Computational Optical Imaging - Optique Numerique

-- Active Light 3D--

Winter 2013

Ivo Ihrke

with slides by Thorsten Thormaehlen
Overview

- 3D scanning techniques
  - Laser triangulation
  - Structured light
  - Photometric stereo
  - Calibration
- Time-of-Flight
- Transient Imaging
Active Light - 3D Scanning

Laser Scanning
Range scanning

- Generate range from stereo information
  - Scales from desktop to whole body scanners
Range scanning systems

- Passive: $n \geq 2$ cameras; match images
Optical Triangulation

- passive setup: match corresponding images
Active Techniques

- project some additional signal into the scene
  - requires signal source, and additional calibration
  - often more or less direct measurements
  - typically higher precision

Examples:
- range scanning
- matting applications
- measurement of reflection properties
Range scanning systems

- Active: Laser light source
  - Sweep & track reflection (triangulation)
  - Project a line instead of a single point
Optical triangulation

- active setup: track light spot

\[
z = \frac{b}{\tan(\alpha) + \tan(\beta)}
\]

\(b\)

\((x, z)\)

ray intersection

(base length)

laser source

sensor

object

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Laser triangulation

Source: The Digital Michelangelo Project, Stanford University
Laser triangulation

- Depth from ray-plane triangulation:
  - Intersect line of sight with light plane (canonical camera)

\[
x = f \frac{X_c}{Z_c} \quad y = f \frac{Y_c}{Z_c} \quad \hat{Z}_c = \frac{-d}{a \frac{x}{f} + b \frac{y}{f} + c}
\]
Laser triangulation

- **Advantages**
  - simple approach
  - works quite reliable
  - accuracy proportional to working volume (typical is ~1000:1)
  - scales down to small working volume (e.g. 5 cm. working volume, 50 µm. accuracy)

- **Disadvantages**
  - long scanning time (no real-time capture of moving objects)
  - does not scale up (baseline too large…)
  - two-lines-of-sight problem (shadowing from either camera or laser)
  - triangulation angle: lower accuracy if too small, shadowing if too big (useful range: 15°-30°)
  - needs stable reliable calibration with good mechanics, thus often expensive to buy
Digital Michelangelio Project, 1997-2000

4 motorized axes

cyberware scanner (laser triangulation)

extensions for tall statues

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Digital Michelangelo Project, 1997-2000

height of gantry: 7.5 meters
weight of gantry: 800 kilograms

Source: The Digital Michelangelo Project, Stanford University

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Digital Michelangelo Project, 1997-2000

working in the museum  
scanning geometry  
scanning color

Source: The Digital Michelangelo Project, Stanford University

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Digital Michelangelo Project, 1997-2000

- 480 individually aimed scans
- 2 billion polygons
- 7,000 color images
- 32 gigabytes
- 30 nights of scanning
- 22 people

Source: The Digital Michelangelo Project, Stanford University
Digital Michelangelo Project, 1997-2000

photograph

1.0 mm computer model

Source: The Digital Michelangelo Project, Stanford University

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Digital Michelangelo Project, 1997-2000

St. Matthew  David  Forma Urbis Romae

Source: The Digital Michelangelo Project, Stanford University

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Range Scanners – Optical Considerations

- Laser Range Scanners – focal plane selection
- Scheimpflug principle
- tilt-shift lenses

Scheimpflug principle

application in range scanning
extend depth of field
Tilt-Shift Lens Photographic Examples
Range Scanning Problems - Shadowing

- longer baseline:
- more shadowing

shorter baseline: less precision
Range Scanning Problems – Acquired Range Image

- A single range image is acquired for each view

Artifacts:
- Ribbed
- Lots of holes
  - Due to surface properties
  - Due to occlusion

Solution:
- Merging of multiple scans \(\rightarrow\) (ICP, Gaël Guennebaud)
Range Scanning Problems
- Beam location error

- Assumption: Reflection has Gaussian shape

- Corrupt due to occlusion or texture → Biased depth estimate
Beam location error

- Possible solution: Spacetime analysis [Curless, Levoy 95]
  - Estimate *when* beam centered on spot
DIY Range Scanners

- Laser Range Scanning – Cheapo Version [Winkelbach06]
- hand-held line laser
- known background geometry
- need two planes that are not co-planar
- known camera calibration
- compute laser plane from lines on the background planes
- triangulate by ray-plane intersection
Active Light - 3D Scanning

Structured Light
Structured Light

- Idea: increase speed by projecting multiple stripes
- But which stripe is which?

- Answer: Coded stripe patterns
  - Binary code
  - Gray code
  - Color code
Range scanning systems

- Active: Structured light source
  - Analyze image of stripe pattern
Structured Lighting: Swept-Planes Revisited

- Swept-plane scanning recovers 3D depth using ray-plane intersection
- Use a data projector to replace manually-swept laser/shadow planes
- How to assign correspondence from projector planes to camera pixels?
- Solution: Project a spatially- and temporally-encoded image sequence
- What is the optimal image sequence to project?
Structured Lighting: Binary Codes

Binary Image Sequence [Posdamer and Altschuler 1982]
- Each image is a bit-plane of the binary code for projector row/column
- Minimum of 10 images to encode 1024 columns or 768 rows
- In practice, 20 images are used to encode 1024 columns or 768 rows
- Projector and camera(s) must be synchronized
Example: 3 binary-encoded patterns which allows the measuring surface to be divided in 8 sub-regions

Structured Light - Binary Coding
Structured Light - Binary Coding

Assign each stripe a unique illumination code over time [Posdamer 82]
Structured Light - Binary Coding

Codeword of this pixel: 1010010
→ identifies the corresponding pattern stripe
Structured Lighting: Gray Codes

Gray Code Image Sequence [Inokuchi 1984]
- Each image is a bit-plane of the Gray code for each projector row/column
- Requires same number of images as a binary image sequence, but has better performance in practice

$$\text{Bin2Gray}(B,G)$$
1  \( G \leftarrow B \)
2  \( \text{for } i \leftarrow n-1 \text{ downto 0} \)
3  \( G[i] \leftarrow B[i+1] \text{ xor } B[i] \)
## Binary vs Gray Codes

<table>
<thead>
<tr>
<th>Decimal</th>
<th>Binary</th>
<th>Gray Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>0000</td>
<td>0000</td>
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<tr>
<td>01</td>
<td>0001</td>
<td>0001</td>
</tr>
<tr>
<td>02</td>
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<td>0011</td>
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<td>0011</td>
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<tr>
<td>04</td>
<td>0100</td>
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<td>1101</td>
</tr>
<tr>
<td>10</td>
<td>1010</td>
<td>1111</td>
</tr>
</tbody>
</table>
Binary vs Gray Codes

<table>
<thead>
<tr>
<th>Pattern 3</th>
<th>Pattern 2</th>
<th>Pattern 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binary</td>
<td>Gray Code</td>
<td>Binary</td>
</tr>
</tbody>
</table>
Gray Codes: Decoding Performance

3D Reconstruction using Structured Light [Inokuchi 1984]
- Implemented using a total of 42 images
  (2 to measure dynamic range, 20 to encode rows, 20 to encode columns)
- Individual bits assigned by detecting if bit-plane (or its inverse) is brighter
- Decoding algorithm: Gray code $\rightarrow$ binary code $\rightarrow$ integer row/column index
Calibration of a Projector-Camera System

- Camera calibration (matlab and OpenCV)  
  http://www.vision.caltech.edu/bouguetj/calib_doc/

- Extention for projector calibration (matlab)  
  http://code.google.com/p/procamcalib/

- Idea: Consider the projector as an inverse camera, which maps 2D image points into 3D rays, thus making the calibration of a projector the same as that of a camera
Calibration of a Projector-Camera System

- Calibrate the camera using [Zhang 2000]

- Recover calibration plane in camera coordinate system

- Project a checkerboard on the calibration board and detect corners

- Apply ray-plane intersection to recover 3D position for each projected corner

- Calibrate the projector using the correspondences between the 2D points of the projector image and the recovered 3D position of projected points (Zhang’s method).
Dynamic Scanning

Spatial encoding strategies [Chen et al. 2007]

“Single-shot” patterns (N-arrays, grids, random, etc.)

De Bruijn sequences [Zhang et al. 2002]

Pseudorandom and M-arrays [Griffin 1992]

Phase-shifting [Zhang et al. 2004]

J. Salvi, J. Pagès, and J. Batlle. Pattern Codification Strategies in Structured Light Systems
Popular example: Kinect I

[Andres Reza]

[Matthew Fisher]
Continuum of Triangulation Methods

- Single-stripe
  - Slow, robust
- Multi-stripe
  - Multi-frame
- Single-frame
  - Fast, fragile
Active Light – Photometric Stereo

The Basics and Some Hints Towards More Complex Issues
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### Photometric Stereo

- **Idea:** One camera, multiple (known) light sources

Lambertian reflection

\[
\begin{align*}
I_1 &= \rho \mathbf{n}^\top \mathbf{s}_1 \\
I_2 &= \rho \mathbf{n}^\top \mathbf{s}_2 \\
I_3 &= \rho \mathbf{n}^\top \mathbf{s}_3
\end{align*}
\]

In matrix form

\[
\begin{pmatrix}
I_1 \\
I_2 \\
I_3
\end{pmatrix} = \rho
\begin{bmatrix}
\mathbf{s}_{1}^\top \\
\mathbf{s}_{2}^\top \\
\mathbf{s}_{3}^\top
\end{bmatrix}
\mathbf{n}
\]
The Reflectance Map

Reflectance Map: image intensity of a pixel as a function of surface orientation of the corresponding scene point

\[ \cos \theta_s = \frac{(-p,-q,1) \cdot (-p_s,-q_s,1)}{\sqrt{1+p^2+q^2} \sqrt{1+p_s^2+q_s^2}} \]

\[ = \frac{1 + p_s \, p + q_s \, q}{\sqrt{1+p^2+q^2} \sqrt{1+p_s^2+q_s^2}} \]

Angle between surface normal and direction to point light source
The Reflectance Map II

Reflectance map of Lambertian surface for $p_s = 0.2$, $q_s = 0.4$

\(R(p,q)\): Reflectance for all surface orientations \((p,q)\) for a given light source distribution and a given surface material

Lambertian surface \(R(p,q) \propto \cos \theta_s = \frac{1 + p_s p + q_s q}{\sqrt{1 + p^2 + q^2} \sqrt{1 + p_s^2 + q_s^2}}\)
Photometric Stereo

- Point light source: lines of constant reflectance in reflectance map defined by second-order polynomial
  - For each image point \((x,y)\), the possible surface orientation \((p,q)\) is restricted to lie on the curve defined by the polynomial
  - 3 different point sources give 3 second-order curves
Photometric Stereo II

Light source from left

Light source from top

Light source from right

http://amba.charite.de/~ksch/spsm/beet.html
For each pixel, the 3 measured intensities corresponding to the 3 different illumination directions lie on 3 different curves in the reflectance map that intersect in one point.
Photometric Stereo IV

Image irradiance

\[ E(x, y) = \rho \cdot R(p, q) \]
\( \rho: \) surface albedo

Surface normal

\[ \hat{n} = \frac{(-p, -q, 1)}{\sqrt{1 + p^2 + q^2}} \]

Point light source direction

\[ \hat{s}_i = \frac{(-p_i, -q_i, 1)}{\sqrt{1 + p_i^2 + q_i^2}} \]

Lambertian reflection

\[ E_i = \rho \hat{s}_i \cdot \hat{n}_i \]

3 illumination directions/
substitution

\[
E = \begin{pmatrix} E_1 \\ E_2 \\ E_3 \end{pmatrix} \quad S = \begin{pmatrix} \hat{s}_1 \\ \hat{s}_2 \\ \hat{s}_3 \end{pmatrix} = \begin{pmatrix} s_{1,x} & s_{1,y} & s_{1,z} \\ s_{2,x} & s_{2,y} & s_{2,z} \\ s_{3,x} & s_{3,y} & s_{3,z} \end{pmatrix} \]

\[ E = \rho S \cdot \hat{n} \]

Linear set of 3 equations
per pixel

\[ \rho \hat{n} = S^{-1}E \]
Photometric Stereo

- **Advantages**
  - A normal value for each pixel with very few images
  - Approach captures details, like pores, wrinkles, or spots

- **Disadvantages**
  - Normals must be integrated to get a 3D model (errors will accumulate)
  - Needs controlled lighting or robust estimation of light direction
Photometric Stereo V

Real Geometry

Normal Map
Integrating the normals

- Normals of a height field surface: \( z = f(x, y) \)
  - Tangent space is spanned by
    \[
    \begin{pmatrix}
    1 \\
    0 \\
    \frac{\partial f}{\partial x} \\
    \frac{\partial f}{\partial y}
    \end{pmatrix}
    \begin{pmatrix}
    0 \\
    1 \\
    \frac{\partial f}{\partial y} \\
    1
    \end{pmatrix}
    \]

  \[
  \Rightarrow \mathbf{n} = \begin{pmatrix}
  1 \\
  0 \\
  \frac{\partial f}{\partial x} \\
  \frac{\partial f}{\partial y}
  \end{pmatrix} \times \begin{pmatrix}
  0 \\
  1 \\
  \frac{\partial f}{\partial f} \\
  1
  \end{pmatrix} = \begin{pmatrix}
  -\frac{\partial f}{\partial x} \\
  \frac{\partial f}{\partial y} \\
  1
  \end{pmatrix}
  \]

- Laplacian operator

  \[
  \nabla \cdot \nabla f = \frac{\partial}{\partial x} \frac{\partial f}{\partial x} + \frac{\partial}{\partial y} \frac{\partial f}{\partial y} = \hat{\triangle} f
  \]
Integrating the normals

- Solve system

\[
\frac{1}{h^2} \begin{pmatrix}
-4 & 1 & 0 & \ldots & 1 & \ldots & 0 & 0 \\
1 & -4 & 1 & 0 & \ldots & 1 & \ldots & 0 \\
0 & 1 & -4 & 1 & \ddots & \ddots & \ddots & 0 \\
0 & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots \\
\end{pmatrix}
\begin{pmatrix}
\hat{f}_{1,1} \\
\hat{f}_{1,2} \\
\vdots \\
\hat{f}_{M,N}
\end{pmatrix}
= \begin{pmatrix}
\nabla \cdot (\nabla f)_{1,1} \\
\nabla \cdot (\nabla f)_{1,2} \\
\vdots \\
\nabla \cdot (\nabla f)_{M,N}
\end{pmatrix}
\]

- Compute right-hand side numerically

- Include Boundary conditions: e.g. von Neumann = 0

  - Modify system above – it corresponds to \( \hat{f} = 0 \) on the boundary
Photometric Stereo VI

- Reconstruct normal directions
- Integrate normal directions to obtain depth map
- Triangulate depth map
Photometric Stereo Assumptions

- Assumptions:
  - Surface has Lambertian reflectance characteristics
  - Illumination directions are known
  - Illumination sources are distant from object
  - Secondary illumination is insignificant
  - There are no cast shadows
  - Distant camera (orthographic projection)

- Extensions
  - Non-local illumination or views
  - Non-Lambertian BRDF
Active Light – Time-of-Flight Imaging
Time-of-Flight – Pulse-based

- time-of-flight scanners [Gvili03]
- NOT triangulation based
- short infrared laser pulse is sent from camera
- reflection is recorded in a very short time frame (ps)
- results in depth profile (intensity image)
Time-of-Flight – Pulse-based

- time-of-flight scanner – examples
- accuracy 1-2 cm in a range of 4 – 7 m
- applications:
  - "depth keying" replaces chroma keying
  - 3D interaction
  - large scale 3D scanning (LIDAR – light detection and ranging)
Canesta/3DV – Kinect 2 (?)
PMDs – Photonic Mixer Devices

Also called “multi-bucket sensors”

Chip layout

Schematic view

Electrical symbol

Fast on-chip modulation

[Luan’01]
PMDs – Photonic Mixer Devices

- Working principle: Measure phase difference of emitted, modulated signal and received one.

\[ d = \frac{c}{f_{\text{mod}}} \cdot \frac{1}{2} \cdot \frac{\phi_d}{2\pi} \]

- Current hardware: ~20MHz modulation frequency – in practice square wave.

[Metrilus]

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Photonic Mixer Device (PMD) sensor:

\[ f_\omega(t + \phi) \]
Single-path Time-of-Flight depth imaging:

\[ g_\omega(t) \]

PMD Sensor

\[ f_\omega(t + \phi) \]

\[ \int_{dt} \]

\[ \alpha_p g_\omega(t + \tau) \]

\[ H_{\omega,\phi} \]
Single-path Time-of-Flight depth imaging:

\[ g_\omega(t) \]

PMD Sensor

\[ f_\omega(t + \phi) \]

\[ \int dt \]

\[ H_{\omega,\phi} \]

distance-dependent correlation

\[ \alpha_p g_\omega(t + \tau) \]
LIDAR

University of Washington

NASA

Time-of-Flight Cameras

PMD
Panasonic

Fotonic
ARTTS
MESA

See [Kolb et al. 10], EG STAR for more details

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Active Light – Transient Imaging
What is Transient Imaging?

a.k.a. Light-in-Flight Imaging

- Ultrafast imaging of non-stationary light distribution in scenes
- Tracking of wavefronts of light as they propagate in the scene
- Equivalent to imaging ultrashort pulses of light
Applications of Transient Imaging

Many applications by analyzing a transient image!

Understanding light transport:
Velten et al.´2013

Surface reflectance capture:
Naik et al.´2011

Decomposing light transport:
Wu et al.´2012

Reconstructing hidden object geometry (and motion):
Velten et al.´2012
Pandharkar et al.´2011

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Visualizing Light in Motion

- Repetitive Event, 1012 FPS, 672 x 1000 pixel resolution, 1 ns+ capture time
- Light moves 0.6 mm per frame
- Ability to see light transport

[Velten et al. 13]
Streak Cameras

- Picosecond time resolution
- 1D: 1x672 pixels
- Result as 2D image ("Streak Photo")

[Velten et al. 13]
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Experimental Setup

Ti:Sapphire Laser

Synchronization

Camera

Scanning Unit

Object

[Velten et al. 13]

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Actual Setup

[Velten et al. 13]
Scattering in Real Scenes

[Velten et al. 13]
[Velten et al. 13]
Transient Imaging

- With PMD Devices – linked to the “multi-path” or “mixed pixel” problem
Multi-path contributions: 

\[ g_\omega(t) \]

\[ f_\omega(t + \phi) \]

\[ \int dt \]

\[ H_{\omega,\phi} \]

\[ \alpha_p g_\omega(t + \tau_{p1}) \]

\[ \alpha_p g_\omega(t + \tau_{p2}) \]
Recovering multi-path contributions:

\[ g_{\omega_1}(t) \]

PMD Sensor

\[ f_{\omega_1}(t + \phi_1) \]

\[ \int dt \]

\[ H_{\omega_1,\phi_1} \]
Recovering multi-path contributions:

\[ f_{\omega_2}(t + \phi_2) \]

\[ g_{\omega_2}(t) \]

PMD Sensor

\[ \int dt \]

\[ H_{\omega_1,\phi_1} \]

\[ H_{\omega_2,\phi_2} \]
Recovering multi-path contributions:
Image formation model:

- Relation of Transient Image to PMD measurement:

\[ H_{\omega_i,\phi_i} = \sum_{\tau=0}^{n} I(x, y, \tau) c_{\omega_i,\phi_i}(\tau) = \vec{i} \cdot \vec{c} \quad \Rightarrow \quad \vec{h} = C \cdot \vec{i} \]

- Linear system is ill-posed: multiple measurements
  - assume model for temporal response (signal sparsity)
    Mixture Model: Gaussian + Exponential
  - and spatial smoothness
  - solve non-linear system

[slides by Felix Heide]
PMDTechnologies CamBoard nano

Too slow

Fixed frequency

LED unit
PLL 25MHz
Control
PMD sensor
ADC
FPGA
Power supply
USB
...

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Modifications to the hardware

Prototype: Max mod. frequency 180 MHz, stable up to 110 MHz

Novatech DDS9m

Laser unit iC-HG + LPC826

2-ch. function generator 0-180 MHz

Control

USB

Prototype: Max mod. frequency 180 MHz, stable up to 110 MHz

FPGA

PLL 25 MHz

Control

MOD

TRIG

PMD sensor

ADC

LED unit

Power supply

USB

...
Prototype setup

Used for results in paper
Result ‘Discoball’:  

Color coding of strongest component:
Results ‘Discoball’:

Different time-steps:
Results ‘Discoball’:

Different time-steps:
Results ‘Discoball’:

Different time-steps:
Results ‘Discoball’:

Different time-steps:
Results ‘Discoball’:

Different time-steps:
Result ‘Bottles’:

Color coding of strongest component:
Emerging Technologies prototype

Camera unit

Light source

AD9958 DDS (function generator) 0-180 MHz

Control

USB

LED unit

FPGA

PLL 25 MHz

Control

PMD sensor

ADC

Power supply

USB

...
Results: People
References

- Velten et al. “Femto-photography: capturing and visualizing the propagation of light”, SIGGRAPH 2013