Structured Light II

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(thanks: slides Prof. S. Narasimhan, CMU, Marc Pollefeys, UNC)

http://www.cs.cmu.edu/afs/cs/academic/class/15385-s06/lectures/ppts/lec-17.ppt
Variant

- **Pattern projection**
  - project a pattern instead of a single point
  - needs only a single image, one-shot recording
  - *but* matching is no longer unique (although still easier)
  - more on this later
Results

including exposures with peas-stuffed pattern the complete surface dataset consists of 43,000 projected dots. Results of a subset of about 15,000 dots are shown in Figure 6 - Figure 8. Figure 8 shows a photorealistic visualization of the dataset, which has been generated from the photogrammetrically determined object surface data by a raytracer program.
Active triangulation: Structured light

- One of the cameras is replaced by a light emitter
- Correspondence problem is solved by searching the pattern in the camera image (pattern decoding)
- No geometric constraints
Faster Acquisition?

- Project multiple stripes/patterns simultaneously.
- Correspondence problem: which stripe/pattern is which? How to uniquely identify patterns?

Zhang 2002: Works in real-time and on dynamic scenes
Space-time stereo
Zhang, Curless and Seitz, CVPR’ 03
Coded structured light

• Correspondence without need for geometrical constraints
• For dense correspondence, we need many light planes:
  – Move the projection device
  – Project many stripes at once: needs encoding
• Each pixel set is distinguishable by its encoding
• Codewords for pixels:
  – Grey levels
  – Color
  – Geometrical considerations
Codeword Classification

• Time-multiplexing:
  – Binary codes
  – N-ary codes
  – Gray code + phase shift

• Spatial Codification
  – De Bruijn sequences
  – M-arrays

• Direct encoding
  – Grey levels
  – Colour
Time-Coded Light Patterns

• Assign each stripe a unique illumination code over time [Posdamer 82]
Binary Coding: Bit Plane Stack

- Assign each stripe a unique illumination code over time [Posdamer 82]
Time Multiplexing

A set of patterns are successively projected onto the measuring surface, codeword for a given pixel is formed by a sequence of patterns.

The most common structure of the patterns is a sequence of stripes increasing its width by the time → single-axis encoding

**Advantages:**
- high resolution → a lot of 3D points
- High accuracy (order of µm)
- Robustness against colorful objects since binary patterns can be used

**Drawbacks:**
- Static objects only
- Large number of patterns

Example: 5 binary-encoded patterns which allows the measuring surface to be divided in 32 sub-regions
Binary Coding

Example: 7 binary patterns proposed by Posdamer & Altschuler

Codeword of this pixel: 1010010 → identifies the corresponding pattern stripe
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
Examples

http://www.youtube.com/watch?v=wryJeq3kdSg
Towards higher precision and real time scanning
Direct encoding with color

- Every encoded point of the pattern is identified by its colour

Tajima and Iwakawa rainbow pattern
(the rainbow is generated with a source of white light passing through a crystal prism)

T. Sato patterns capable of cancelling the object colour by projecting three shifted patterns
(it can be implemented with an LCD projector if few colours are projected)
Rainbow Pattern

http://cmp.felk.cvut.cz/cmp/demos/RangeAcquisition.html

Assumes that the scene does not change the color of projected light
Real time by direct encoding

Works despite complex appearances

Works in real-time and on dynamic scenes

- Need very few images (one or two).
- But needs a more complex correspondence algorithm

Zhang et al
De Bruijn Sequences

- A De Bruijn sequence (or pseudorandom sequence) of order $m$ over an alphabet of $n$ symbols is a circular string of length $n^m$ that contains every substring of length $m$ exactly once (in this case the windows are one-dimensional).

$$1000010111101001$$

$$\begin{align*}
m &= 4 \quad \text{(window size)} \\
n &= 2 \quad \text{(alphabet symbols)}
\end{align*}$$

- The De Bruijn sequences are used to define colored slit patterns (single axis codification) or grid patterns (double axis codification).

- In order to decode a certain slit it is only necessary to identify one of the windows in which it belongs to) can resolve occlusion problem.

Zhang et al.: 125 slits encoded with a De Bruijn sequence of 8 colors and window size of 3 slits

Salvi et al.: grid of $29 \times 29$ where a De Bruijn sequence of 3 colors and window size of 3 slits is used to encode the vertical and horizontal slits
M-Arrays

- An m-array is the bidimensional extension of a De Bruijn sequence. Every window of w×h units appears only once. The window size is related with the size of the m-array and the number of symbols used.

Example: binary m-array of size 4×6 and window size of 2×2

```
0 0 1 0 1 0
0 1 0 1 1 0
1 1 0 0 1 1
0 0 1 0 1 0
```

Shape primitives used to represent every symbol of the alphabet

Morano et al. M-array represented with an array of coloured dots

M-array proposed by Vuylsteke et al. Represented with shape primitives
Binary spatial coding

http://cmp.felk.cvut.cz/cmp/demos/RangeAcquisition.html
Problems in recovering pattern
Local spatial Coherence

http://www.mri.jhu.edu/~cozturk/sl.html

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Experimental results

- **Time-multiplexing**
  - Posdamer (128 stripes)
  - Horn (64 stripes)
  - Gühring (113 slits)

- **Spatial codification**
  - De Bruijn (64 slits)
  - Salvi (29x29 slits)
  - Morano (45x45 dot array)

- **Direct codification**
  - Gühring
  - Morano (45x45 dot array)
Discussion Structured Light

• Advantages
  – robust - solves the correspondence problem
  – fast - instantaneous recording, real-time processing

• Limitations
  – less flexible than passive sensing: needs specialised equipment and suitable environment

• Applications
  – industrial inspection
  – entertainment
  – healthcare
  – heritage documentation
  – …..
Microsoft Kinect
Microsoft Kinect

The Kinect combines structured light with two classic computer vision techniques: depth from focus, and depth from stereo.

http://users.dickinson.edu/~jmac/selected-talks/kinect.pdf
Consumer application

- Now people have it in their living room
  - Xbox Kinect - periodic infrared dot pattern
Microsoft Kinect

Inferring body position is a two-stage process: first compute a depth map, then infer body position.

http://users.dickinson.edu/~jmac/selected-talks/kinect.pdf
## Conclusions

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<tr>
<th>Types of techniques</th>
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| Time-multiplexing       | • Highest resolution  
                          • High accuracy  
                          • Easy implementation | • Inapplicability to moving objects  
                          • Large number of patterns |
| Spatial codification    | • Can measure moving objects  
                          • A unique pattern is required | • Lower resolution than time-multiplexing  
                          • More complex decoding stage  
                          • Occlusions problem |
| Direct codification     | • High resolution  
                          • Few patterns | • Very sensitive to image noise  
                          • Inapplicability to moving objects |
## Guidelines

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Best technique</th>
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<tbody>
<tr>
<td>• High accuracy</td>
<td>Phase shift + Gray code → Gühring’s line-shift technique</td>
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<tr>
<td>• Highest resolution</td>
<td></td>
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<tr>
<td>• Static objects</td>
<td></td>
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<tr>
<td>• No matter the number of patterns</td>
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<tr>
<td>• High accuracy</td>
<td>N-ary pattern → Horn &amp; Kiryati</td>
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<td>• High resolution</td>
<td>Caspi et al.</td>
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<tr>
<td>• Static objects</td>
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<tr>
<td>• Minimum number of patterns</td>
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<tr>
<td>• High accuracy</td>
<td>De Bruijn pattern → Zhang et al.</td>
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<td>• Good resolution</td>
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<td>• Moving objects</td>
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