Structured-Light Based Acquisition (Part 1)

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Passive vs. Active Acquisition

• Passive
  + Just take pictures
  + Does not intrude in the environment (=passive)
    – Some surfaces cannot be acquired
    – Robustness is problematic

• Active
  + Emit “light” into the scene so as to force the generation of robust correspondence
    – Environment is intruded (=active)
Active Acquisition

• Some options:
  – Laser scanning
  – “Structured Light”
Laser Scanning
Light Stripe Scanning (Single Stripe)

- Optical triangulation
  - Project a single stripe of laser light
  - Scan it across the surface of the object
  - This is a very precise version of structured light scanning
  - Good for high resolution 3D, but needs many images and takes time
Stripe Triangulation

Object

Camera

Laser

Light Plane

\[ Ax + By + Cz + D = 0 \]

• Project laser stripe onto object
• Depth from ray-plane triangulation:
  – Intersect camera ray with light plane

\[
\begin{align*}
  x &= x' \frac{z}{f} \\
  y &= y' \frac{z}{f} \\
  z &= \frac{-Df}{Ax' + By' + Cf}
\end{align*}
\]
Example: Laser scanner

+ very accurate < 0.01 mm
- more than 10 sec per scan

Cyberware® face and head scanner
Example: Laser scanner

Digital Michelangelo Project
http://graphics.stanford.edu/projects/mich/
Example: Laser scanner

Portable scanner by Minolta
Digital Projector Structured Light

- Goal: generate correspondences so as to enable a robust 3D reconstruction
Digital Projector Structured Light

• Method:
  – Use the projector as a “pattern” generator
  – Have the camera see the “pattern” and generate 1 or more corresponded points

![Digital Projector Structured Light](image)
Digital Projector Structured Light

• What are possible patterns?
  – Spatial patterns
  – Temporal patterns
  – Color patterns
  – And combinations of the above
Digital Projector Structured Light

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Binary Pattern Structured Light
For a structured light system, we can use a calibrated projector and camera pair. We can also use an uncalibrated projector and a pair of calibrated cameras.

Yi Xu, 5/23/2007
Binary Coding

- Assign each pixel a unique illumination code over time [Posdamer 82]
Binary Coding

• Assign each pixel a unique illumination code over time [Posdamer 82]
Binary Coding

$2^n - 1$ stripes in $n$ images

Example:

3 binary-encoded patterns which allows the measuring surface to be divided in 8 sub-regions
# Binary vs Gray Codes

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<th>Binary</th>
<th>Gray Code</th>
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<tbody>
<tr>
<td>0</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

Pattern 3

Pattern 2

Pattern 1

Binary code

Gray code
Standard Pixel Classification

ON(1)  OFF(0)  Uncertain
Pixel Classification Challenges

- Illuminated (ON)
- Non-illuminated (OFF)

?
Standard Pixel Classification

• Interval

- Simple threshold
- Albedo threshold
- Dual pattern
1. Simple Threshold

User specifies one threshold $t$ for all pixels

$p$ is ON

$q$ is OFF
1. Simple Threshold

User specifies two thresholds $t_1$, $t_2$

$p$ is ON

$q$ is OFF
2. Albedo Threshold

Compute the albedo $t_p$ for each pixel

$p$ is ON

$P_{off}$ $t_p$ $P_{on}$

Albedo image
2. Albedo Threshold

Compute the albedo $t_p$ for each pixel

Albedo image
3. Dual Pattern: Pattern and Inverse

Without explicitly computing $t_p$

$P_{\text{off}}$ $P_{\text{on}}$

$p$ is ON $p$ is OFF

Inverse pattern
Limitations of Standard Methods

• All three methods assume the two intervals do not overlap
  – This is incorrect when there is strong indirect (global) light

• Haven’t actually established the correct bounds
Example Reconstruction

(lost samples are due to missing and incorrect classifications)
Key Observations

- We can estimate tight intensity value bounds for when the pixel is ON and for when it is OFF.

- A pixel is classifiable when its intensity value falls into one interval but not in the other.

[Xu07, Xu09]
Example Comparison

Using standard pixel classification

Using our pixel classification
Pixel Intensity ($p$ is ON)

$p$ is directly illuminated

\[ p = d + i_{on} \]  

(direct)  \hspace{1cm} (indirect)
Pixel Intensity ($p$ is OFF)

$p$ is not directly illuminated

$$p = i_{off} \quad \text{(indirect)}$$
Pixel Intensity

\[ p = \begin{cases} 
  d + i_{on} & \text{if } p \text{ is ON} \\
  i_{off} & \text{if } p \text{ is OFF} 
\end{cases} \]

- Chicken and egg problem is
  - Need to know \( d, i_{on}, i_{off} \) to classify a pixel.
  - Need to classify a pixel to know \( d, i_{on}, i_{off} \)

ALL white pattern
(all projector pixels on)
Direct and Indirect Separation

• Direct and indirect (global) components of each pixel under ALL white pattern can be separated easily (Nayar et al. SIGGRAPH’06).

\[ p = d_{\text{total}} + i_{\text{total}} \]
Direct and Indirect Separation

- Project high frequency binary pattern and its inverse to separate light components.

- Structured light patterns include the separation patterns.
  - Thus, separation can be applied to previously captured data to obtain per pixel
    \[ p = d_{total} + i_{total} \]
Pixel Classification Scenarios

\[ d_{\text{total}} > i_{\text{total}} \]

\[ 0 \quad P_{\text{off}} \quad i_{\text{total}} \quad d_{\text{total}} \quad P_{\text{on}} \quad d_{\text{total}} + i_{\text{total}} \]

0 \quad OFF \quad ON \quad 255
Pixel Classification Scenarios

\[ d_{\text{total}} \approx 0 \]

0 \hspace{1cm} P_{\text{off}} \hspace{1cm} i_{\text{total}} \hspace{1cm} d_{\text{total}} \hspace{1cm} P_{\text{on}} \hspace{1cm} d_{\text{total}} + i_{\text{total}} \]

0 \hspace{1cm} \text{Uncertain} \hspace{1cm} 255
Pixel Classification Scenarios

\[ d_{total} \leq i_{total} \]

Diagram showing the classification scenarios with different regions for OFF, Uncertain, and ON states.
Single Pattern Classification Rules

• \( d_{\text{total}} < m \rightarrow \text{pixel is uncertain} \)

• \( p < \min(d_{\text{total}}, i_{\text{total}}) \rightarrow \text{pixel is off} \)

• \( p > \max(d_{\text{total}}, i_{\text{total}}) \rightarrow \text{pixel is on} \)

• otherwise \( \rightarrow \text{pixel is uncertain} \)
Classification Results

ON(1)  OFF(0)  Uncertain

Hand-painted ground truth
### Classification Results

<table>
<thead>
<tr>
<th>ON (1)</th>
<th>OFF (0)</th>
<th>Uncertain</th>
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Hand-painted ground truth

![Image of classification results]
Increased Reconstructed Points
Increased Reconstructed Points

Using standard pixel classification

Using our pixel classification
Increased Reconstructed Points
Increased Reconstructed Points
Increased Reconstructed Points

Using standard pixel classification         Using our pixel classification

Zoom-in view of the reconstructed points in white
Increased Reconstructed Points

Using standard pixel classification

Using our pixel classification
Another issue...
Another issue...

- Classify...
  - pixels at stripe boundaries?
  - pixels at strip middle?
  - all pixels?