Sensing Deforming and Moving Objects with Commercial Off the Shelf Hardware

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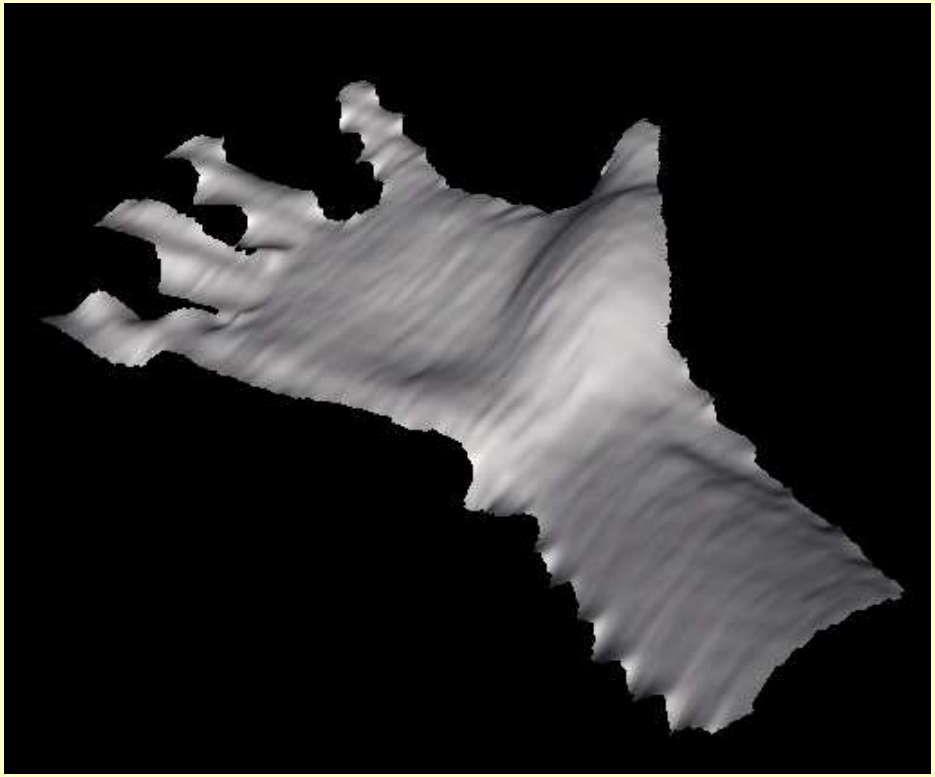
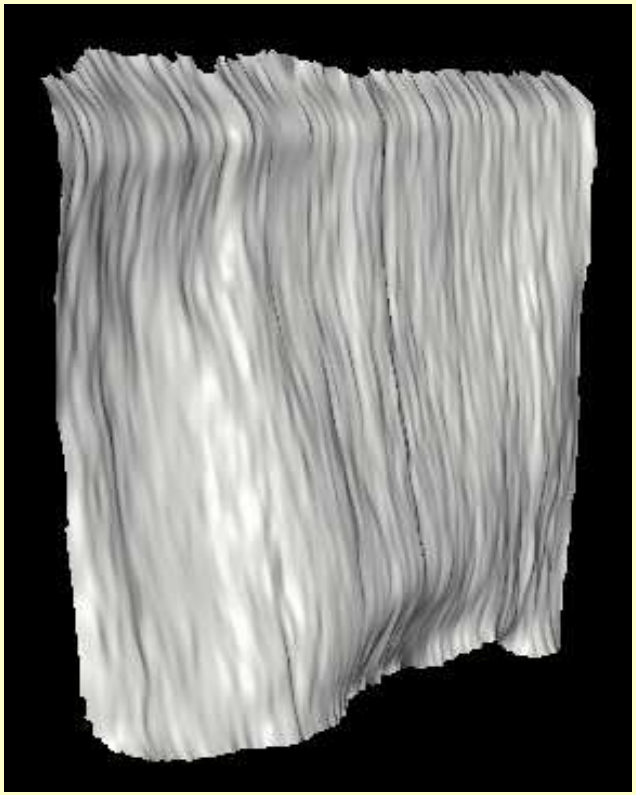
This work supported by:

Motivational Applications



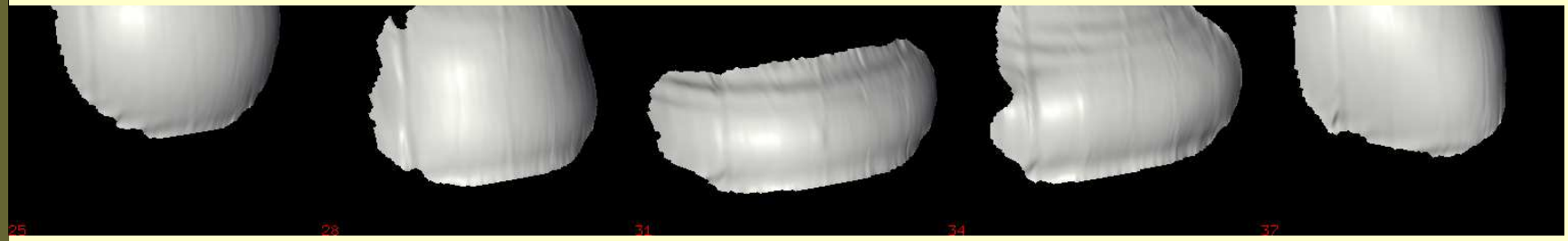
Human tissue modeling for surgical simulation



Robotic manipulation of fabric or rope

Motivational Applications

Need to sense 3D geometry of moving/deforming objects



Deformable object modeling

Goal

- Generate rangemaps (2.5D) from single images
  - No temporal coherence assumption
  - No restriction on motion
- Use commercially available hardware

Existing 3D Sensing Methods

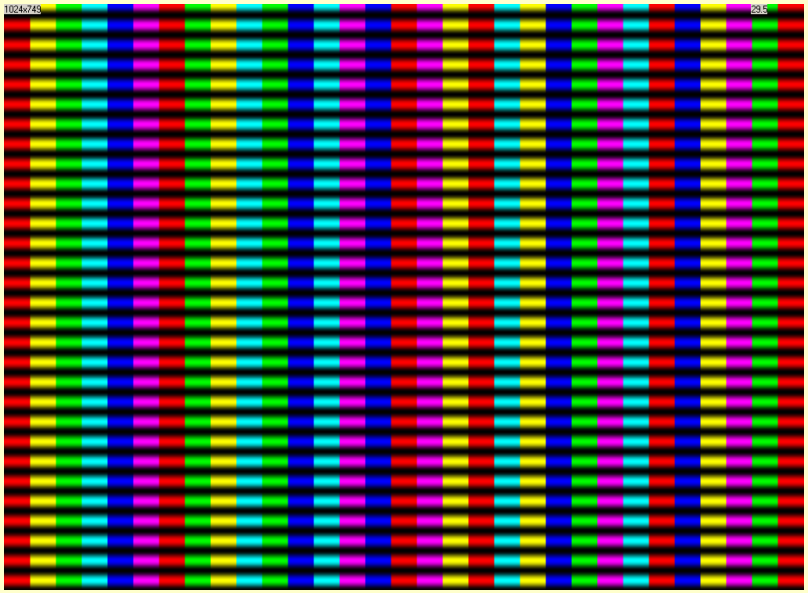
- Time of flight
  - Lidar, radar, sonar, shuttered light pulse
- Triangulation
  - Laser stripe scanner
  - Stereo
  - Structured Light
    - Can be implemented with commercial cameras and projectors
    - Sinusoids / Moiré gratings (Takeda and Kitoh; Tang and Hung, Sansoni *et al*)
    - Stripe patterns (Koninckx, Griesser, and Van Gool; Zhang, Curless, and Seitz; Caspi, Kiryati, and Shamir; Liu, Mu, and Fang)

Limitations of Existing Methods

- Requires scene be rigid and not moving
  - Laser scanner
- Requires non-repeating texture
  - Stereo vision
    - Applied to deforming cloth (Pritchard and Heidrich)
- Requires known scene topology and known anchor points
  - Sinusoids / Moiré gratings
- Requires multiple frames
  - Restricts movement
  - Spacetime Stereo (Davis, Ramamoothi, and Rusinkiewicz)
  - Stripes
    - In single frames, spatial resolution does not scale due to fixed number of encodings

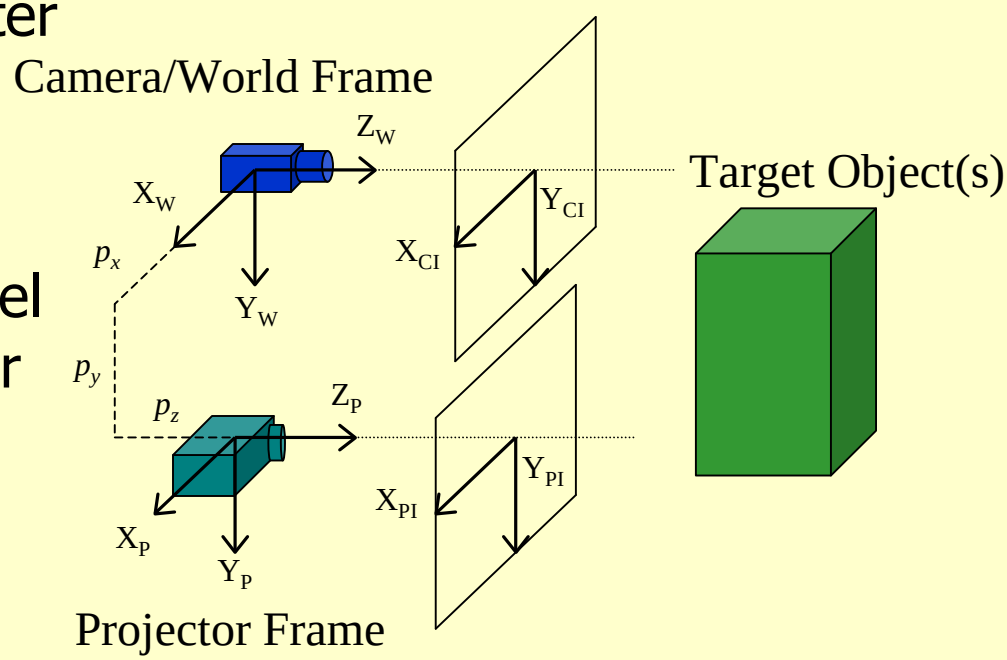
System Overview

- Idea: Combine colored stripes with sinusoid pattern
- Use sinusoidal pattern to produce dense rangemap
- Colored stripe transitions give sparse absolute depths
  - Use as known anchor points

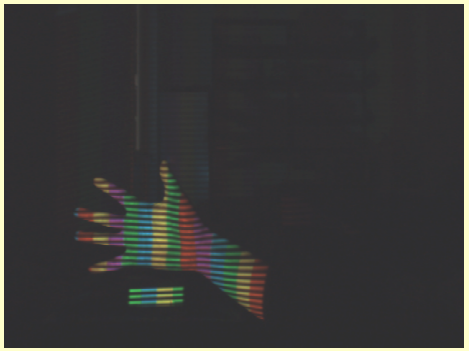


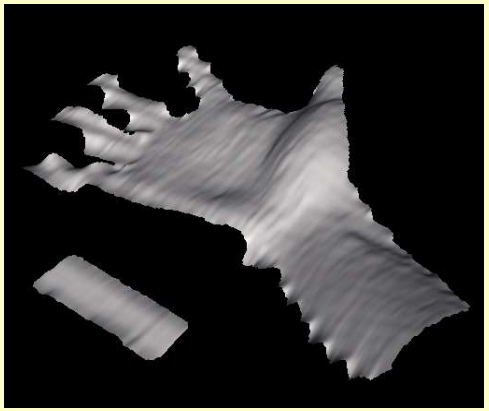
System Geometry

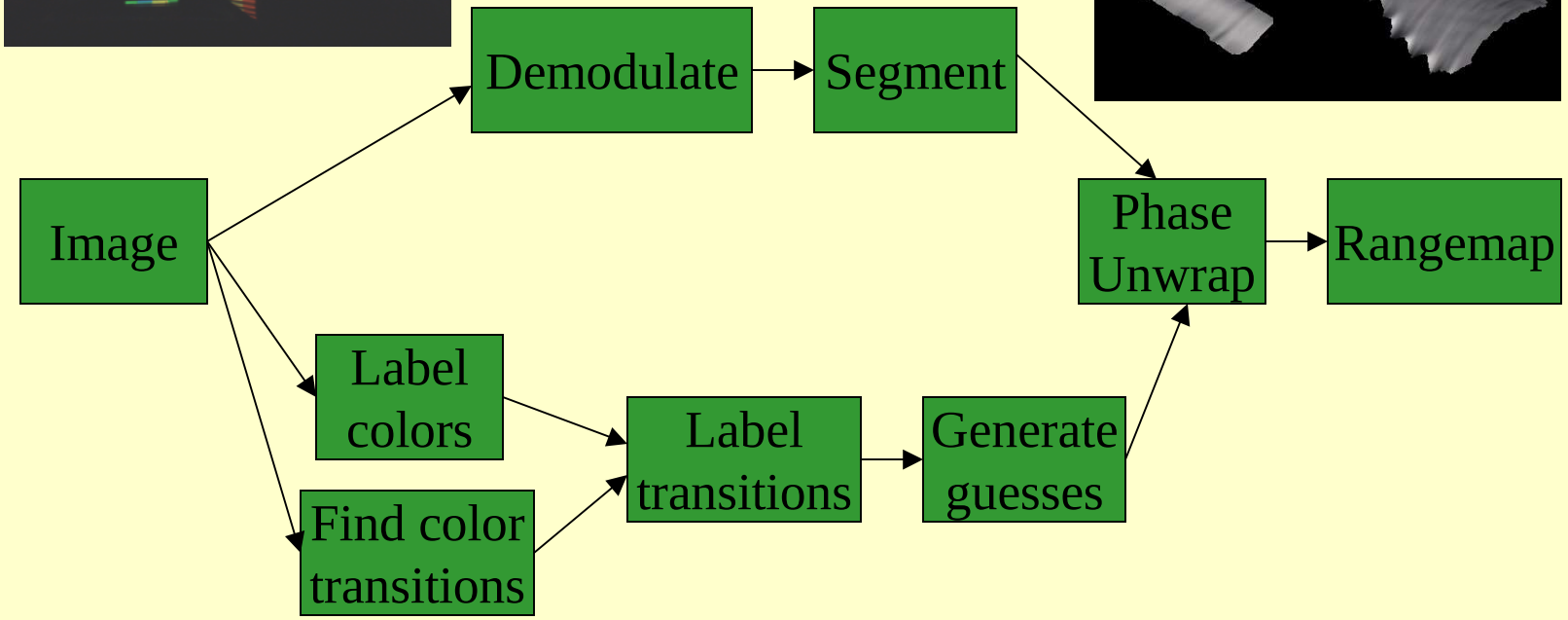
- Camera projection center at (0,0,0)
- Projector at (p_x, p_y, p_z)
- Parallel optical axes
- Pinhole projection model for camera and projector



System Overview







Depth from Sinusoid

- Projected sinusoid:

$$v({}^{\mathrm{PI}}x, {}^{\mathrm{PI}}y) = A\cos(\omega\, {}^{\mathrm{PI}}y) + C$$

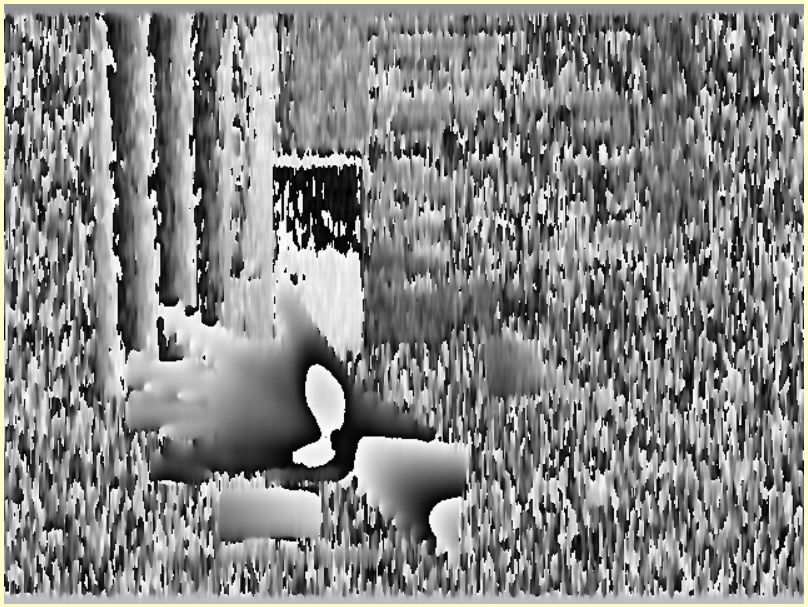
- Camera sees deformed sinusoid:

$$v({}^{\mathrm{CI}}x, {}^{\mathrm{CI}}y) = A\cos\left(\omega\, {}^{\mathrm{CI}}y - \theta({}^{\mathrm{CI}}x, {}^{\mathrm{CI}}y)\right)$$

$$\theta({}^{\mathrm{CI}}x, {}^{\mathrm{CI}}y) = \omega\left(\frac{-{}^{\mathrm{W}}p_{\mathrm{Z}}\, {}^{\mathrm{CI}}y + {}^{\mathrm{W}}p_{\mathrm{Y}}}{{}^{\mathrm{W}}z({}^{\mathrm{CI}}x, {}^{\mathrm{CI}}y) - {}^{\mathrm{W}}p_{\mathrm{Z}}}\right)$$

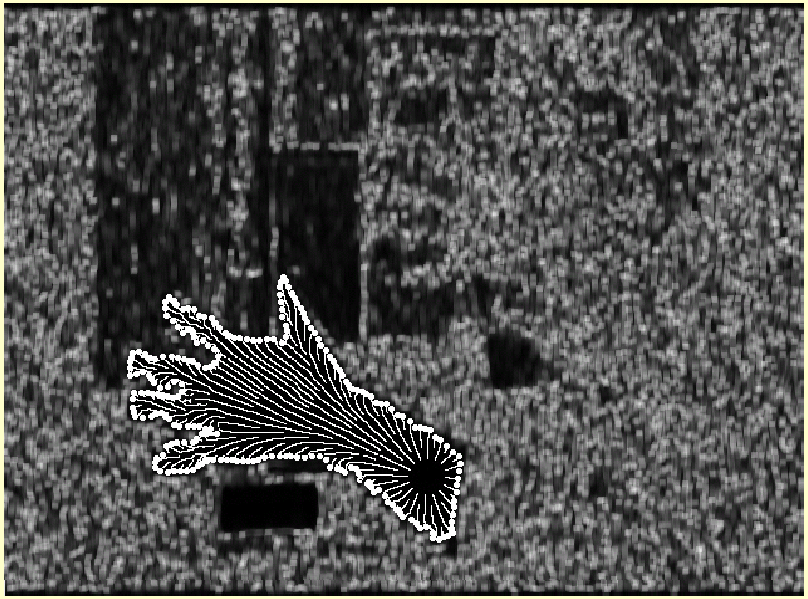
- Demodulate to get wrapped phase (Tang and Hung):

$$\theta_{\mathrm{w}} = \arctan 2(\sin(\theta), \cos(\theta))$$



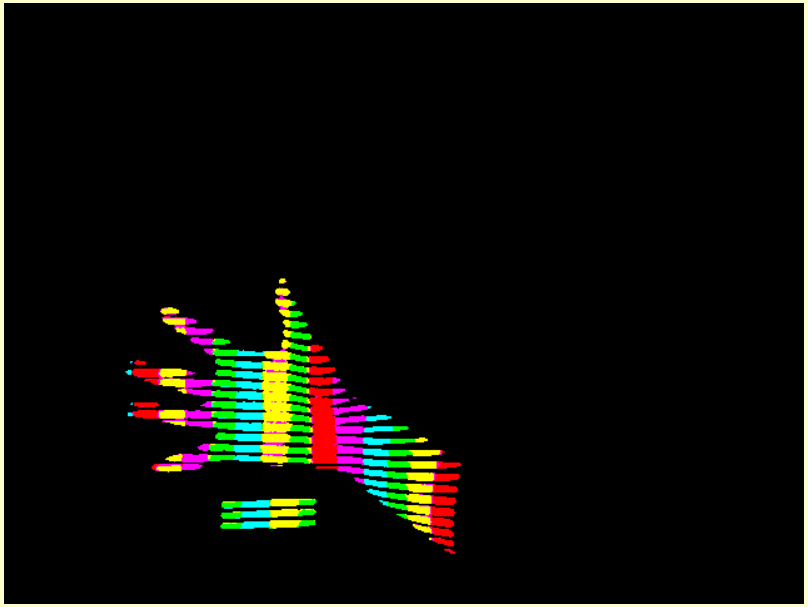
Segmenting

- Phase unwrapping assumes θ changes by less than 2π between pixels
- Segment image into regions based on phase variance (Ghiglia and Pritt) using snakes



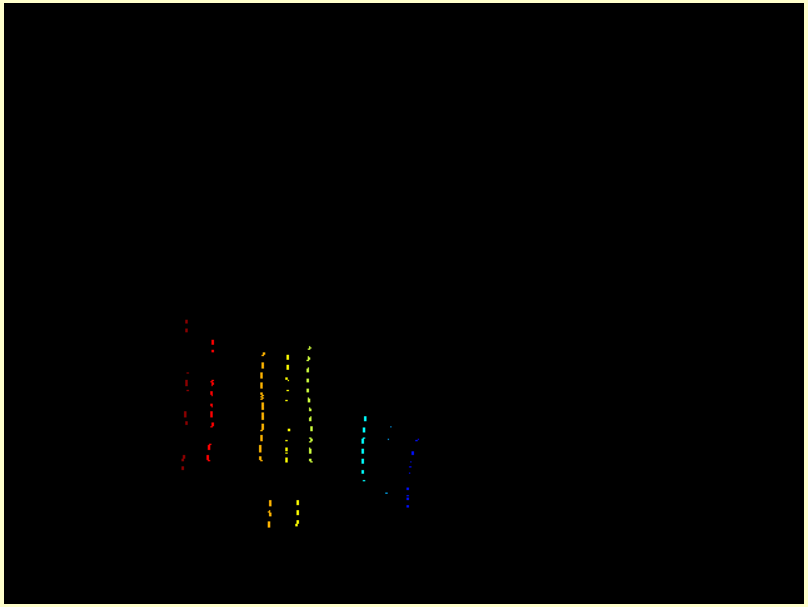
Labeling Colors

- Label and score pixels with colors using Bayesian classifier
- PDFs of colors in hue space are approximated with a gaussian distribution



Labeling Color Transitions

- Threshold change in hue between pixels along X direction
- Label each detected transition according to the projected pattern
  - Based on color label scores in pixel windows to the left and right of transition
  - Ignore transitions:
    - Not consistent with projected pattern
    - Over a max width



Generating Guesses

- In projected pattern
  - Each transition appears only once
  - Identifies unique vertical plane
- Intersect with ray corresponding to transition location in camera to compute depth
- Use as guesses in phase unwrapping

Phase Unwrapping

- Compute phase gradient assuming no jumps greater than 2π
- Integrate to get θ_u

$$\theta(x, y) = \theta_u(x, y) + 2\pi k$$

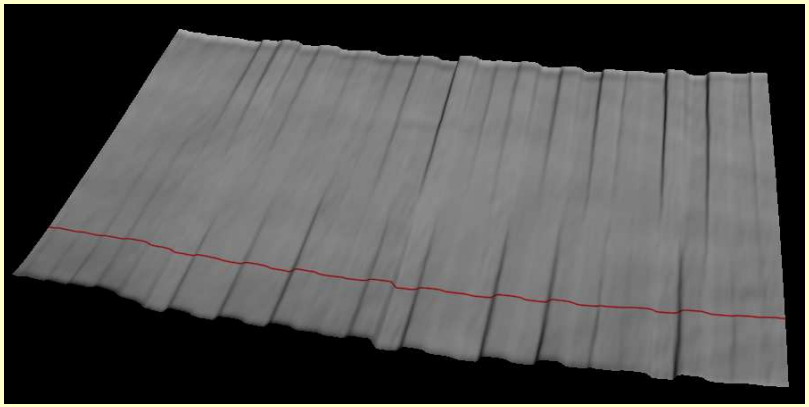
- For each region compute *k* from median of the difference between guesses and θ_u
- Compute rangemap from θ

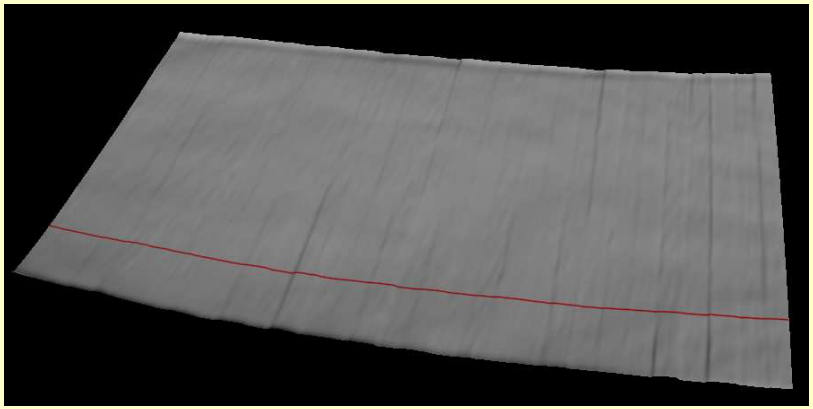
Calibrating for Chromatic Aberration

- Chromatic aberration in camera and projector lenses distort pattern
- Model distortion with:
  - Focal length ratio of red and green in camera and projector (α, β)
  - Red optical center shift (γ) in projector
- Minimize:

$$\sum_{Q}(\theta_s(x\alpha, y\alpha) - \theta_g(x, y))^2$$

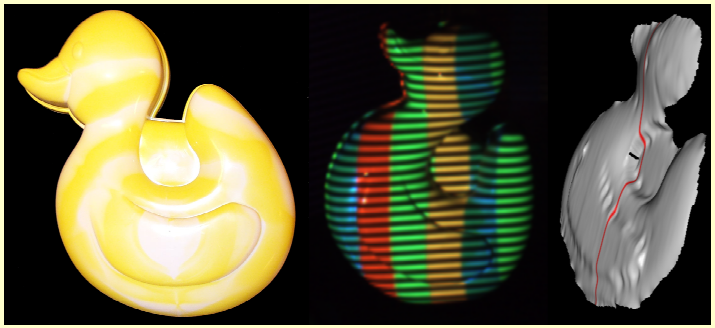
$$\theta_s(x, y) = \beta(\theta_r(x, y) - \omega((\tfrac{1}{\alpha} - 1)y - \gamma)$$

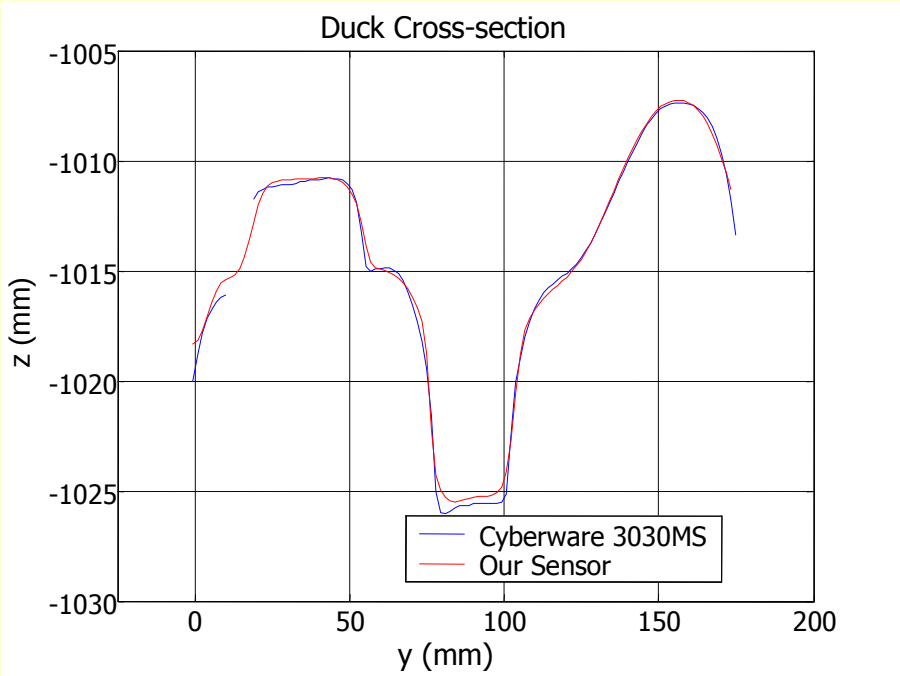




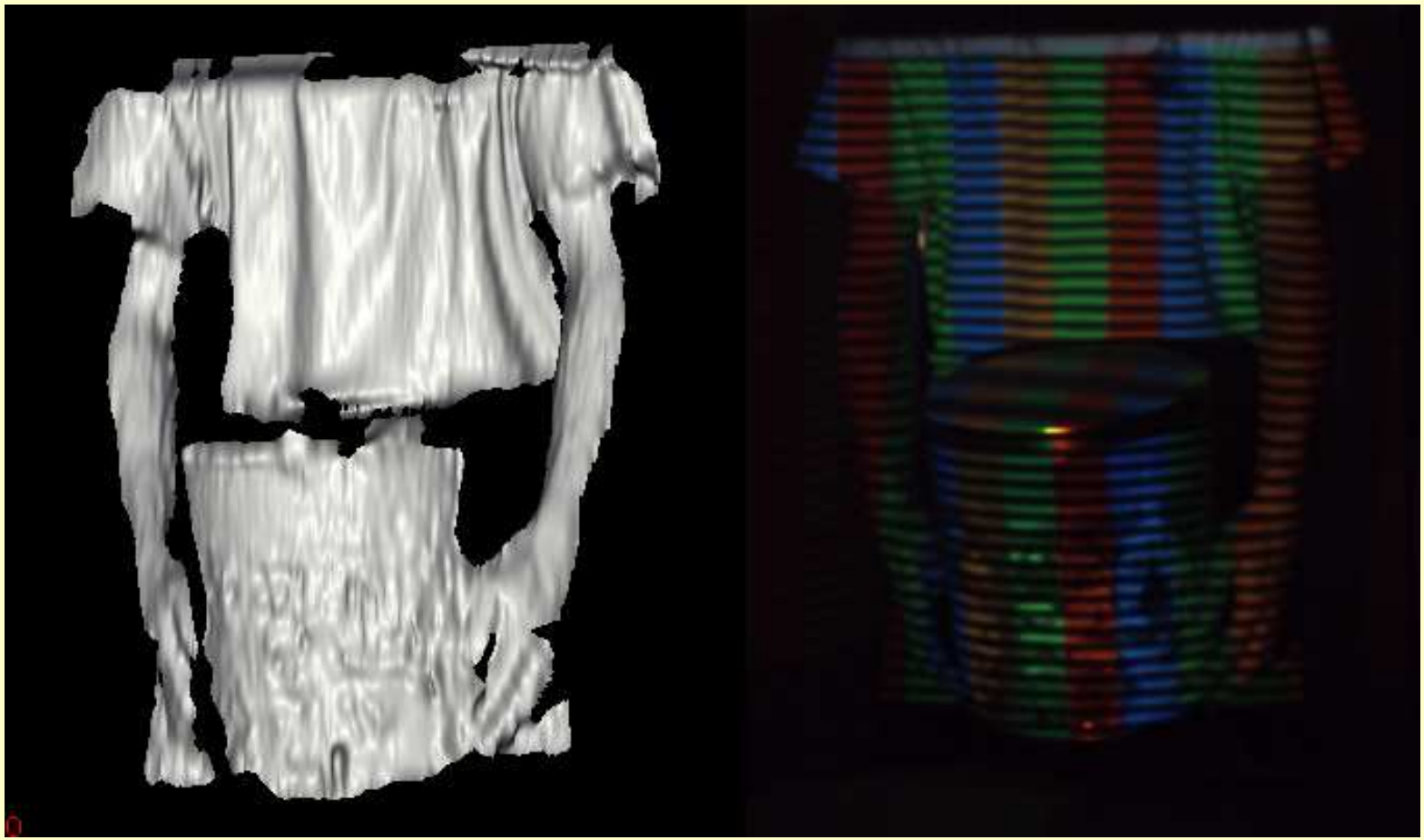
Results: Plastic Duck

- 0.48mm (0.1%) RMS error compared to Cyberware 3030MS laser scanner

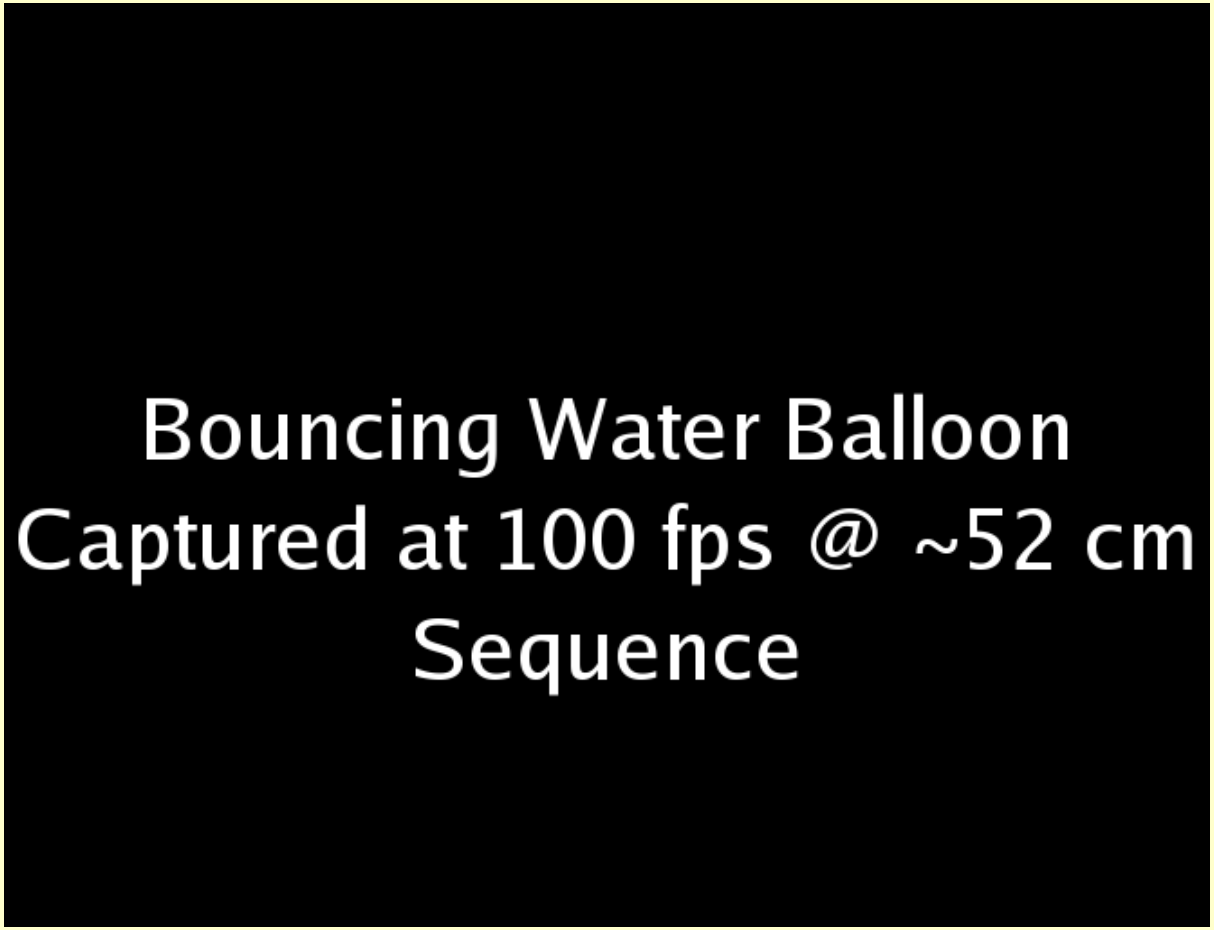




Results: Popcorn Tin



Results: Water Balloon



Advantages / Limitations

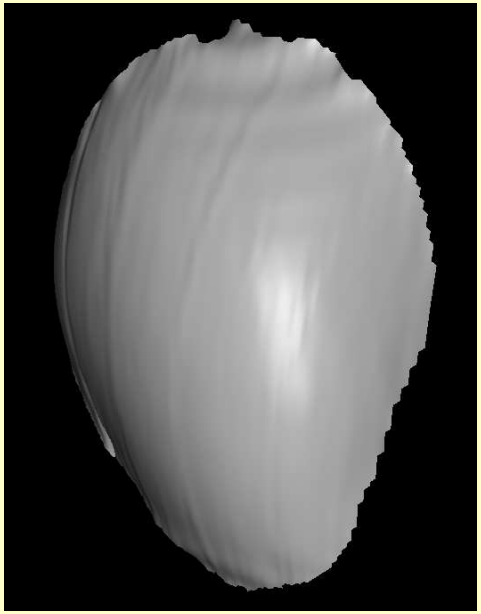
- Spatial resolution scales with camera and projector resolution
- Temporal resolution scales with camera speed
  - Not limited by projector speed

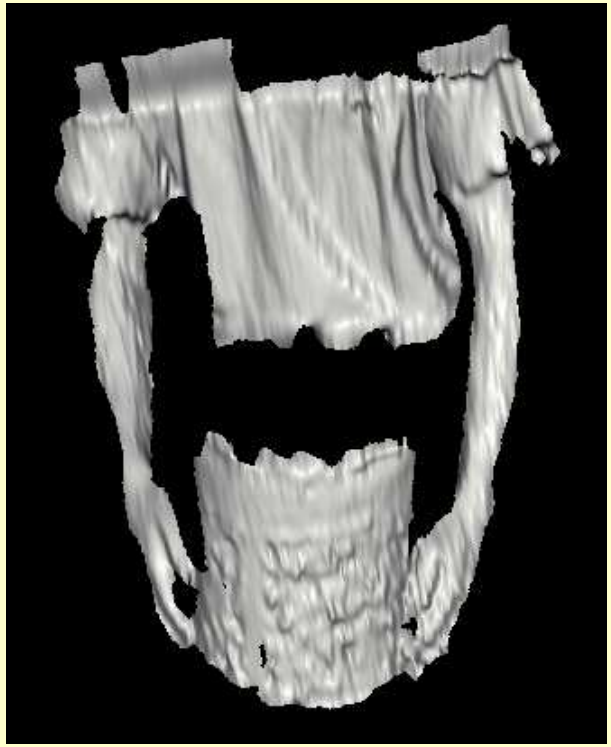
- Each segmented region must contain at least one recognized color transition
- Objects with many saturated colors are hard to sense
  - Mitigated by choosing right set of colors in pattern
- Single viewpoint only senses one side of objects
  - No straight forward way to project and sense from multiple viewpoints simultaneously

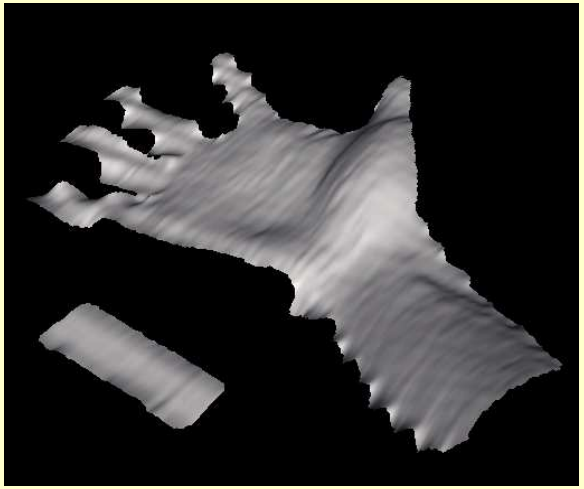
Conclusions / Results

- Combined sinusoidal and colored stripe pattern is effective
  - Produces good quality dense range maps of moving and deforming objects
- Chromatic aberration calibration allows use of commercial cameras and projectors

Questions?







These and more at:
http://www.stanford.edu/~fongpwf/research.html