Lighting and Photometric Stereo

Computer Vision I
CSE252A
Lecture 7

Announcement

• Read Chapter 2 of Forsyth & Ponce
• Might find section 12.1.3 of Forsyth & Ponce useful.
• HW Problem

The Reflection Equation

\[ L_r(x, \omega_i) = \int \frac{f_l(x, \omega_i) \rightarrow \omega_i}{|\omega_i|} L_i(x, \omega_i) \cos \theta \, d\omega_i \]

where \( \omega_i = (\theta_i, \phi_i) \)

Surface Reflectance Models

Common Models

• Lambertian
• Phong
• Physics-based
  – Specular
    [Blinn 1977], [Cook-Torrance 1982], [Ward 1992]
  – Diffuse
    [Hanrahan, Kreeger 1993]
  – Generalized Lambertian
    [Oren, Nayar 1995]
  – Thoroughly Pitted Surfaces
    [Koenderink et al 1999]
• Phenomenological
  [Koenderink, Van Doom 1996]

Lambertian (Diffuse) Surface

• BRDF is a constant called the albedo, \( \rho \). \[ L_r(x, \omega_i) = \rho_i \]
• Emitted radiance is NOT a function of the outgoing direction—i.e. constant in all directions.
• For lighting coming in single direction \( \omega_i \), we can write \( L_r(x, \omega_i) = \delta(\omega_i - \omega_i) \), and consequently the emitted radiance is proportional to cosine of the angle between normal and light direction.

\[ L_r = \rho_i \hat{N} \cdot \omega_i \]
Lambertian reflection

Light is emitted equally in all directions

Specular Reflection: Smooth Surface

Rough Specular Surface

Phong Model

Non-Lambertian Reflectance

General BRDF: e.g. Velvet

[After Koenderink et al., 1998]
Three degrees of freedom spread among light source, detector, and/or sample.

Can add fourth degree of freedom to measure anisotropic BRDFs.

Collect reflected light with hemispherical (should be ellipsoidal) mirror [SIGGRAPH 92].

Result: each image captures light at all exitant angles.

For uniform BRDF, capture 2-D slice corresponding to variations in normals.
Light Sources

Distant point source model
Also called Light Source at Infinity

- The sun illuminating the earth
- A source that is far enough away so that all light rays coming from the source can be treated as being parallel and of the same radiance.
- For a Lambertian surface, illuminated by a distant light source in direction $S/|S|$ and with strength $|S|$, image brightness is:
  $$\rho_0(x)(N(x) \cdot S)$$
  works because a dot-product is basically a cosine

Diffuse lighting at infinity: Spherical Harmonic expansion

$$Y_{lm}(\theta, \varphi)$$

Order

Green: Positive
Blue: Negative

(Borrowed from: Ramamoorthi, Hanrahan, SIGGRAPH'01)

Standard nearby point source model

- $N$ is the surface normal
- $\rho_0$ in the diffuse (Lambertian) albedo
- $S$ is source vector - a vector from $x$ to the source, whose length is the intensity term
  - works because a dot-product is basically a cosine
Line sources

\[ \text{radiosity due to line source varies with inverse distance, if the source is long enough} \]

Area sources

- Examples: diffuser boxes, white walls.
- The radiosity at a point due to an area source is obtained by adding up the contribution over the section of view hemisphere subtended by the source:
  - change variables and add up over the source
- See Forsyth & Ponce or a graphics text for details.

Images as a Collection of Rays

Conversely, the light emitted at a given point also is a function on a 2D space (sphere).

The Plenoptic Function

Conversely, the set of light rays emitted from all points...

Shadows cast by a point source

- A point that can’t see the source is in shadow
- For point sources, the geometry is simple

Area Source Shadows

- Fully illuminated
- Penumbra
- Umbra (shadow)
Shading models

Local shading model
• Surface has incident radiance due only to sources visible at each point
• Advantages:
  – often easy to manipulate, expressions easy
  – supports quite simple theories of how shape information can be extracted from shading
• Used in vision & real-time graphics

Global shading model
• Surface radiosity is due to radiance reflected from other surfaces as well as from surfaces
• Advantages:
  – usually very accurate
• Disadvantage:
  – extremely difficult to infer anything from shading values
• Rarely used in vision, often in photorealistic graphics

What’s going on here?

• Local shading model is a poor description of physical processes that give rise to images
  – because surfaces reflect light onto one another
• This is a major nuisance; the distribution of light (in principle) depends on the configuration of every radiator; big distant ones are as important as small nearby ones (solid angle)
• The effects are easy to model
• It appears to be hard to extract information from these models

Photometric Stereo

At the top, geometry of a gutter with triangular cross-section; below, predicted radiosity solutions, scaled to lie on top of each other, for different albedos of the geometry. When albedo is close to zero, shading follows a local model; when it is close to one, there are substantial reflexes.
Shading reveals 3-D surface geometry

Two shape-from-X methods that use shading

- Shape-from-shading: Use just one image to recover shape. Requires knowledge of light source direction and BRDF everywhere. Too restrictive to be useful.

- Photometric stereo: Single viewpoint, multiple images under different lighting.
  1. Arbitrary known BRDF
  2. Lambertian BRDF, known lighting
  3. Lambertian BRDF, unknown lighting.

Photometric Stereo Rigs: One viewpoint, changing lighting

Multi-view stereo vs. Photometric Stereo: Assumptions

- Multi-view (binocular) Stereo
  - Multiple images
  - Dynamic scene
  - Multiple viewpoints
  - Fixed lighting

- Photometric Stereo
  - Multiple images
  - Static scene
  - Fixed viewpoint
  - Multiple lighting conditions

An example of photometric stereo

Photometric Stereo: General BRDF and Reflectance Map
BRDF

- Bi-directional Reflectance Distribution Function
  \( \rho(\theta_{in}, \phi_{in}; \theta_{out}, \phi_{out}) \)
- Function of
  - Incoming light direction:
    \( \theta_{in}, \phi_{in} \)
  - Outgoing light direction:
    \( \theta_{out}, \phi_{out} \)
- Ratio of incident irradiance to emitted radiance

Coordinate system

Surface: \( s(x,y) = (x, y, f(x,y)) \)
Tangent vectors:
\[
\frac{\partial s(x,y)}{\partial x} = (1, \frac{\partial f}{\partial x}, \frac{\partial f}{\partial y})
\]
\[
\frac{\partial s(x,y)}{\partial y} = (0, \frac{\partial f}{\partial x}, \frac{\partial f}{\partial y})
\]
Normal vector
\[
\hat{n} = \frac{\frac{\partial f}{\partial x} \mathbf{i} + \frac{\partial f}{\partial y} \mathbf{j} - \mathbf{k}}{\sqrt{\left(\frac{\partial f}{\partial x}\right)^2 + \left(\frac{\partial f}{\partial y}\right)^2 + 1}}
\]
Gradient Space (p, q)

Gradient Space: \( (p, q) \)
\[
p = \frac{\partial f}{\partial x}, \quad q = \frac{\partial f}{\partial y}
\]
Normal vector
\[
\hat{n} = \frac{\frac{\partial f}{\partial x} \mathbf{i} + \frac{\partial f}{\partial y} \mathbf{j} - \mathbf{k}}{\sqrt{\left(\frac{\partial f}{\partial x}\right)^2 + \left(\frac{\partial f}{\partial y}\right)^2 + 1}}
\]
\[
\hat{a} = \frac{1}{\sqrt{p^2 + q^2 + 1}} (p, q, -1)
\]