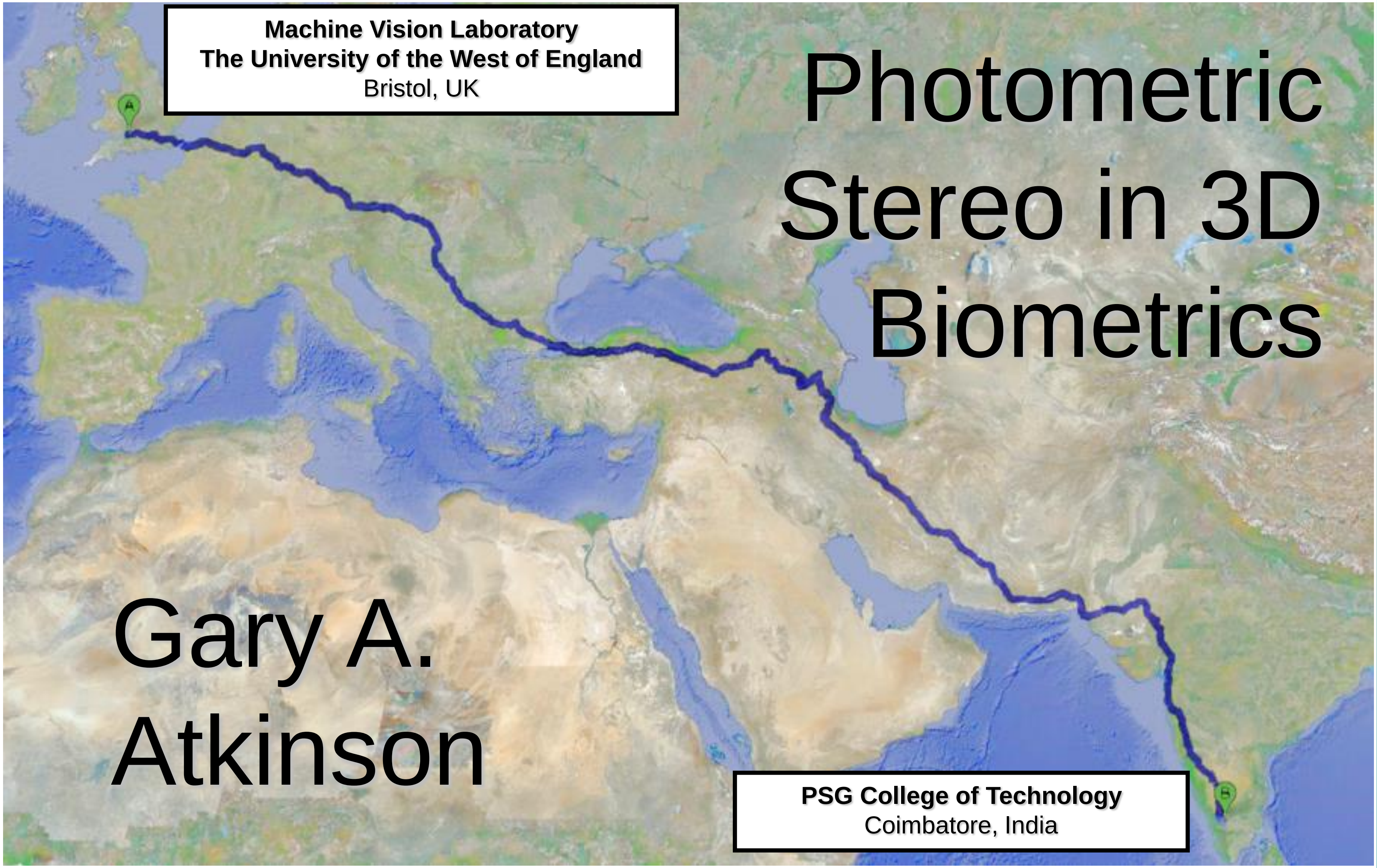
University of the West of England
BRISTOL

Machine Vision Laboratory

2nd September 2010
ICEBT



Machine Vision Laboratory
The University of the West of England
Bristol, UK

Photometric Stereo in 3D Biometrics

Gary A. Atkinson

PSG College of Technology
Coimbatore, India

Overview

1. What is photometric stereo?
2. Why photometric stereo?
3. The basic method
4. Advanced methods
5. Applications

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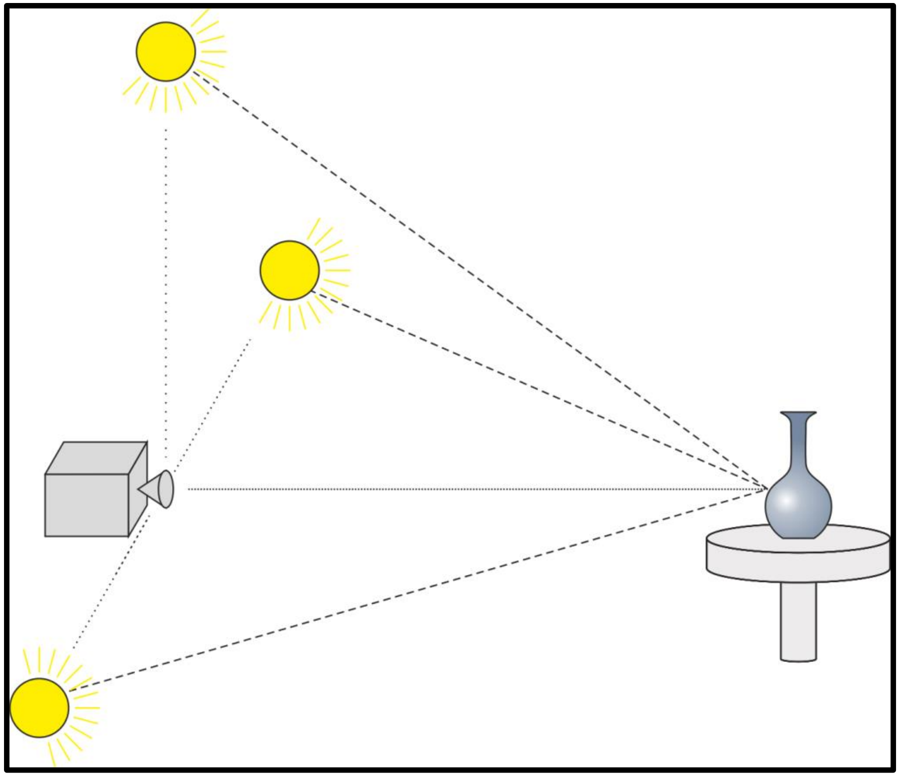
1. What is Photometric Stereo?

A method of estimating surface geometry using multiple light source directions



Captured images

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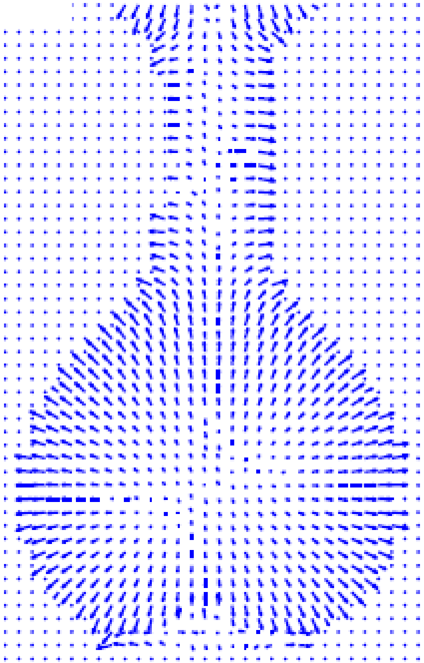


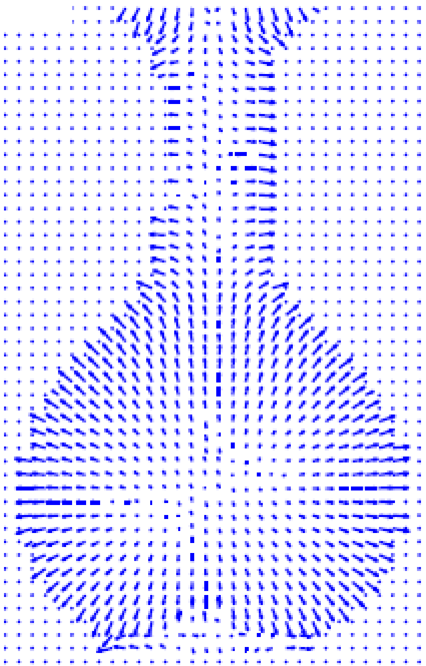
Captured images

Surface normals

1. What is Photometric Stereo?

A method of estimating surface geometry using multiple light source directions

Depth map



Surface normals

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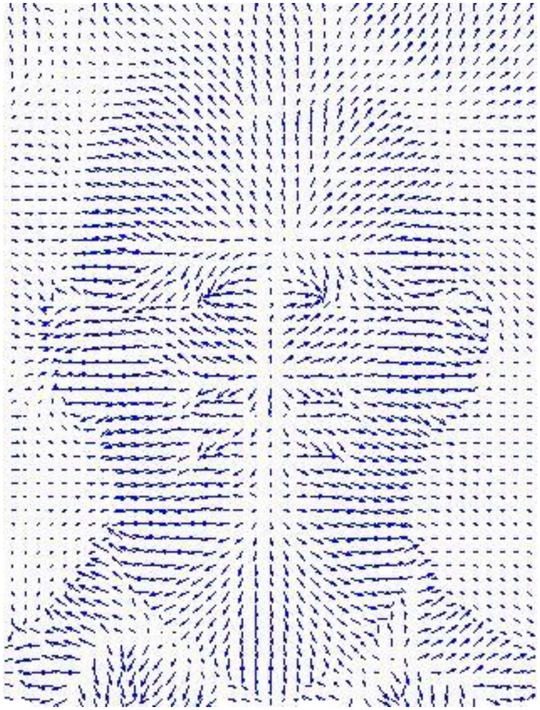

Depth map

Surface normals

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2. Why photometric Stereo?

Why 3D?

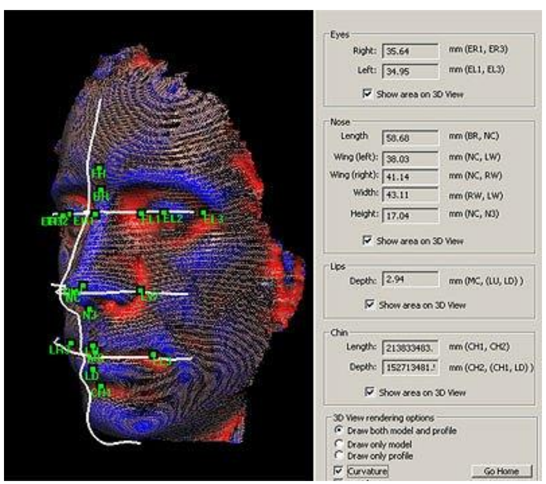
Why PS in particular?

2. Why photometric Stereo?

Why 3D?

Why PS in particular?

1. Robust face recognition
2. Ambient illumination independence
3. Facilitates pose correction
4. Non-contact fingerprint analysis



Richer dataset in 3D

2. Why photometric Stereo?

Why 3D?

Why PS in particular?

1. Robust face recognition
2. Ambient illumination independence
3. Facilitates pose, expression correction
4. Non-contact fingerprint analysis

- Same day
- Same camera
- Same expression
- Same pose
- Same background
- Even same shirt
- Different illumination

Completely different image

2. Why photometric Stereo?

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Why PS in particular?

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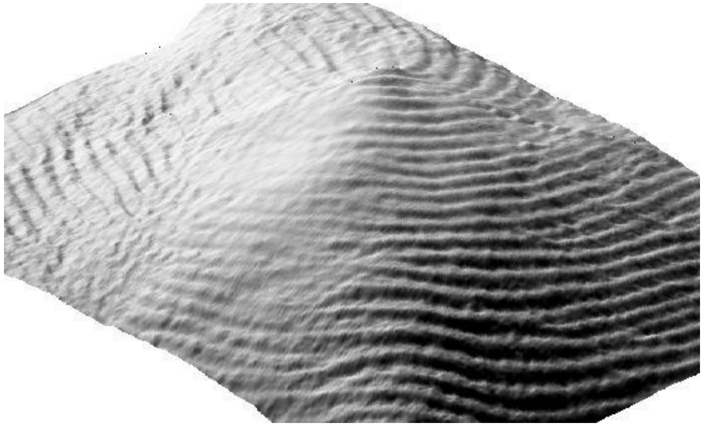

2. Why photometric Stereo?

Why 3D?

Why PS in particular?

1. Captures reflectance data for 2D matching

2. Compares well to other methods

	Cost	Computation	Accuracy	Resolution	Calibration	Practicality
SFS	Good	Average	Poor	Good	Good	Good
GS	Good	Good	Average	Variable*	Good	Average
LT	Average	Good	Average	Average	Good	Poor
PPT	Poor	Poor	Good	Good	Poor	Average
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*Depending on correspondence density

SFS Shape-from-shading
GS Geometric stereo
LT Laser triangulation
PPT Projected pattern triangulation
PS Photometric stereo

2. Why Photometric Stereo? – Alternatives

Shape-from-Shading

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Estimate surface normals from shading patterns.
→ More to follow...

2. Why Photometric Stereo? – Alternatives

Geometric stereo

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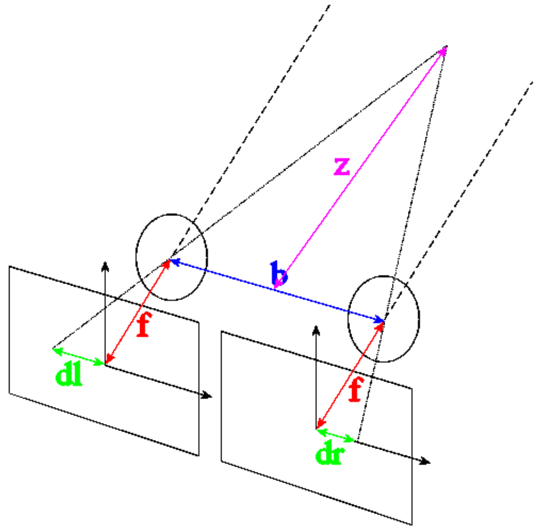

$$z = \frac{bf}{|dl - dr|}$$

2. Why Photometric Stereo? – Alternatives

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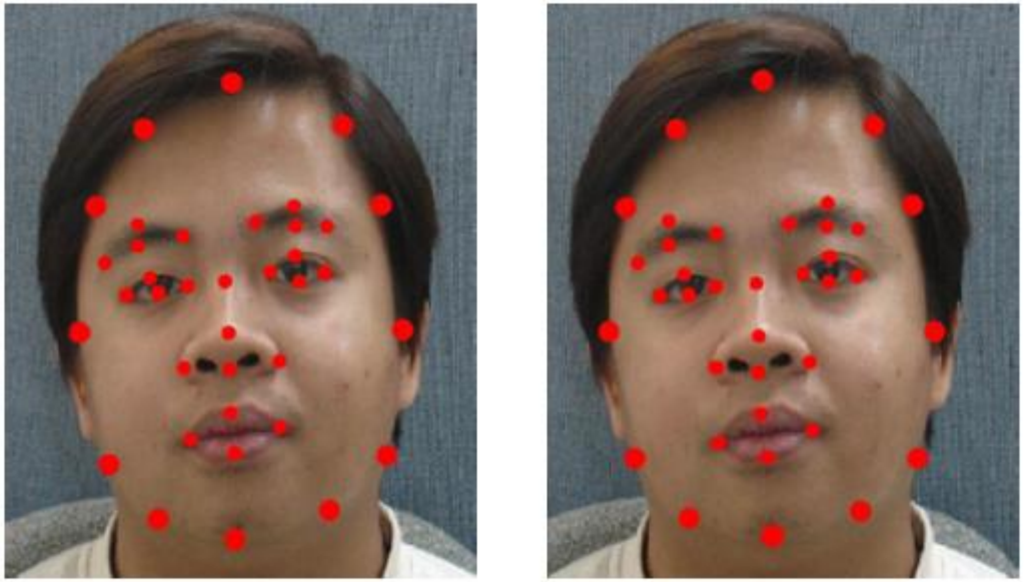
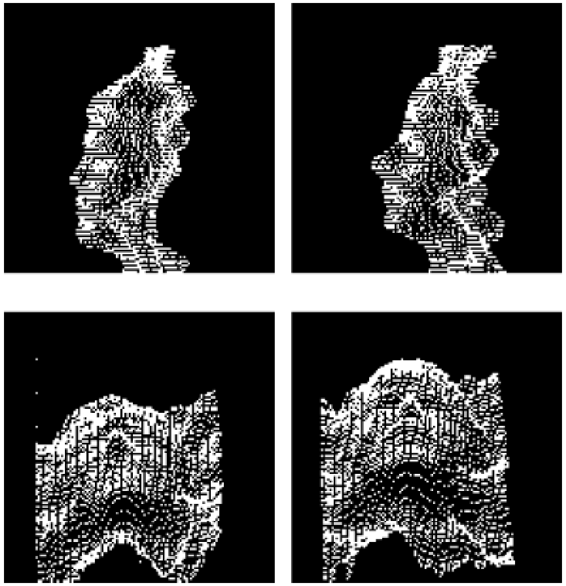


[Li Wei, and Eung-Joo Lee, JDCTA 2010]



[Wang, et al. JVLSI 2007]

2. Why Photometric Stereo? – Alternatives

Laser triangulation

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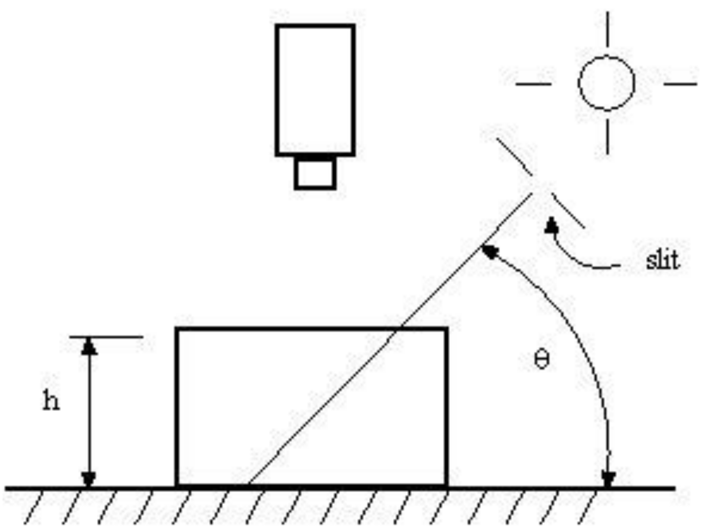

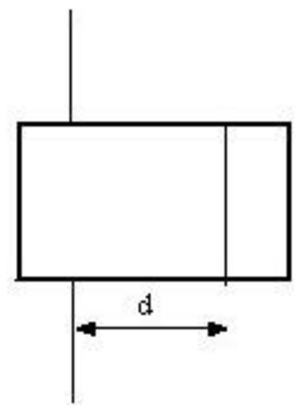

$$h = d \tan \theta$$

Laser triangulation

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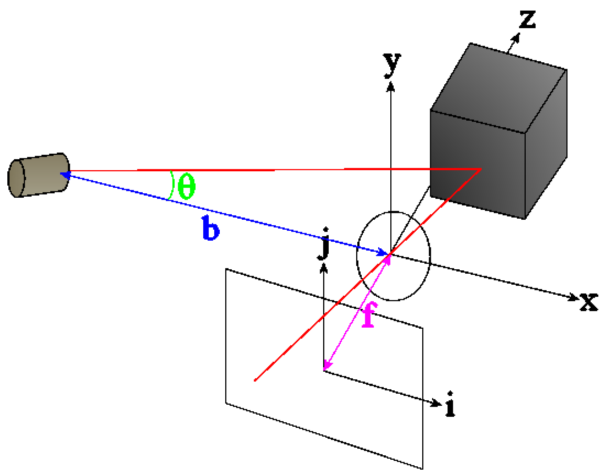

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \frac{b}{f \cot\theta - i} \begin{pmatrix} i \\ j \\ f \end{pmatrix}$$

General case

2. Why Photometric Stereo? – Alternatives

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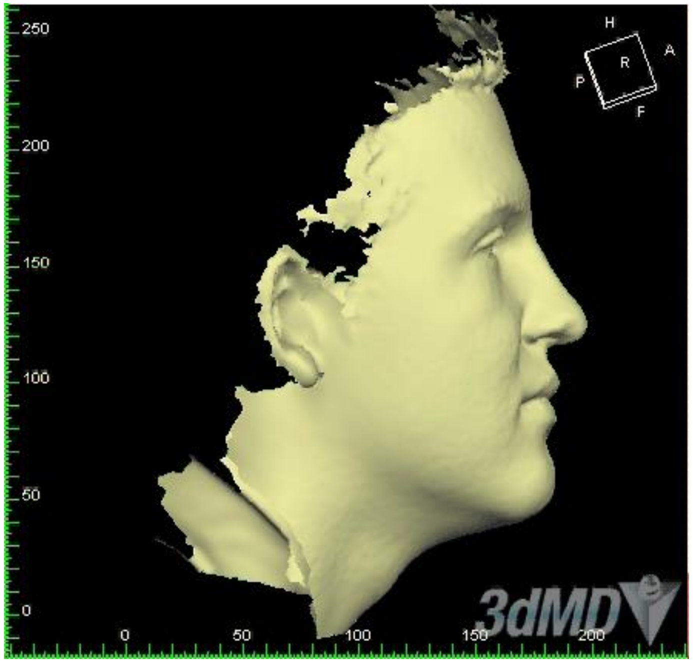

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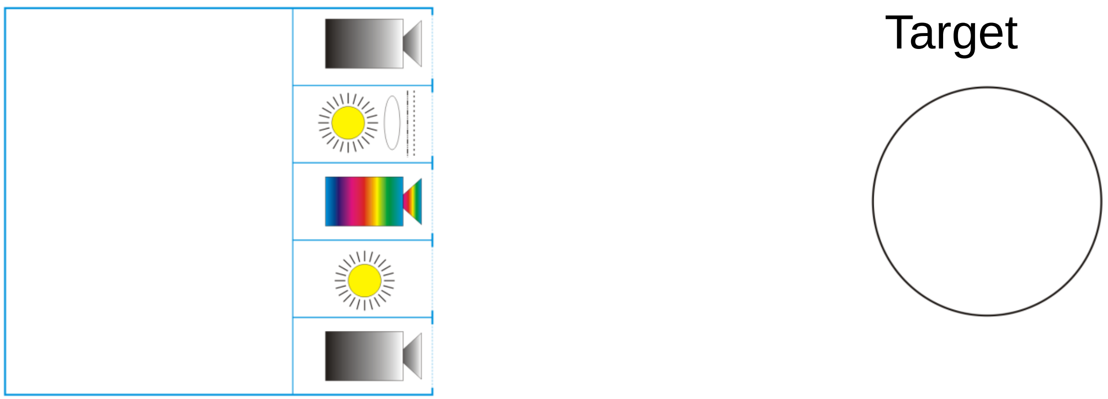
Greyscale camera

Pattern projector

Colour camera

Flash

Greyscale camera



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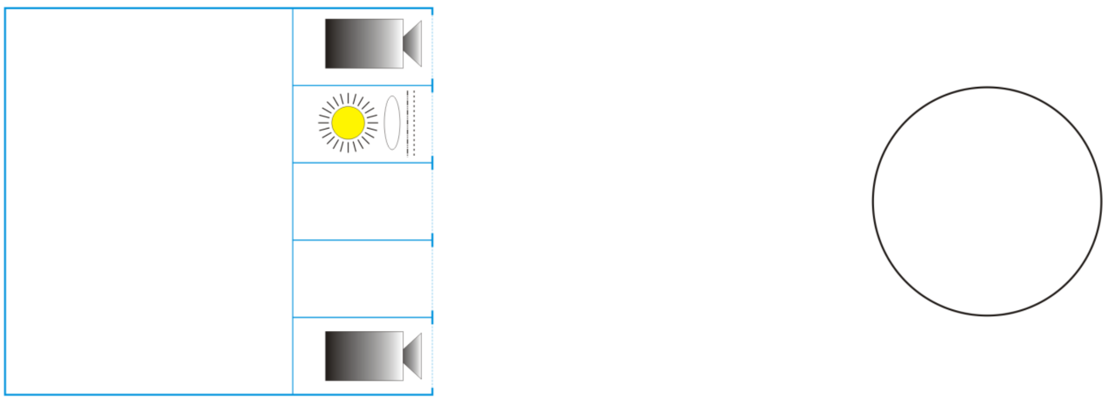

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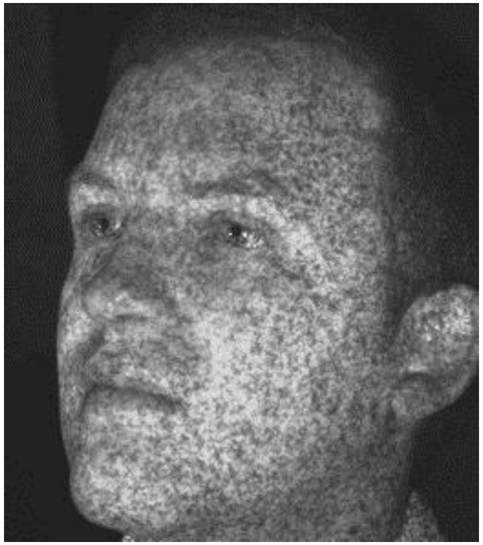

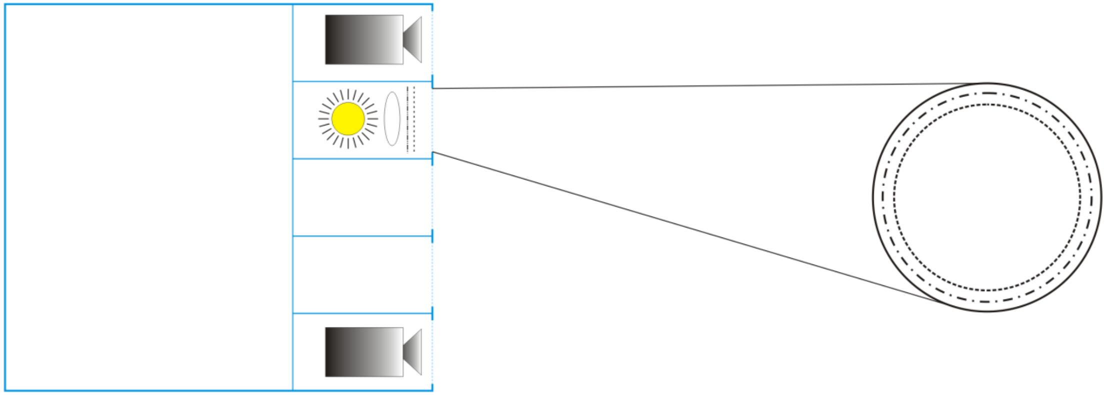

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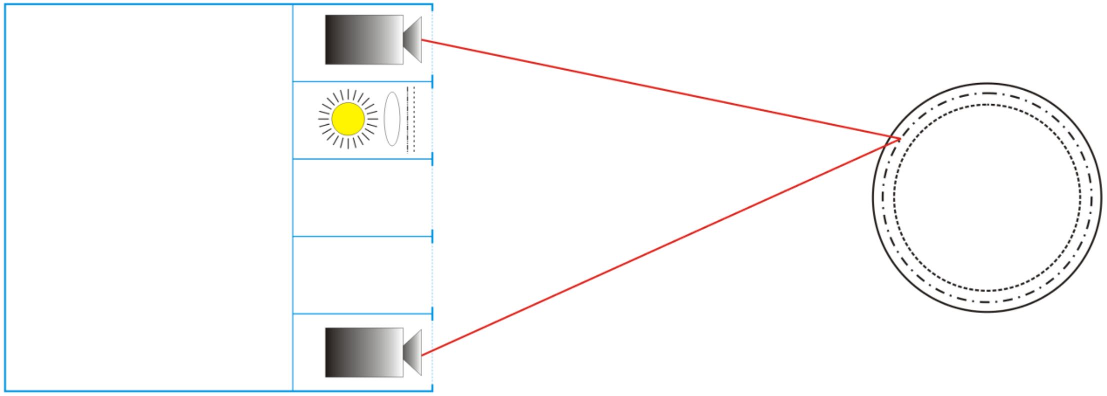

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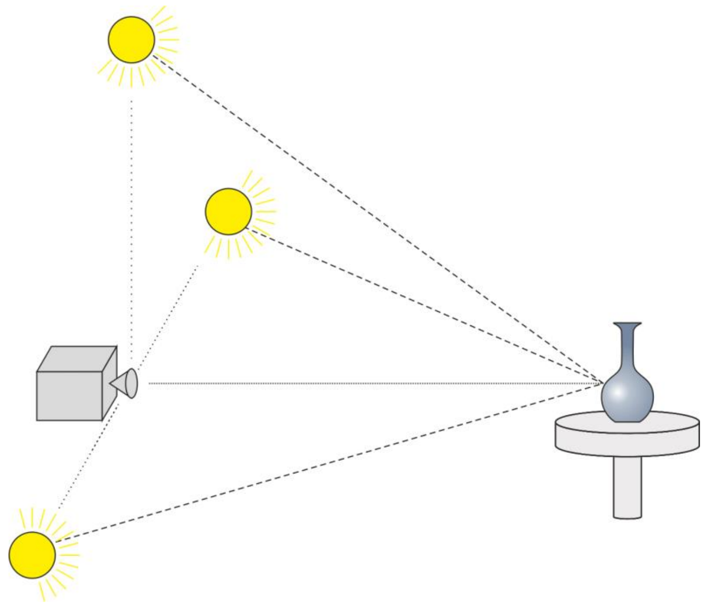

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3. The Basic Method – Assumptions

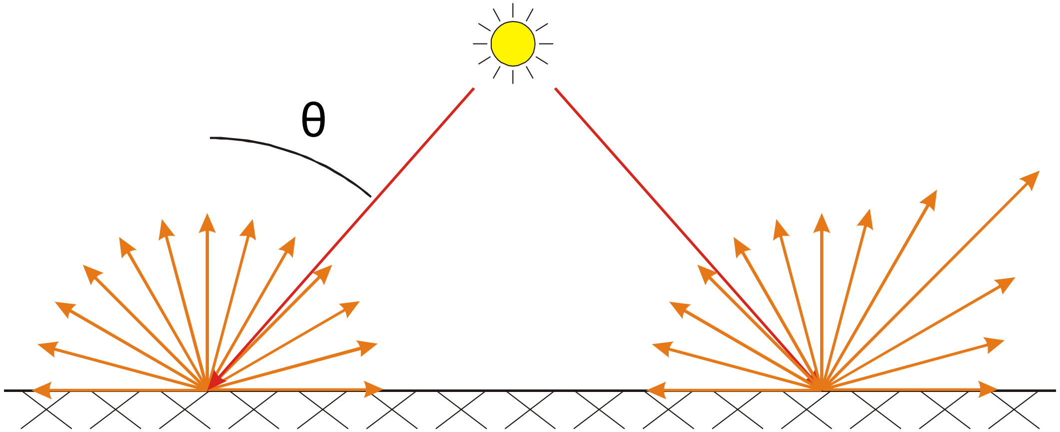
Assumptions:

1. No cast/self-shadows or specularities
2. Greyscale/linear imaging
3. Distant and uniform light sources
4. Orthographic projection
5. Static surface
6. Lambertian reflectance

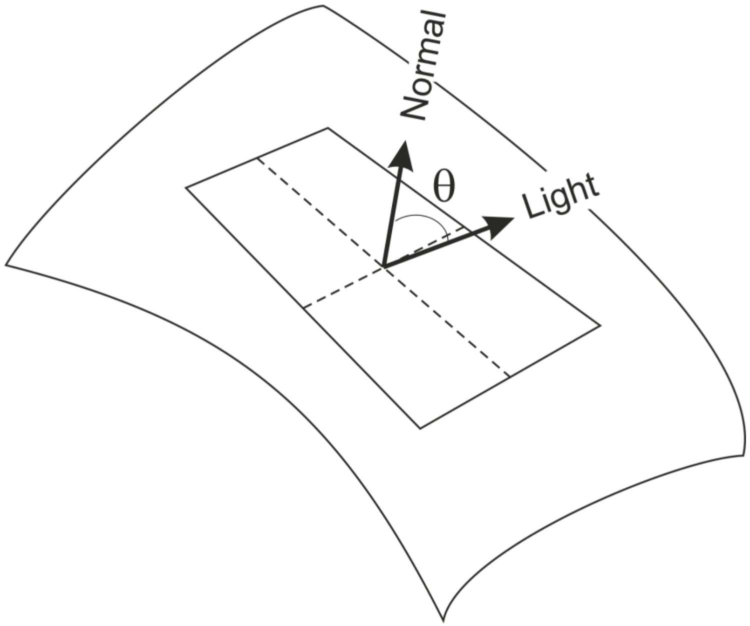
[Argyriou and Petrou]

$$I \propto \cos\theta = \mathbf{N}\cdot\mathbf{L}$$

I = radiance (intensity)
$\mathbf{N}$ = unit normal vector
$\mathbf{L}$ = unit source vector
θ = angle between $\mathbf{N}$ and $\mathbf{L}$



3. The Basic Method – Preliminary notes



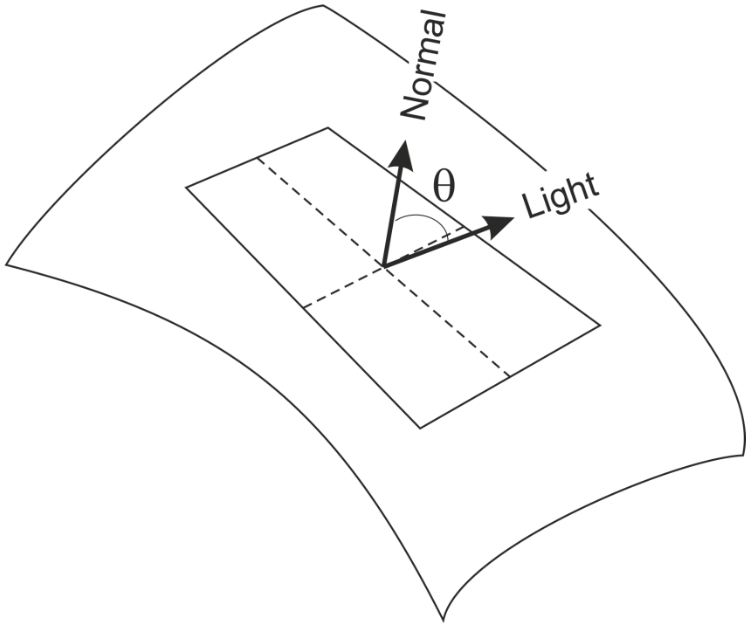
Equation of a plane

$$Ax + By + Cz + D = 0$$

Surface normal vector to plane

$$\mathbf{N} = [A, B, C]^T$$

3. The Basic Method – Preliminary notes



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$$z = -\frac{A}{C}x - \frac{B}{C}y - \frac{D}{C}$$

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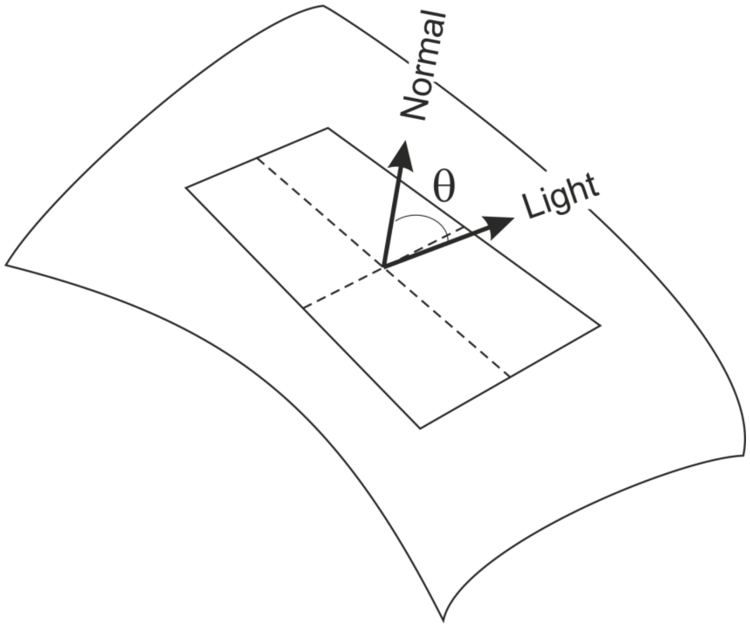

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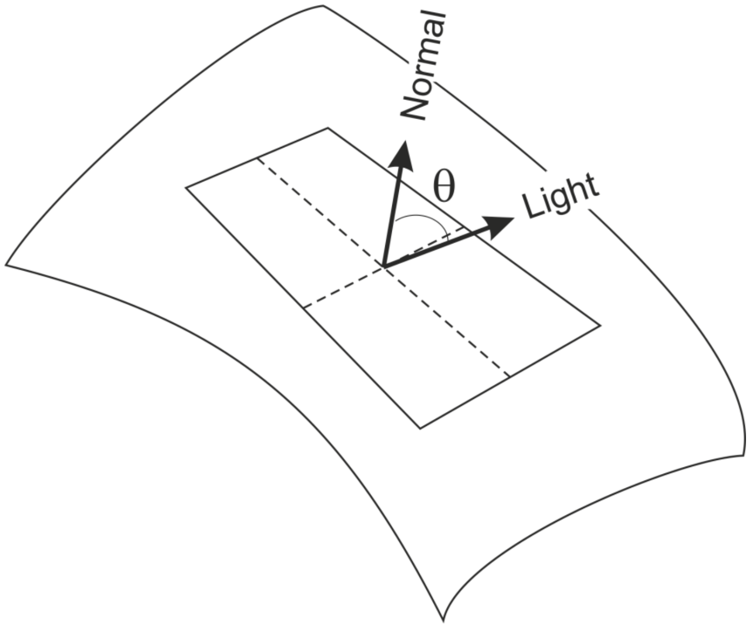

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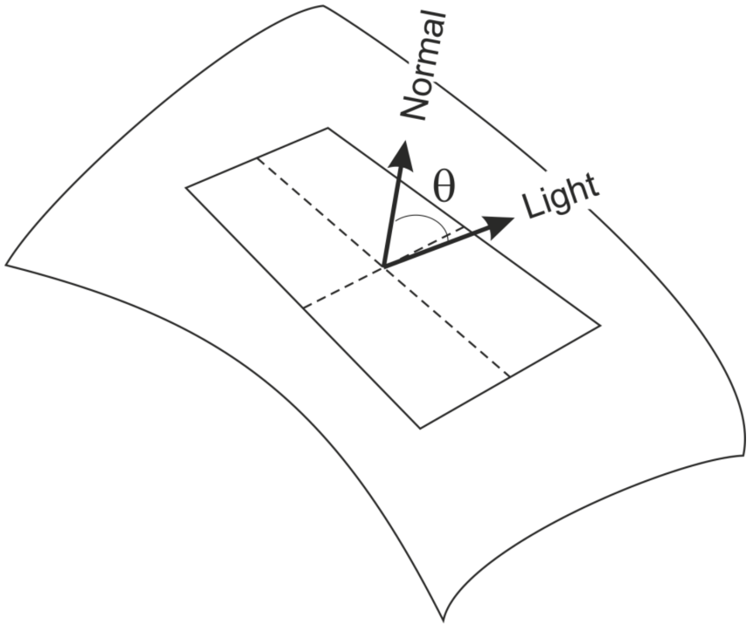
$$\frac{\partial z}{\partial x} = -\frac{A}{C} \qquad \frac{\partial z}{\partial y} = -\frac{B}{C}$$

Rescaled surface normal

$$\mathbf{n} = \left[\frac{A}{C}, \frac{B}{C}, 1\right]^T = \left[-\frac{\partial z}{\partial x}, -\frac{\partial z}{\partial y}, 1\right]^T$$

3. The Basic Method – Preliminary notes



Equation of a plane

$$Ax + By + Cz + D = 0$$

Surface normal vector to plane

$$\mathbf{N} = [A, B, C]^T$$

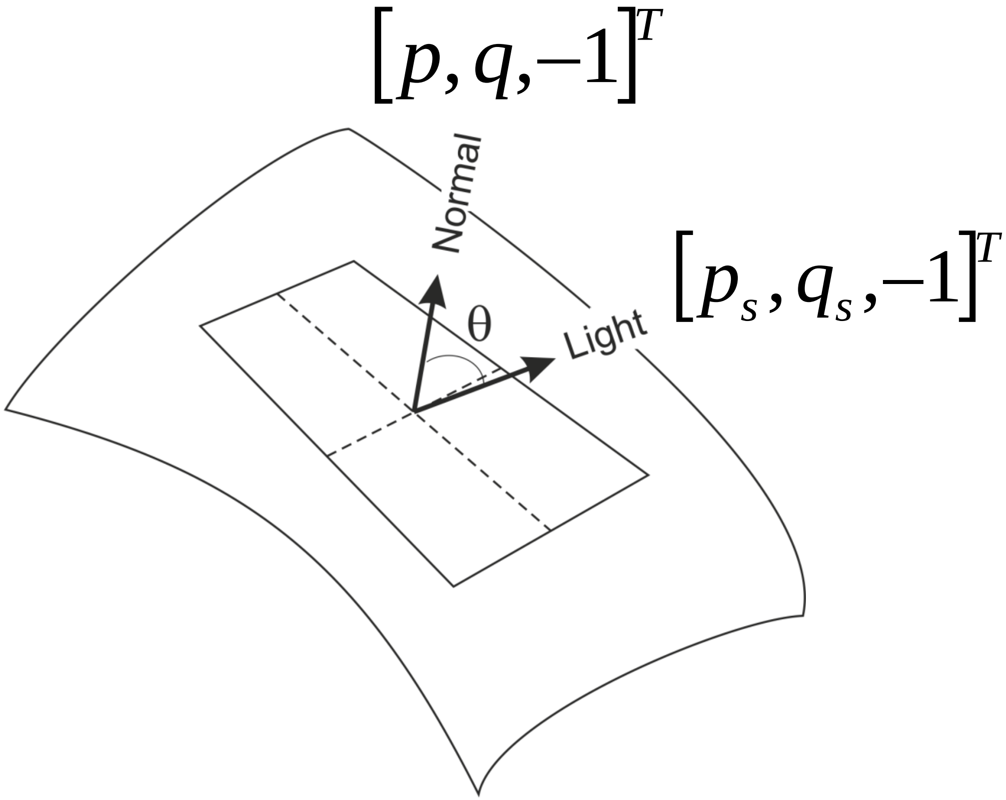
$$z = -\frac{A}{C}x - \frac{B}{C}y - \frac{D}{C}$$

$$\frac{\partial z}{\partial x} = -\frac{A}{C} \qquad \frac{\partial z}{\partial y} = -\frac{B}{C}$$

Rescaled surface normal typically written

$$\mathbf{n} = \left[\frac{\partial z}{\partial x}, \frac{\partial z}{\partial y}, -1\right]^T = [p, q, -1]^T$$

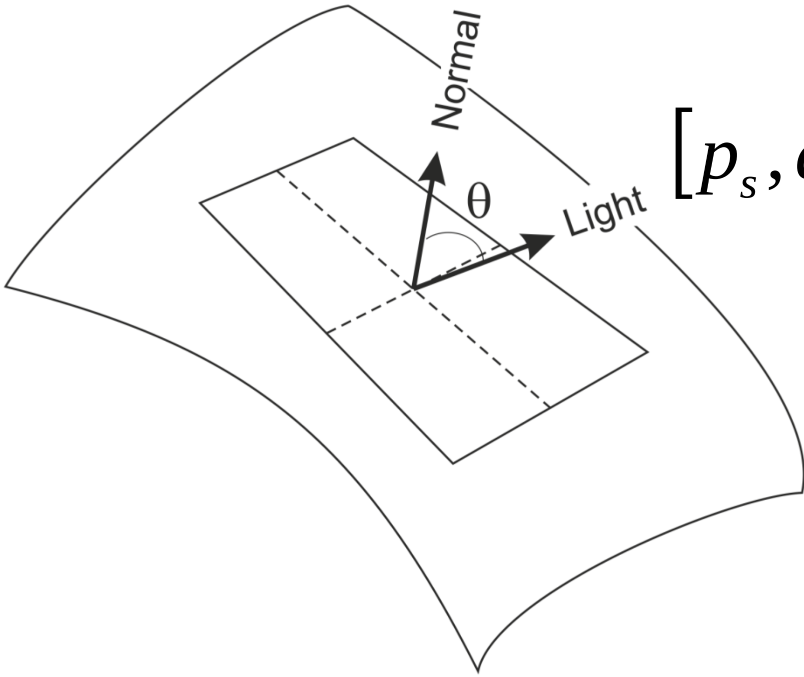
3. The Basic Method – Reflectance Equation



Consider the imaging of an object with one light source.

3. The Basic Method – Reflectance Equation

$$[p, q, -1]^T$$



$$[p_s, q_s, -1]^T$$

Lambertian reflection

$$E = \rho L \cos\theta$$

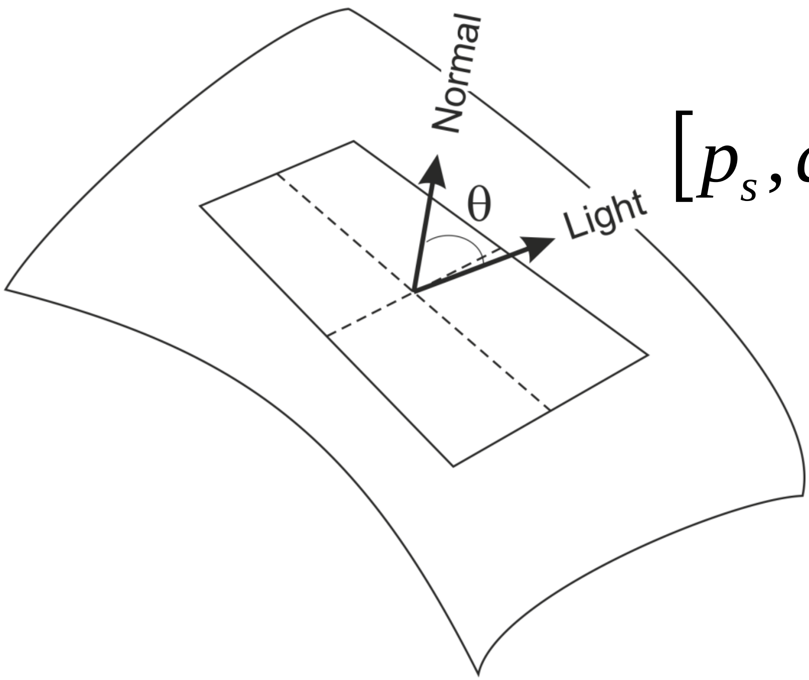
E = emittance

ρ = albedo

L = irradiance

3. The Basic Method – Reflectance Equation

$$[p, q, -1]^T$$



$$[p_s, q_s, -1]^T$$

Lambertian reflection

$$E = \rho L \cos\theta$$

E = emittance

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Take scalar product of light source vector and normal vector to obtain $\cos\theta$:

$$pp_s + qq_s + 1 = \sqrt{p^2 + q^2 + 1}\sqrt{p_s^{\,2} + q_s^{\,2} + 1}\cos\theta$$

3. The Basic Method – Shape-from-Shading

Perform substitution with Lambert's law $E = \rho L \cos\theta$

$$E = \rho L \frac{pp_s + qq_s + 1}{\sqrt{p^2 + q^2 + 1}\sqrt{p_s{}^2 + q_s{}^2 + 1}}$$

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$$E = \rho L \frac{pp_s + qq_s + 1}{\sqrt{p^2 + q^2 + 1}\sqrt{p_s^{\,2} + q_s^{\,2} + 1}}$$

If ρ is re-defined and the camera response is linear, then

$$I = \rho' \frac{pp_s + qq_s + 1}{\sqrt{p^2 + q^2 + 1}\sqrt{p_s^{\,2} + q_s^{\,2} + 1}}$$

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$$I = \rho \frac{pp_s + qq_s + 1}{\sqrt{p^2 + q^2 + 1}\sqrt{p_s{}^2 + q_s{}^2 + 1}}$$

Known: p_s, q_s, I

Unknown: p, q, ρ

1 equation,

3 unknowns

→ Insoluble

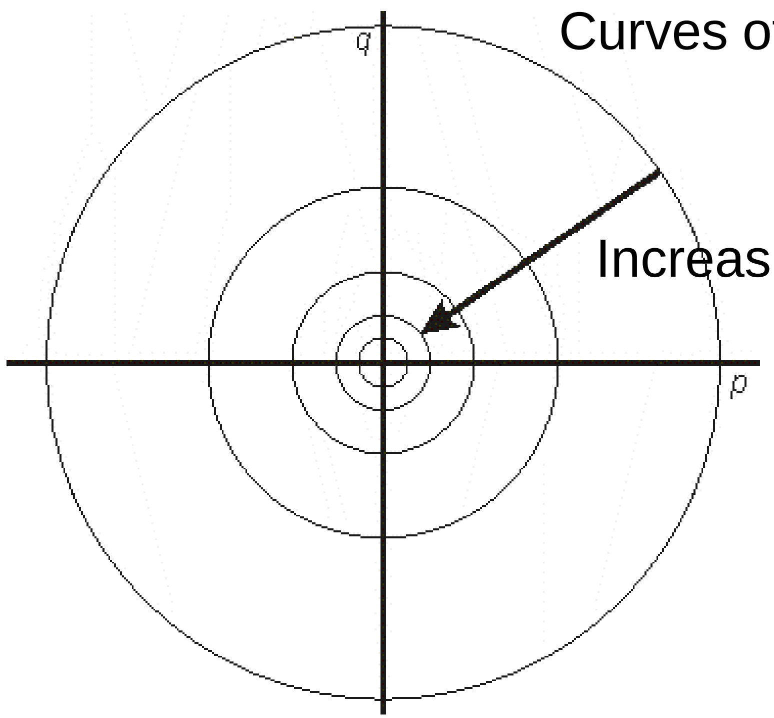
3. The Basic Method – Shape-from-Shading

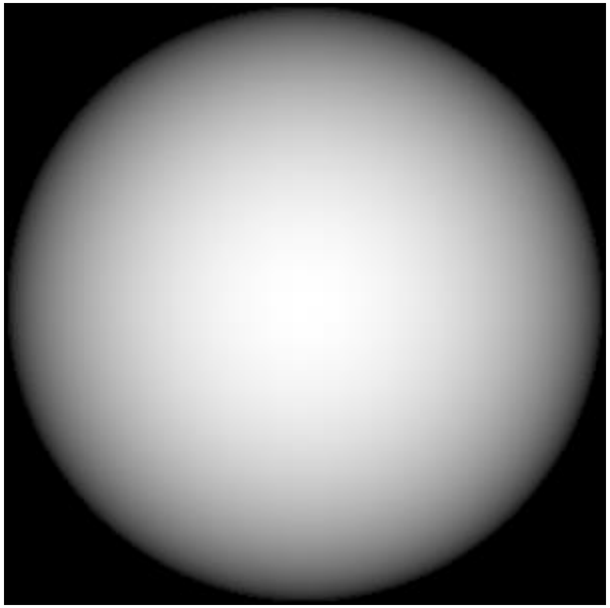
$$I = \rho \frac{p p_s + q q_s + 1}{\sqrt{p^2 + q^2 + 1}\sqrt{p_s{}^2 + q_s{}^2 + 1}}$$

For a given intensity measurement, the values of p and q are confined to one of the lines (circles here) in the graph.

Curves of constant I/ρ

$$p_s = q_s = 0$$





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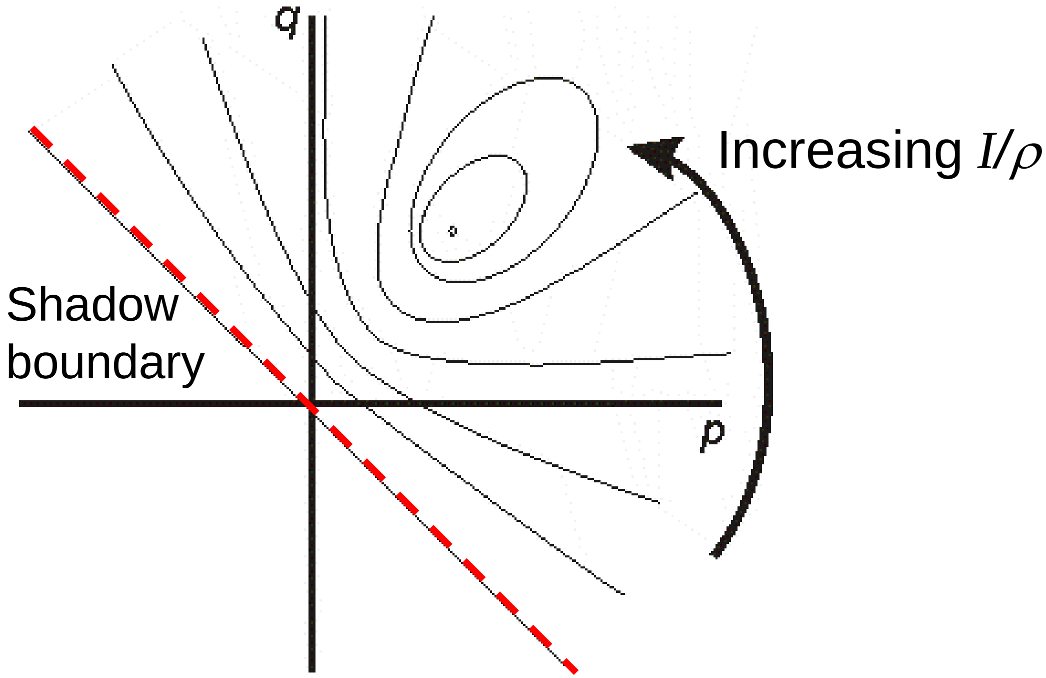
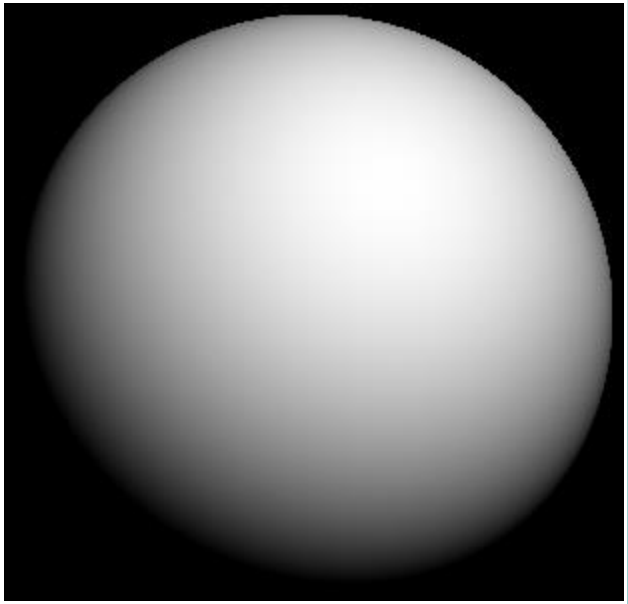
For a given intensity measurement, the values of p and q are confined to one of the lines (circles here) in the graph.

$$p_s = q_s = 0.5$$

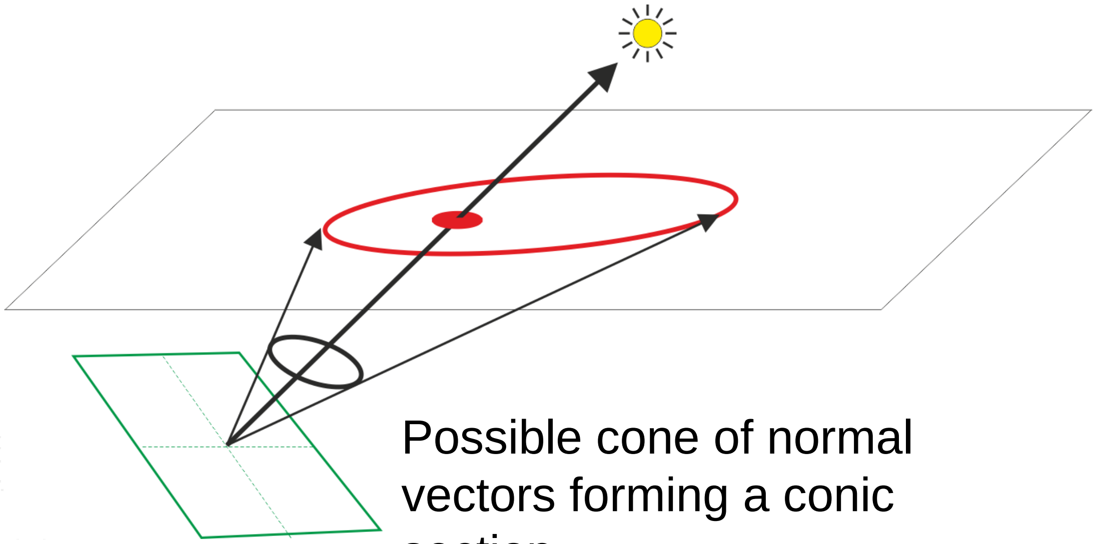




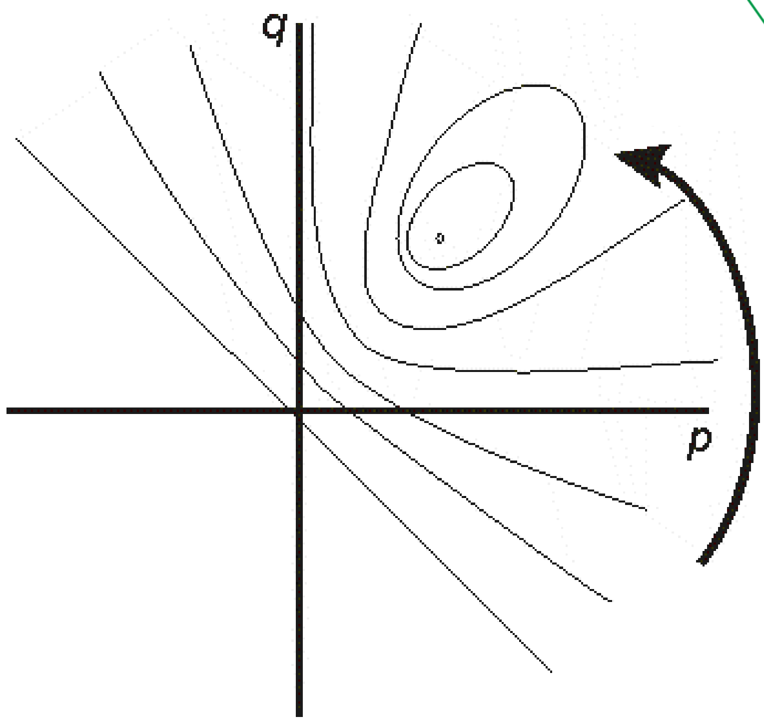
This is the result for a different light source direction.

3. The Basic Method – Shape-from-Shading

Representation using conics

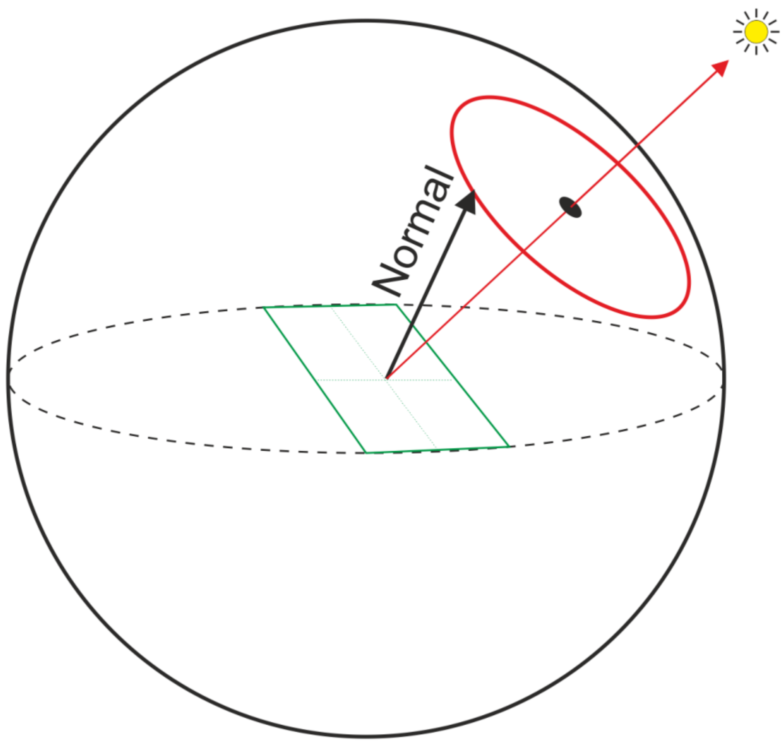


Possible cone of normal vectors forming a conic section.



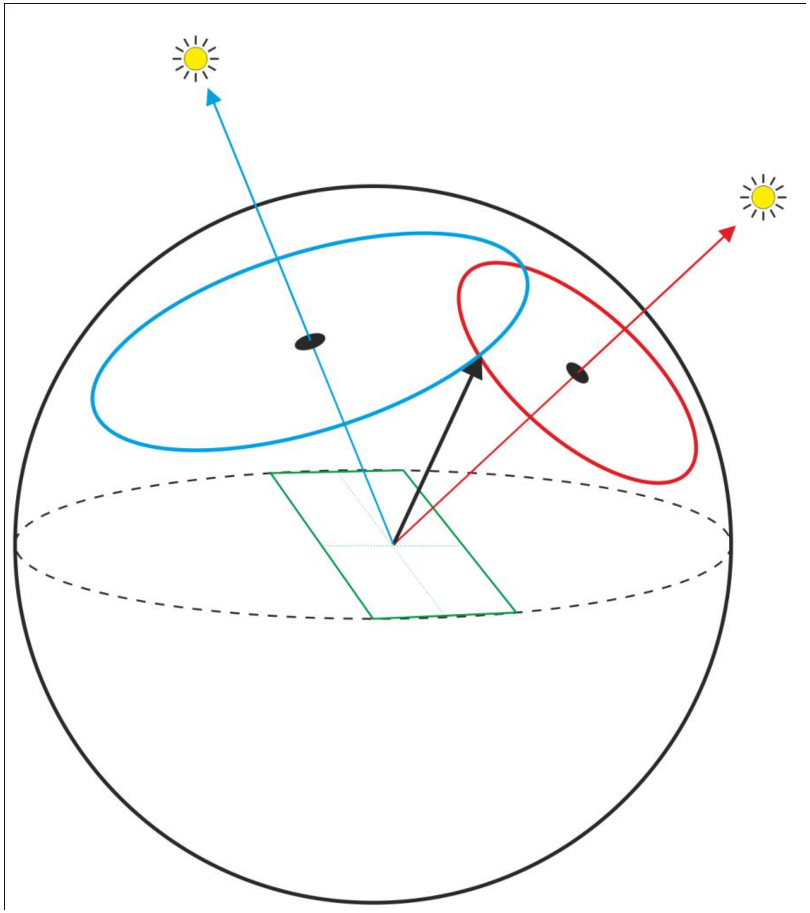
3. The Basic Method – Shape-from-Shading

Representation on unit sphere



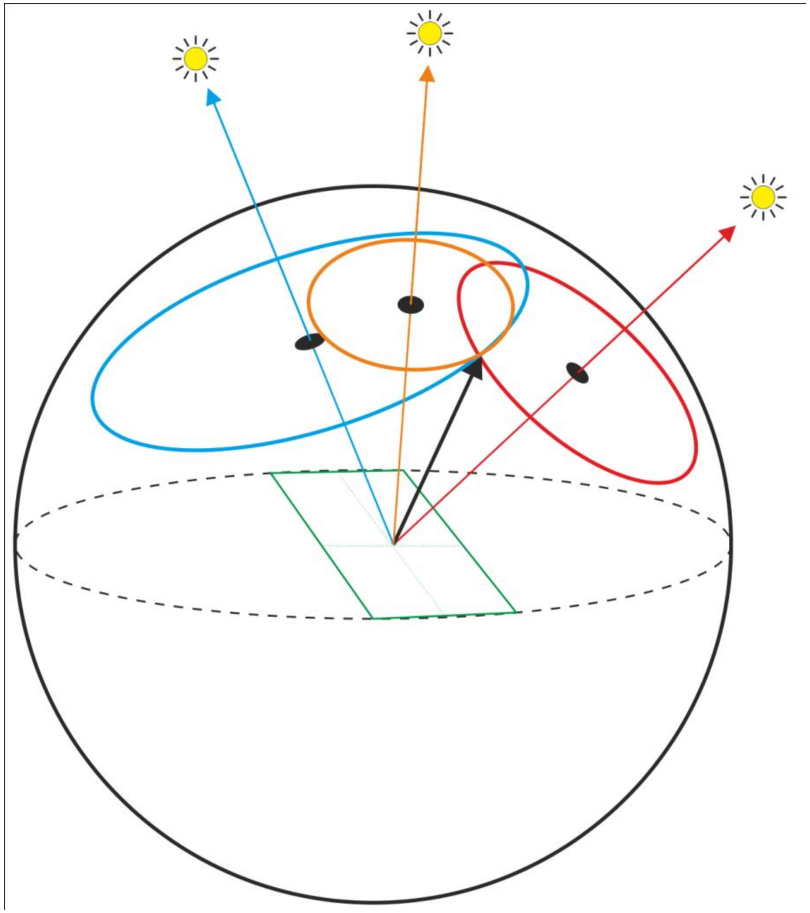
We can overcome the cone ambiguity using several light source directions: Photometric Stereo

3. The Basic Method – Two Sources



Two sources: normal confined to two points
– Or fully constrained if the albedo is known

3. The Basic Method – Three Sources



Three sources: fully constrained

3. The Basic Method – Matrix Representation

$$I = \rho \cos \theta$$

$$I = \rho \mathbf{N} \cdot \mathbf{s} = \rho \begin{bmatrix} s_x \\ s_y \\ s_z \end{bmatrix}^T \begin{bmatrix} N_x \\ N_y \\ N_z \end{bmatrix}$$

$\mathbf{N} =$ **Unit** surface normal

$\mathbf{s} =$ **Unit** light source vector

(using slightly different symbols to aid clarity)

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Recall that, based on the surface gradients, $\mathbf{n} = [p, q, -1]^T$

$$\mathbf{N} = \left[\frac{p}{\sqrt{p^2 + q^2 + 1}}, \frac{q}{\sqrt{p^2 + q^2 + 1}}, \frac{-1}{\sqrt{p^2 + q^2 + 1}} \right]^T$$

3. The Basic Method – Matrix Representation

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Substituting and re-arranging these equations gives us

$$p = -\frac{m_x}{m_z}, \quad q = -\frac{m_y}{m_z}, \quad \rho = \sqrt{m_x{}^2 + m_y{}^2 + m_z{}^2}$$

That is, the surface normals/gradient and albedo have been determined.

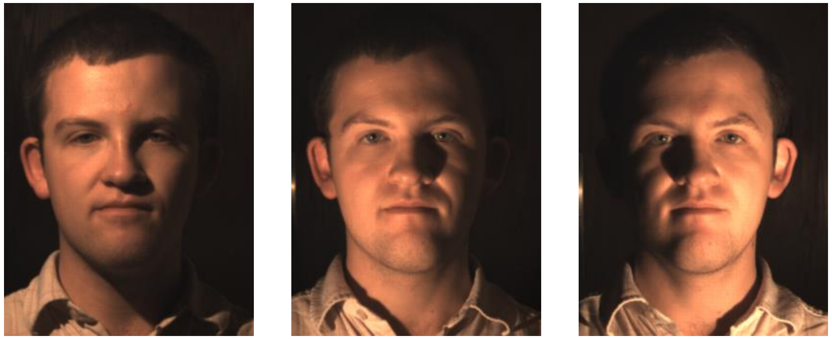
3. The Basic Method – Linear Algebra Note

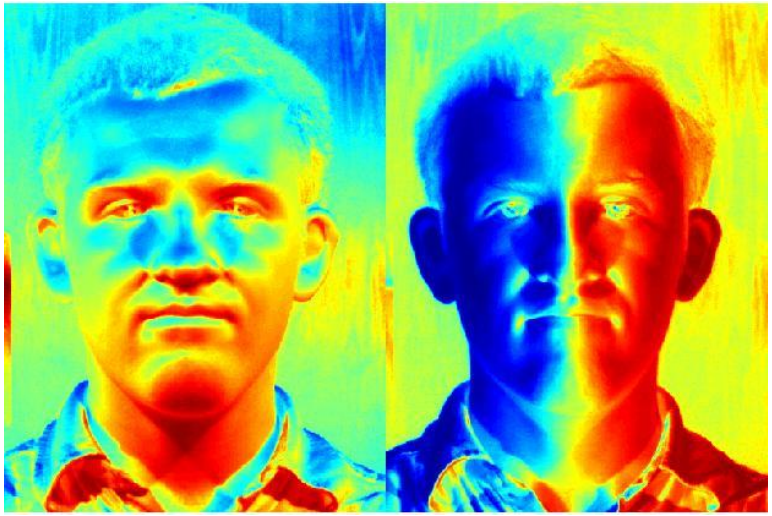
If the three light source vectors are co-planar, then the light source matrix becomes non-singular – i.e. cannot be inverted, and the equations are insoluble.

$$p = -\frac{m_x}{m_z}, \quad q = -\frac{m_y}{m_z}, \quad \rho = \sqrt{m_x{}^2 + m_y{}^2 + m_z{}^2}$$

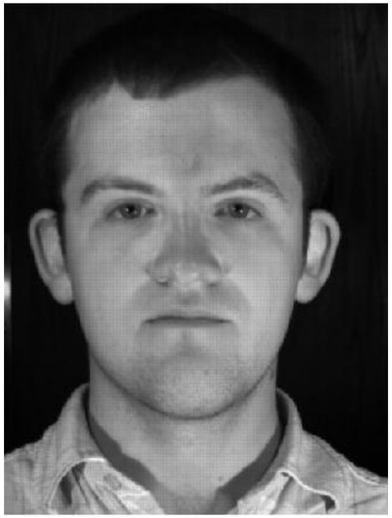
That is, the surface normals/gradient and albedo have been determined.

3. The Basic Method – Example results





Surface normals



Albedo map

More on applications of this later...

What about the depth?

3. The Basic Method – Surface Integration

Recall the relation between surface normal and gradient:

$$\mathbf{n} = \left[\frac{\partial z}{\partial x}, \frac{\partial z}{\partial y}, -1 \right]^T$$

Memory jogger from calculus:

$$p = \frac{\mathrm{d}z}{\mathrm{d}x}$$

$$z = \int \mathrm{d}z = \int p\,\mathrm{d}x$$

$$z = \sum \delta z = \sum p\,\delta x$$

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$$z = \sum \delta z = \sum p\,\delta x$$

So the height can be determined via an integral (or summation in the discrete world of computer vision). This can be written in several ways:

$$z(P) = z(P_0) + \int_{P_0}^{P} (p\,\mathrm{d}x + q\,\mathrm{d}y)$$

$$z(u,v) = \int_0^u q(0,y)\,\mathrm{d}y + \int_0^v p(x,v)\,\mathrm{d}x + c$$

$$z(x,y) = \oint_C (p,q)\,d\boldsymbol{l} + c$$

3. The Basic Method – Surface Integration

So we can generate a height map by summing up individual normal components. Simple, right?

WRONG!!!

<u>3. The Basic Method – Surface Integration</u>

So we can generate a height map by summing up individual normal components. Simple, right?

WRONG!!!

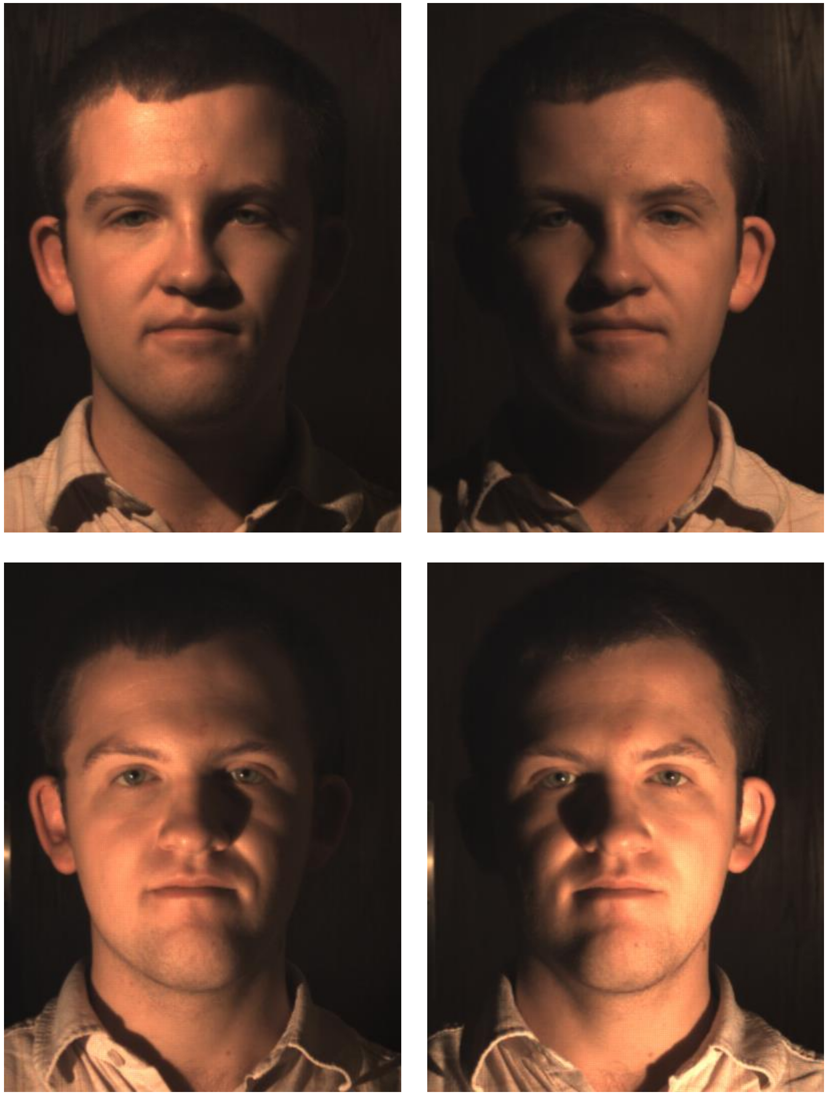
- Depends on the path taken
- Is affected by noise
- Cannot handle discontinuities
- Suffers from non-integrable regions

(there's some overlap here)

$$\frac{\partial^2 z}{\partial x \partial y} = \frac{\partial^2 z}{\partial y \partial x}$$

Further details are beyond the scope of this talk.

3. The Basic Method – Surface Integration



Overview

1. What is photometric stereo?
2. Why photometric stereo?
3. The basic method
4. Advanced methods
5. Applications

4. Advanced Methods

Recall the assumptions of standard PS:

1. No cast/self-shadows or specularities
2. Greyscale imaging
3. Distant and uniform light sources
4. Orthographic projection
5. Static surface
6. Lambertian reflectance

4. Advanced Methods

Recall the assumptions of standard PS:

1. No cast/self-shadows or specularities
2. Greyscale imaging
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5. Static surface
6. Lambertian reflectance

The two highlighted assumptions are the two most problematic, and studied, assumptions.

4. Advanced Methods – Shadows and Specularities

Recall that:

$$\begin{bmatrix} s_x^1 & s_y^1 & s_z^1 \\ s_x^2 & s_y^2 & s_z^2 \\ s_x^3 & s_y^3 & s_z^3 \end{bmatrix}^{-1} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \rho \begin{bmatrix} N_x \\ N_y \\ N_z \end{bmatrix} = \begin{bmatrix} m_x \\ m_y \\ m_z \end{bmatrix}$$

$$p = -\frac{m_x}{m_z}, \quad q = -\frac{m_y}{m_z}, \quad \rho = \sqrt{{m_x}^2 + {m_y}^2 + {m_z}^2}$$

Suppose we have a fourth light source

- Apply the above equation for each combination of three light sources.

→ Four normal estimates

- Where error in estimates > camera noise an anomaly is present.

→ Ignore one light source here

[Coleman and Jain-esque]

4. Advanced Methods – Shadows and Specularities / Lambert's Law

Due to the linear dependence of light source vectors, we know that

$$a_1\mathbf{s}_1 + a_2\mathbf{s}_2 + a_3\mathbf{s}_3 + a_4\mathbf{s}_4 = 0$$

For some combination of constants a_1, a_2, a_3 and a_4.

[Barsky and Petrou]

4. Advanced Methods – Shadows and Specularities / Lambert's Law

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For some combination of constants a_1, a_2, a_3 and a_4.

Multiply by albedo and take scalar product with surface normal:

$$a_1\rho(\mathbf{s}_1 \cdot \mathbf{N}) + a_2\rho(\mathbf{s}_2 \cdot \mathbf{N}) + a_3\rho(\mathbf{s}_3 \cdot \mathbf{N}) + a_4\rho(\mathbf{s}_4 \cdot \mathbf{N}) = 0$$

[Barsky and Petrou]

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$$\Rightarrow \quad a_1 I_1 + a_2 I_2 + a_3 I_3 + a_4 I_4 = 0$$

[Barsky and Petrou]

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Multiply by albedo and take scalar product with surface normal:

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$$\Rightarrow \quad a_1 I_1 + a_2 I_2 + a_3 I_3 + a_4 I_4 = 0$$

Where this is satisfied (subject to the confines of camera noise) the pixel is not specular, not in shadow and follows Lambert's law.

[Barsky and Petrou]

4. Advanced Methods – Lambert’s Law / Gauges

Attempt to overcome lighting non-uniformities and non-Lambertian behaviour using gauges.

$$\mathbf{I}^{(\text{scene})} = \left[I_1^{(\text{scene})} \; I_2^{(\text{scene})} \ldots I_M^{(\text{scene})} \right]^T$$

$$\mathbf{I}^{(\text{gauge})} = \left[I_1^{(\text{gauge})} \; I_2^{(\text{gauge})} \ldots I_M^{(\text{gauge})} \right]^T$$

Image scene in the presence of a “gauge” object of known geometry and uniform albedo.

Seek a mapping between normals on the object with normals on the gauge.

$$\mathbf{I}^{(\text{scene})}[i] \mapsto \mathbf{I}^{(\text{gauge})}[j] : \mathbf{N}^{(\text{scene})}[i] = \mathbf{N}^{(\text{gauge})}[j]$$

[Leitão et al.]

Overview

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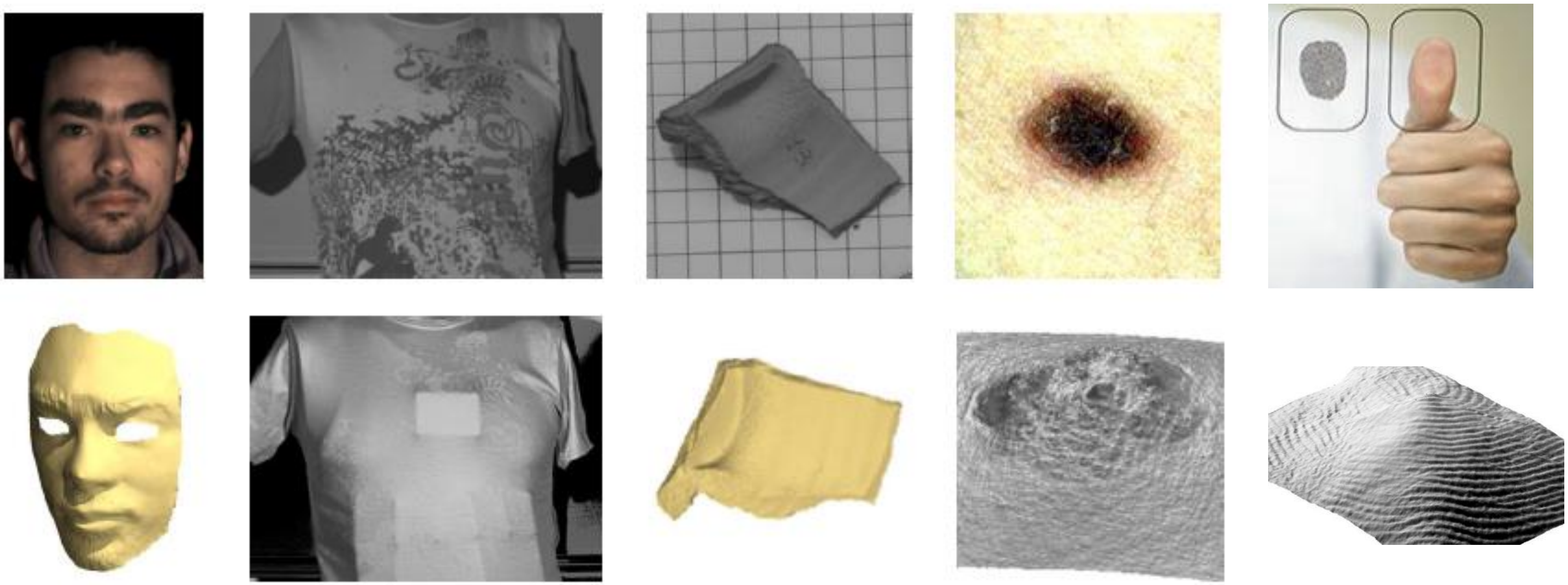
5. Applications



Face recognition

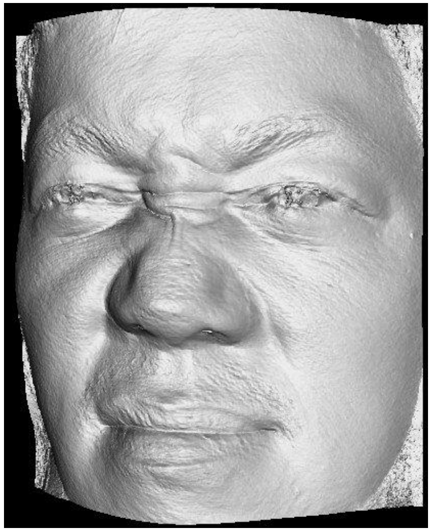
Weapons detection

Archaeology

Skin analysis

Fingerprint recognition

5. Applications – Face recognition



Computer monitor [Schindler]

Recognition rates (on 61 subjects)

2D Photograph: 91.2%
Surface normals: 97.5%

5. Applications – Fingerprint recognition

Demo

[Sun et al.]

Conclusion

1. What is photometric stereo?
   Shape / normal estimation from multiple lights

2. Why photometric stereo?
   Cheap, high resolution, efficient

3. The basic method – Covered

4. Advanced methods – Introduced

5. Applications
   Faces, weapons, fingerprints

Photometric Stereo in 3D Biometrics

Thank You

Questions?

UWE BRISTOL
University of the West of England

Machine Vision Laboratory