



Structured Light II

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(thanks: slides Prof. S. Narasimhan, CMU, Marc Pollefeys, UNC) <u>http://www.cs.cmu.edu/afs/cs/academic/class/15385-</u> <u>s06/lectures/ppts/lec-17.ppt</u>



Faster Acquisition?

- Project multiple stripes simultaneously
- Correspondence problem: which stripe is which?
- Common types of patterns:
 - Binary coded light striping
 - Gray/color coded light striping



Static Light Pattern Projection





Static Light Pattern Projection

- Project a pattern of stripes into the scene to reduce the total number of images required to reconstruct the scene.
- Each stripe/line represents a specific angle a of the light plane.
- **Problem**: How to uniquely identify light stripes in the camera image when several are simultaneously projected into the scene.



Time-Coded Light Patterns

- Assign each stripe a unique illumination code over time [Posdamer 82]
- #stripes = mⁿ : m gray levels, n images



Binary Coding: Bit Plane Stack

• Assign each stripe a unique illumination code over time [Posdamer 82]





Binary Encoded Light Stripes



Figure 2. (a) Standard light sectioning with one light stripe. (b) Top view of light sectioning using more than one stripe. (c) Light sectioning using structured light.

- Set of light planes are projected into the scene
- Individual light planes are indexed by an encoding scheme for the light patterns
 - Obtained images form a bit-plane stack
 - Bit-plane stack is used to uniquely address the light plane corresponding to every image point

http://www.david-laserscanner.com/





Binary Encoded Light Stripes





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 \rightarrow a lot of 3D points
- High accuracy (order of μ m)
- 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





Binary Coding (II)

Binary coding

- Only two illumination levels are commonly used, which are coded as 0 and 1.
- Gray code can be used for robustness (adjacent stripes must only differ in 1 bit)
- Every encoded point is identified by the sequence of intensities that it receives
- n patterns must be projected in order to encode
 2ⁿ stripes
- Advantages
 - Easy to segment the image patterns
 - Need a large number of patterns to be projected



Binary Coding



Binary Image Sequence

- Each image is a bit-plane of the binary code for each 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/camera(s) must be roughly synchronized



Gray Code



Frank Gray (-> name of coding sequence)
Code of neighboring projector pixels only differ by 1bit, possibility of error correction!



Concept Gray Code (adjacent stripes must only differ in 1 bit)









Alternatives



Figure 8. Flowchart of the Line Shift algorithm.



N-ary codes

- Reduce the number of patterns by increasing the number of intensity levels used to encode the stripes.
 - Multi grey levels instead of binary
 - Multilevel gray code based on color.
- Alphabet of *m* symbols encodes *mⁿ* stripes

3 patterns based on a n-ary code of 4 grey levels (Horn & Kiryati) → 64 encoded stripes





Gray Code + Phase Shifting (I)

• A sequence of binary patterns (Gray encoded) are projected in order to divide the object in regions

• An additional periodical pattern is projected

• The periodical pattern is projected several times by shifting it in one direction in order to increase the resolution of the system \rightarrow similar to a laser scanner

Gühring's line-shift technique



Example: three binary patterns divide the object in 8 regions



Without the binary patterns we would not be able to distinguish among all the projected slits



Every slit always

falls in the same region



Phase Shift Method (Guehring et al)



Figure 3. Gray code (top) and Phase Shift (bottom) of a n = 32 stripe code sequence.

•Project set of patterns

•Project sin functions

Interpolation between adjacent light planes

•Yields for each camera pixel corresponding strip with subpixel accuracy!

•See <u>Videometrics01-Guehring-4309-24.pdf</u> for details

Source:

http://www.igp.ethz.ch/photogrammetry/education/lehrveranstaltun/MachineVisionFS2011/coursematerial/MV-SS2011-structured.pdf

- Increasing the resolution
 - project three phase-shifted sinusoidal patterns
 - can be projected sequentially, or simultaneously in different colours
 - the recorded intensities allow to compute the phase angle of a pixel within a wavelength



- Phase angle from brightness values
 - computing the phase angle from the three images
 - although the method relies on brightness, the ambient light and the power of the projector need not be known

observed intensities $I_{-} = I_{base} + I_{var} \cos(\phi - \theta)$ $I_{0} = I_{base} + I_{var} \cos(\phi)$ $I_{+} = I_{base} + I_{var} \cos(\phi + \theta)$

 \blacksquare removed dependence on I_{base}

removed dependence on Ivar



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from trigonometry

$$\tan\left(\frac{\theta}{2}\right) = \frac{1 - \cos(\theta)}{\sin(\theta)}$$

$$\cos(\phi - \theta) = \cos(\phi)\cos(\theta) + \sin(\phi)\sin(\theta)$$

$$\cos(\phi + \theta) = \cos(\phi)\cos(\theta) - \sin(\phi)\sin(\theta)$$

$$\frac{\cos(\phi-\theta) - \cos(\phi+\theta)}{2\cos\phi - \cos(\phi-\theta) - \cos(\phi+\theta)} = \frac{2\sin(\phi)\sin(\theta)}{2\cos(\phi)(1-\cos(\theta))}$$

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$$\frac{2\sin(\phi)\sin(\theta)}{2\cos(\phi)(1-\cos(\theta))} = \frac{\tan(\phi)\sin(\theta)}{1-\cos(\theta)} = \frac{\tan(\phi)}{\tan(\theta/2)}$$

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observed intensities

$$I_{-} = I_{base} + I_{var} \cos(\phi - \theta)$$
$$I_{0} = I_{base} + I_{var} \cos(\phi)$$
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phase angle
$$\frac{I_{-} - I_{+}}{2I_{0} - I_{-} - I_{+}} = \frac{\tan(\phi)}{\tan(\theta/2)}$$
$$\phi'(0, 2\pi) = \arctan\left(\tan\left(\frac{\theta}{2}\right)\frac{I_{-} - I_{+}}{2I_{0} - I_{-} - I_{+}}\right)$$

- Total phase
 - phase angle within a period from intensity
 - number of period from stereo triangulation (or light stripe)
 - stereo matching is easy: only N possibilities



- Total phase
 - the phase angle only determines the relative position within one cycle of the periodic sine wave
 - need to know which stripe we are in (c.f. GPS phase ambiguity)
 - achieved by ordering assumption, or combination with stereo





Example: Quality Control in Manufacturing



Figure 7. (a) One image of the *line shift* sequence. (b) Computed range image (z component). (c) Rendered view of the obtained surface. The holes are caused by points that have been eliminated by consistency checks, e.g. due to saturated pixels.

Consumer application

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



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

Pattern encoding/decoding

 A pattern is encoded when after projecting it onto a surface, a set of regions of the observed projection can be easily matched with the original pattern. Example: pattern with two-encoded-columns



 Decoding a projected pattern allows a large set of correspondences to be easily found thanks to the a priori knowledge of the light pattern



Rainbow Pattern





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

Assumes that the scene does not change the color of projected light.



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)

Pattern encoding/decoding

 Two ways of encoding the correspondences: single and double axis codification ⇒ it determines how the triangulation is calculated



 Decoding the pattern means locating points in the camera image whose corresponding point in the projector pattern is a priori known

Gray Code Structured Lighting



3D Reconstruction using Structured Light [Inokuchi 1984]

- Our implementation uses 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 → binary code → integer row/column index



Gray Code Structured Lighting: Results





More complex patterns







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



Spatial Codification

- Project a certain kind of spatial pattern so that a set of neighborhood points appears in the pattern only once. Then the codeword that labels a certain point of the pattern is obtained from a neighborhood of the point around it.
- The codification is condensed in a unique pattern instead of multiplexing it along time
- The size of the neighborhood (**window size**) is proportional to the number of encoded points and inversely proportional to the number of used colors
- The aim of these techniques is to obtain a **one-shot measurement** system ⇒ moving objects can be measured

• Advantages:

- Moving objects supported
- Possibility to condense the codification to a unique pattern

• Drawbacks:

 Discontinuities on the object surface can produce erroneous window decoding (occlusions problem)

 The higher the number of used colours, the more difficult to correctly identify them when measuring nonneutral surfaces

Maximum resolution cannot be reached



Local spatial Coherence



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

•Medical Imaging Laboratory Departments of Biomedical Engineering and Radiology Johns Hopkins University School of Medicine Baltimore, MD 21205



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).

 $1000010111101001 \begin{cases} m=4 \text{ (window size)} \\ n=2 \text{ (alphabet symbols)} \end{cases}$

• 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 29×29 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 marray of size 4×6 and window size of 2×2



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



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



Shape primitives used to represent every symbol of the alphabet



Binary spatial coding



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



Examples

Boyer - Kak 1987

- · Multiple coloured vertical slits.
- Codification from slit colour sequence.
- Column Coded / Dynamic / Colour / Absolute Monks '93 : Utilisation of the same pattern for speech interpretation.

Chen '97 : Unique codification and colour improvement.



Griffin - Narasimhan - Yee 1992

 Mathematical study to obtain the largest codification matrix from a fixed number of colours.

Dot position coded by the colour of its four neighbours.

Both axis coded / Static / Colour / Absolute Davies '96 : Re-implementation.



Decoding table





Decoding table

vertices	d(0)	d(1)	d(2)	d(3)
V(<mark>00</mark>)	0	3	6	9
V(<mark>0</mark> 1)	14	17	19	11
V(<mark>02</mark>)	28	34	22	24
V(1 0)	26	29	18	21
V(11)	1	31	33	35
V(1 <mark>2)</mark>	15	4	8	13
V(<mark>20</mark>)	16	23	32	12
V(<mark>21</mark>)	27	5	7	25
V(<mark>22</mark>)	2	10	20	30







Experiment









Results



igure 5: Electhowen basi with projected det pattern

Including exposures with phase-shifted pattern the complete surface dataset consists of 43,000 projected dots. Results of a subset of about 18,000 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 naytracer program.



Figure 6: Beethoven - grid Madel



Figure 7: Beetkoven - Isoline plot



Figure S: Deethoven - Photorentiatic visualisation



Conclusions

Types of techniques		
Time-multiplexing	Highest resolutionHigh accuracyEasy 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 resolutionFew patterns	 Very sensitive to image noise Inapplicability to moving objects

Guidelines

Requirements	Best technique	
 High accuracy Highest resolution Static objects No matter the number of patterns 	Phase shift + Gray code → Gühring's line-shift technique	7
 High accuracy High resolution Static objects Minimum number of patterns 	N-ary pattern → Horn & Kiryati Caspi et al.	
High accuracyGood resolutionMoving objects	De Bruijn pattern → Zhang et al.	