Smaller size makes pigment particles less visible
    - No binder needed
    - Allows for a thinner skin
    - Dark sensor reduces interreflections
- New lighting design - 6 LEDs mounted around glass plate
    - Need to achieve sufficient contrast with new diffuse pigment
    - Contrast is maximized under grazing illumination
- New near-field stereo algorithm



Sensor Design



Near-Field Stereo Algorithm

1. Linear estimate
2. Quadratic estimate
3. Dealing with shadows
4. Surface reconstruction
5. Noise reduction

Linear Model

- Good initial approximation of illumination
- Assumptions
  - Lambertian reflectance
  - Constant albedo
  - Light source positioned at infinity
- Channel k
  - Surface normal at position $\vec{p}$ is $N(\vec{p})$
  - Light direction $\vec{L}_k$
  - Albedo ρ_k (absorbed into the light direction vector $\vec{L}_k$ as length)
  - Intensity in channel k is given as,

$$s_k(\vec{N}) = \rho_k \vec{L}_k^T N(\vec{p})$$

Linear Estimate of Surface Normal

- For m observed light intensities I_1 to I_m at pixel $\vec{p}$, we estimate the surface normal $\vec{N}$ using least squares,

$$\vec{N} = \begin{bmatrix} \vec{L}_1^T \\ \vdots \\ \vec{L}_m^T \end{bmatrix}^+ \begin{bmatrix} I_1(\vec{p}) \\ \vdots \\ I_m(\vec{p}) \end{bmatrix} = L^+ \vec{I}(\vec{p})$$

Adjusting Linear Model for Shadows

- Estimate will be biased by cast shadows
- Use a predefined threshold τ, to set the weight of a pixel that influences the computation of the surface normal, and set the weight to zero if its in the shadow region
- For W, the diagonal weight matrix, surface normal is now defined as:

$$\vec{N} = (WL)^{+} W \vec{I}(\vec{p})$$

- Pixels that are mostly in shadow across the channels are processed separately later

Quadratic Model

- The m^{th} spherical harmonic basis function of order n, $Y^{m,n}$
- The associated illumination coefficient for channel k, $l^{m,n}$
- Good approximation for Lambertian reflectance under arbitrary lighting

$$s_k(\vec{N}) = \sum_{n=0}^{2} \sum_{m=-n}^{n} l_k^{n,m} Y^{n,m}(\vec{N})$$

Quadratic Model Cont.

- Spherical-harmonic shadowing model expressed as a quadratic:

$$s_k(\vec{N}) = \vec{N}^T A_k \vec{N} + \vec{b}^T \vec{N} + c_k$$

- The associated error function:

$$E_1(\vec{N}) = \|\sqrt{W} f(\vec{N})\|^2 = \|\sqrt{W}(\vec{s}(\vec{N}) - \vec{I}(\vec{p}))\|^2$$

- W is the diagonal weight matrix to account for shadows
- Gauss-Newton is used to optimize the error function above

Quadratic Model Cont.

- The Gauss-Newton is updated using the following Jacobian:

$$\left[\frac{\partial J}{\partial u} \quad \frac{\partial J}{\partial v}\right] = \frac{\partial \vec{f}}{\partial \vec{n}} R_0 \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ \frac{-u}{r} & \frac{-v}{r} \end{bmatrix}$$

- The quadratic model is applied iteratively to each pixel using the error function below:

$$E(\vec{p}) = E_1(\vec{N}(\vec{p})) + \omega E_2(\vec{N}(\vec{p}), \vec{N}(\vec{p_l}), \vec{N}(\vec{p_u}))$$

Shadow pixels

- Iterative Reweighted Least Squares (IRLS) approach
  - Works when at least 2 channels are not in shadow
  - Weight matrix update

$$w_k = \begin{cases} 0 & I_k < \tau \\ \frac{\epsilon}{max(|s_k(\vec{N}) - I_k|, \epsilon)} & \text{otherwise} \end{cases}$$

Surface Reconstruction

- Error function P on depth z
  - D_x and D_y are matrices representing the x and y derivative operators on the vectorized image $\vec{z}$
  - $\vec{p} = \frac{-N_x}{N_z}$ and $\vec{q} = \frac{-N_y}{N_z}$ at every pixel

$$P(z) = \| \begin{bmatrix} D_x \\ D_y \end{bmatrix} \vec{z} - \begin{bmatrix} \vec{p} \\ \vec{q} \end{bmatrix} \|^p$$

- Let D be the differentiation matrix and $\vec{r} = [\vec{p} \ \ \vec{q}]^T$, we can use IRLS to find depth estimate as follows,

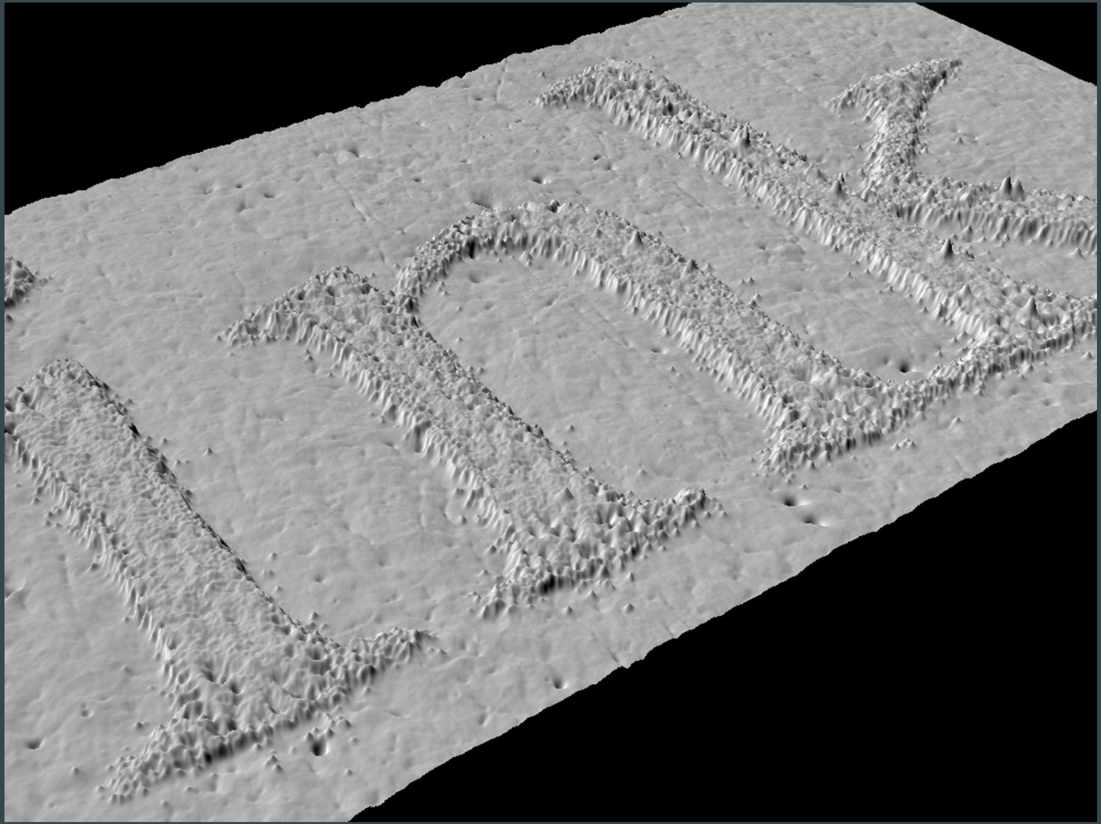
$$\vec{z}_{i+1} = (D^T W_i D)^{-1} D^T W_i \vec{r}$$

$$W_i = diag \begin{bmatrix} \frac{\epsilon}{max(D_x \vec{z_i} - \vec{p}, \epsilon)} \\ \frac{\epsilon}{max(D_y \vec{z_i} - \vec{q}, \epsilon)} \end{bmatrix}$$

Median Noise Reduction

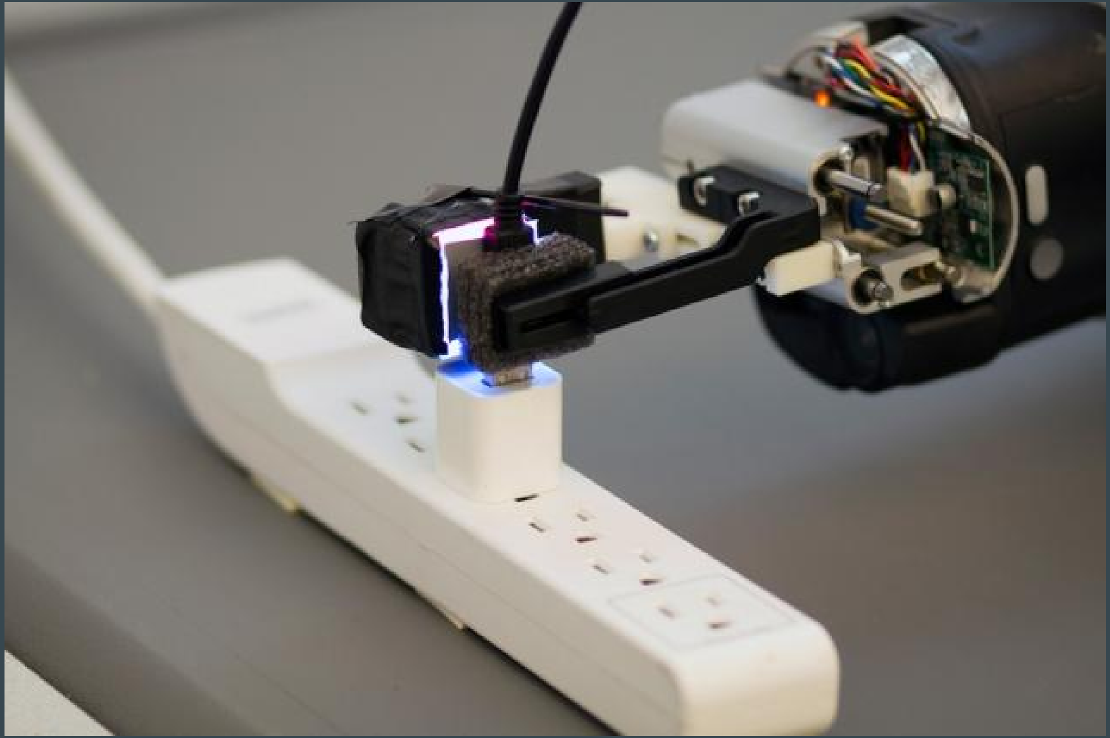
- Noise in measurements due to random imperfections in the reflective skin, dust or debris attached to the skin
- Solution:
  - Capture multiple images with different sensor positions (object position is fixed), compute median across multiple scans
  - Median computation done via image alignment (hierarchical coarse to fine grid search over different spatial alignments of images)

Capabilities

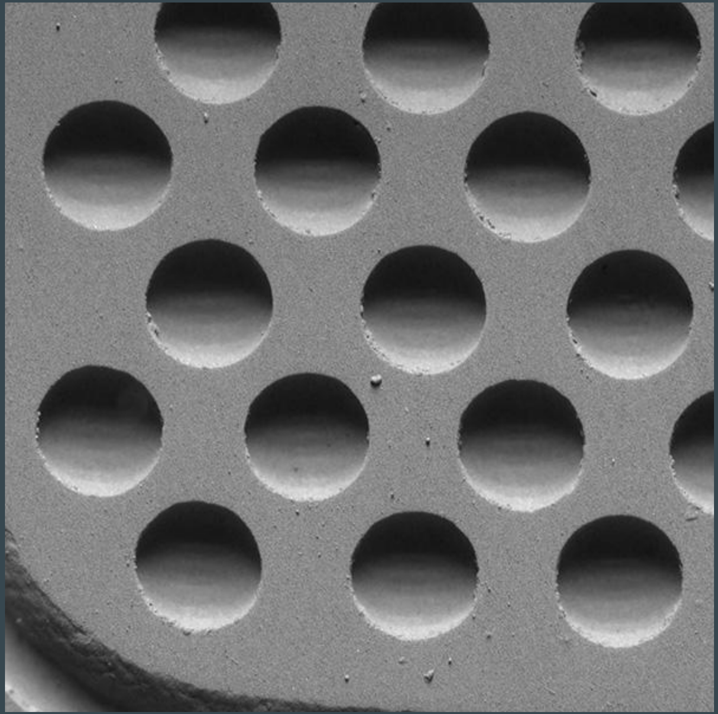


- Spatial resolution of 2 microns
- Invariant to optical characteristics of measured surface
- Low cost
- Non-destructive
- Portable
- Real-time
- Can be adapted into a variety of form factors

Products



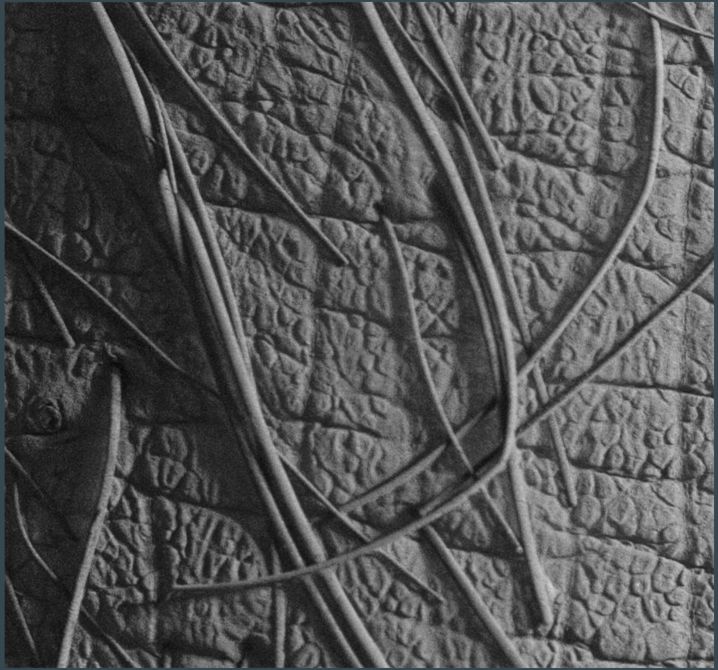
Raw Images Captured Using GelSight



Speaker grill on a cell phone

500 Yen coin

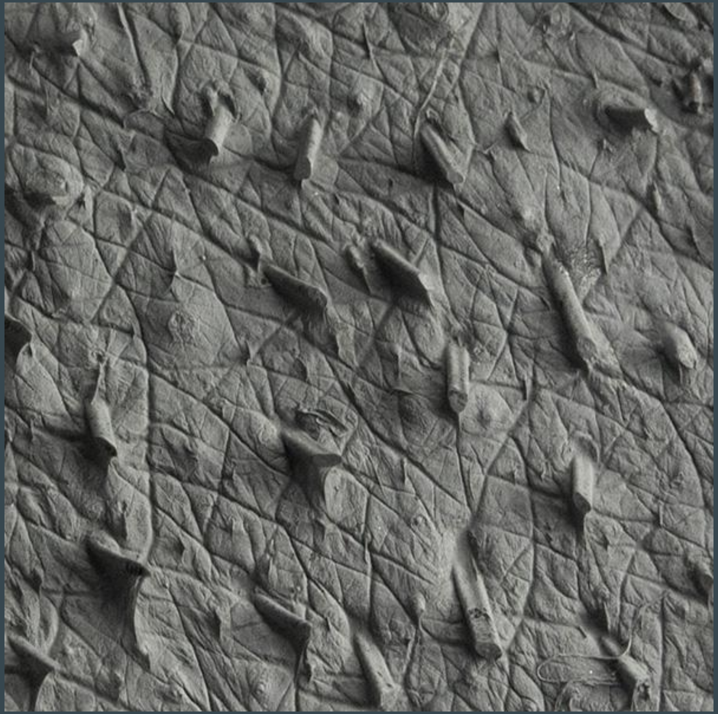
Raw Images Captured Using GelSight Cont.



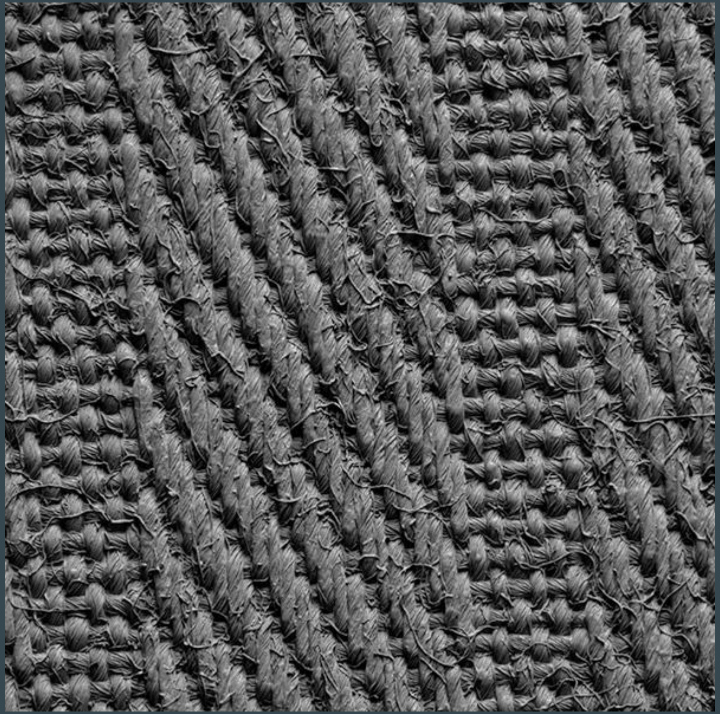
Hairs on a finger

Fingerprint

Raw Images Captured Using GelSight Cont.



Beard stubble



Fabric

Limitations

- Cannot capture geometry of holes or deep indentations
- Can flatten small hairs and deformable details
- Requires contact with sensor and for pressure to be applied
  - This is undesirable for fragile items
- Surface must be kept clean of debris for an accurate reading
- Surface must be maintained undamaged
- Can only capture the geometry of a surface; an entire object cannot be imaged

Score

- 2.5 - (the average of 2 & 3)
- Rationale
  - Jenna's Score: 2
    - The paper is well written
    - Impressive results were achieved
    - More experiments could have been documented
    - This paper has not been cited many times
  - Esha's Score: 3
    - Idea : well presented
    - Product development
    - Math: Could explain more about why use certain methods, how results were achieved

Works Cited

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