Shadow Scanning  [Bouguet 1999]


Basic Idea

Calibration issues:
- where’s the camera wrt. ground plane?
- where’s the shadow plane?
  - depends on light source position, shadow edge

(from Jiwon Kim and Jia-chi Wu)
Two Plane Version

Advantage
- don’t need to pre-calibrate the light source
- shadow plane determined from two shadow edges

Angel experiment

Accuracy: 0.1mm over 10cm ~ 0.1% error
Textured objects

Accuracy: 1mm over 50cm

~ 0.5% error

Scanning with the sun
Scanning with the sun

Accuracy: 1cm over 2m
~ 0.5% error

Shading as a 3D Cue

Merle Norman Cosmetics, Los Angeles
Shape from Shading [Horn, 1970]

Classical Approach

• Suppose reflected light depends only on $\alpha$

\[\text{radiance} = k \cos \alpha\]

The Reflectance Map

Suppose

• image intensity = $\cos \alpha$
• $L$ is known

\[\mathbf{N} = \begin{bmatrix} \frac{\partial z}{\partial x} & \frac{\partial z}{\partial y} & -1 \end{bmatrix} = \begin{bmatrix} p & q & -1 \end{bmatrix}\]
The Reflectance Map

Finding a Unique Solution

Three Approaches

• Characteristic Strip Method [Horn, 77]
  – select a few points where normal is known
  – grow solution by moving direction of $\nabla R$

• Variational Method [Ikeuchi & Horn, 81]
  – start with an initial guess of surface shape
  – define energy function
  – refine to minimize energy function

• Photometric Stereo [Woodham 80]
  – use more images
Shape from Shading

Lee & Kau 91 (from survey by Zhang et al., 1999)

Photometric Stereo

Two Images Under Different Lighting

*Need Three Images for Unique Solution*
Photometric Stereo: Matrix Formulation

Write Equations in Matrix Form

\[
\begin{align*}
I_1 &= \hat{L}_1^T \hat{N} \\
I_2 &= \hat{L}_2^T \hat{N} \\
I_3 &= \hat{L}_3^T \hat{N}
\end{align*}
\]

\[
L_{3\times3} \tilde{N}_{3\times1} = k \tilde{I}_{3\times1} = L_1^{-1} I
\]

\[
k = \| \tilde{N} \|
\]

Advantage:
- Can solve for reflectance \( k \) that varies over the surface

Depth from Normals

- Solve for \( z(i,j) \) from \( (p,q) \)
- This is an integration problem—can be solved by minimizing an energy function:

\[
E = E_{\text{data}} + E_{\text{smooth}} + E_{\text{constraint}}
\]

\[
= \sum_{i,j} E_{\text{data}} + \sum_{i,j} E_{\text{smooth}} + \sum_{(i,j)\text{constraint}} E_{\text{constraint}}
\]

\[
= \sum_{i,j} \left( \left( \frac{\partial z(i,j)}{\partial x} - p\right)^2 + \left( \frac{\partial z(i,j)}{\partial y} - q\right)^2 \right) + \sum_{i,j} \left( \left( \frac{\partial^2 z(i,j)}{\partial x^2} \right)^2 + 2 \left( \frac{\partial^2 z(i,j)}{\partial x \partial y} \right)^2 + \left( \frac{\partial^2 z(i,j)}{\partial y^2} \right)^2 \right) + \sum_{(i,j)\text{constraint}} \left( z[i,j] - c_{i,j} \right)^2
\]

(from Yung-Yu Chuang and David Ely)
Issues

Limitations?
- Lambertian assumption
- No interreflections
  - work by Shree Nayar & colleagues addresses this issue
- No transparency
- No discontinuities
- Requires known light source

Strengths (compared to stereo)?
- No correspondence problem
- Recovers reflectance parameter
- Easier to implement

Bibliography

Shape from Shading/Photometric Stereo

Shadow Scanning
- For papers, images, models, talks, and more, see: http://www.vision.caltech.edu/bouguetj/ICCV98/