Range Sensing of Dynamic and Deformable Objects

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Target Applications of Range Sensor

Building models for surgical training simulations
- Human Tissue (skin, etc.)

Sensing in robotic manipulation
- Fabric and rope

Sensing holds for rock climbing robot
- Climbing walls and rock walls

Building models for films or videogames
- Virtual actors, clothes, curtains, etc.

Sensor Requirements

Ability to capture moving and deforming objects
- Extract depth information from single frames
- Sense entire scene at the same instant

Limitations of Current Methods

Laser Scanners
- Sweeps a laser across the field of view
- Limited to non moving rigid objects

Traditional Stereo Matching
- Matches features from two viewpoints
- No depth information in areas of uniform or repeating
- texture

Depth from Structured Light

General Approach
- Project a pattern on the object
- Use deformation of pattern to compute depth

Many types of patterns
- Ramp (Carihill et al. '85)
  - Very sensitive to noise
- Sinusoids (Takeda et al. '83)
  - Requires starting guesses
- Colored stripes (Zhang et al. '02, Lu et al.), Hierarchical stripes (Sansoni et al. '94)
  - Requires multiple images

System Geometry

- Camera at (0,0,0)
- Projector at (Px, Py, Pz)
- Pinhole camera model

$$x_{ci} = f_{cx}\frac{x}{z},\; x_{pi} = f_{px}\frac{x-P_x}{z-P_z}$$

$$y_{ci} = f_{cy}\frac{y}{z},\; y_{pi} = f_{py}\frac{y-P_y}{z-P_z}$$

Project:

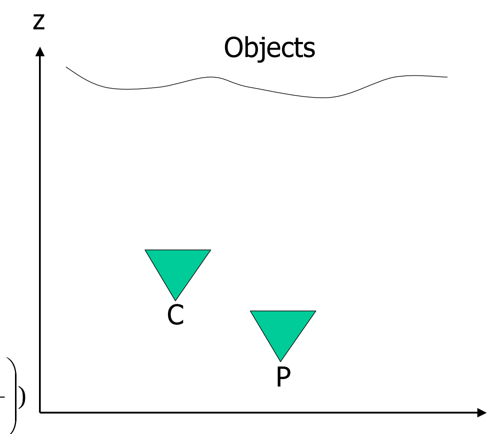
$$g(x_{pi}, y_{pi}) = A\cos(\omega y_{pi})$$

Camera sees:

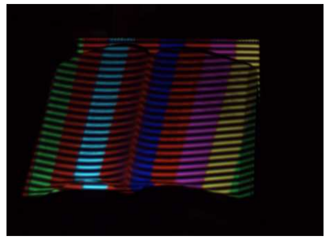
$$g(y_{ci}) = A(x,y)\cos\left(\omega f_{px}\left(\frac{\frac{z y_{ci}}{f_{cx}} - P_y}{z - P_z}\right)\right)$$

$$= A(x,y)\cos\left(\omega \frac{f_{py}}{f_{cy}} y_{ci} - \theta(y_{ci})\right)$$

$$\theta(y_{ci}) = \omega f_{py}\left(\frac{-P_z y_{ci}}{(z-P_z) f_{cy}} + \frac{P_y}{(z-P_z)}\right)$$



Projected Pattern



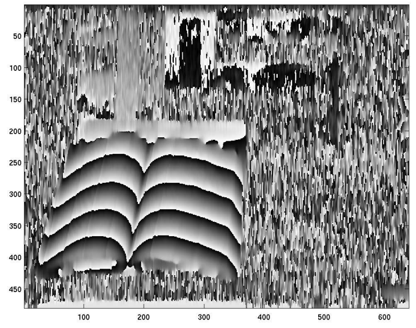
Combination Pattern
- Vertical sinusoidal pattern
  - Phase (Θ) provides dense depth information
  - Requires starting guesses to unwrap phase
- Horizontal color stripes
  - 31 unique color transitions
  - Provides starting guesses for phase unwrapping

Depth from Sinusiodal Pattern

1. Demodulate to get wrapped phase (Θ_w=atan2(sin(Θ),cos(Θ))
2. Use initial guesses to unwrap phase and get Θ

$$\theta(y_{ci}) = \omega f_{py}\left(\frac{-P_z y_{ci}}{(z-P_z) f_{cy}} + \frac{P_y}{(z-P_z)}\right)$$

$$z(y_{ci}) = \frac{\omega f_{py}(-P_z y_{ci} + P_y f_{cy})}{f_{cy}\theta(y_{ci})} - P_z$$

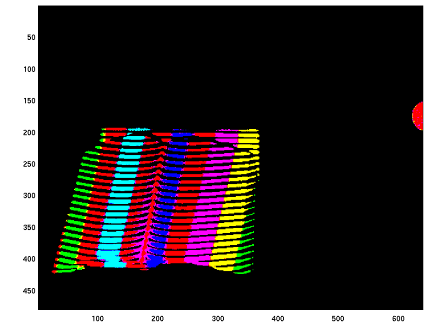


Depth from Stripe Transitions

1. Find transitions using derivative of hue in HSV space
2. Label color of each pixel using Bayesian classifier
3. Label each transition based on color labels of pixels on each side of the transition

If transition at x_{ci} corresponds to transition at x_{pi}:

$$z(x_{ci}) = \frac{P_x f_{cx} f_{px} - x_{pi} P_z f_{cx}}{x_{ci} f_{px} - x_{pi} f_{cx}}$$

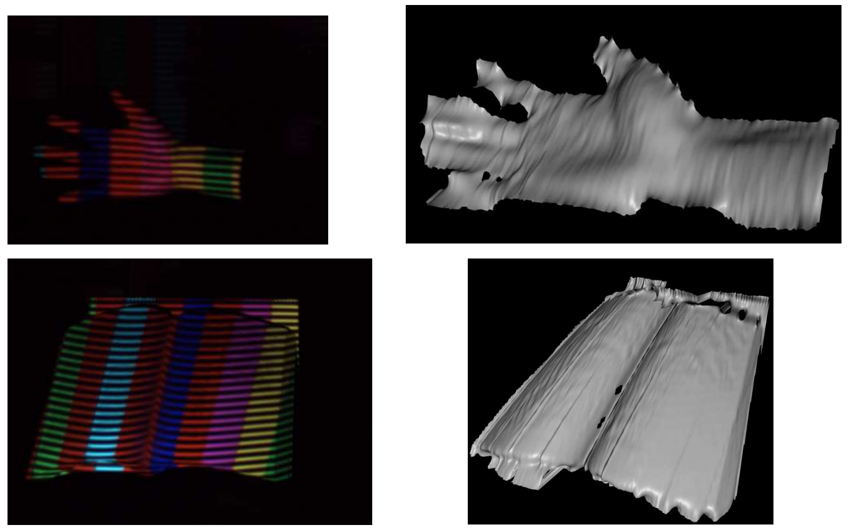


Hardware Prototype

Basler A602fc Firewire camera
- 640x480 @ 100 fps

Viewsonic PJ551 LCD Projector
- 1024x768 native resolution

Sample Results



Selected References

M. Takeda and K. Mutoh, *Applied Optics.* Vol 22 p. 3977, 1983

L. Zhang, B. Curless, and S. M. Seitz. *1st International Symposium on 3D Data Processing, Visualization, and Transmission*, Padova, Italy, June 19-21, 2002.