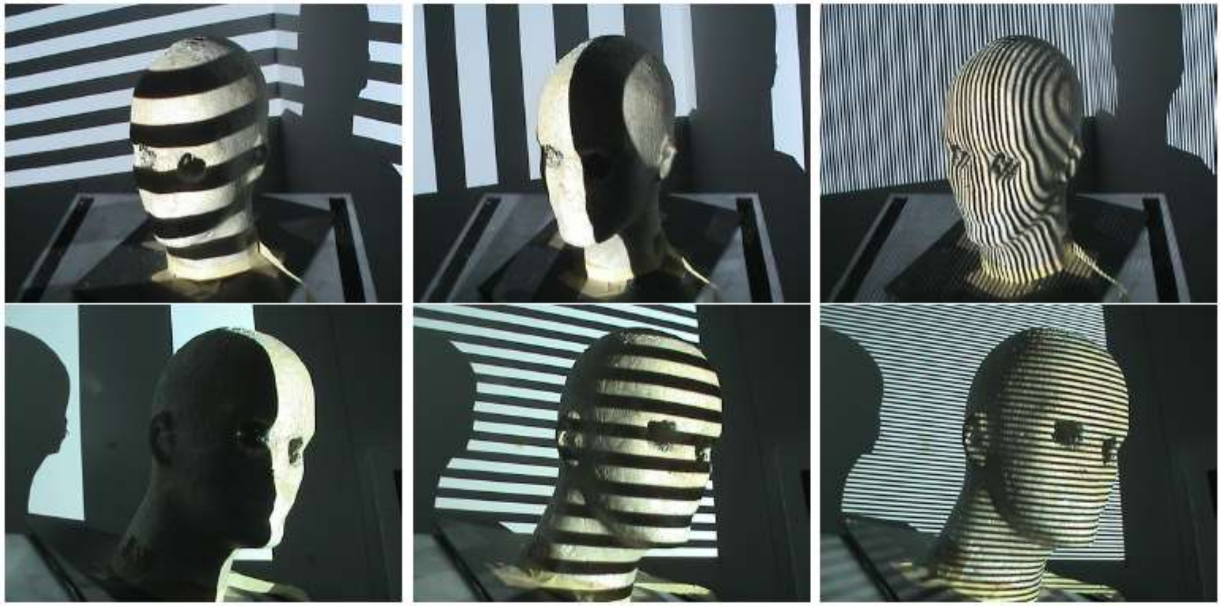


Structured Light II

Guido Gerig

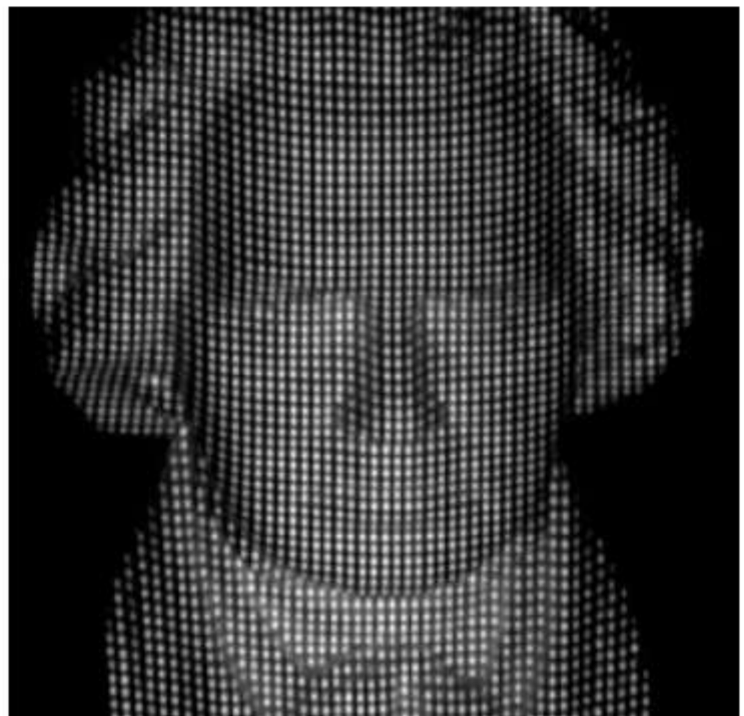
CS 6643, Spring 2016

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

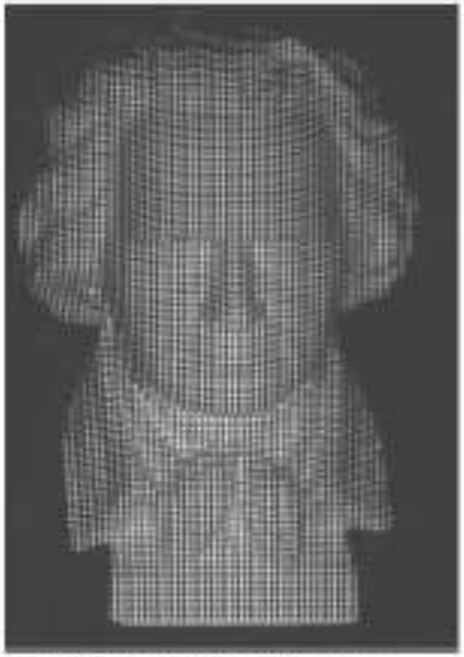
http://www.cs.cmu.edu/afs/cs/academic/class/15385-s06/lectures/ppts/lec-17.ppt

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



igure 5: Beethoven bust with projected dot 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 photo-realistic visualization of the dataset, which has been generated from the photogrammetrically determined object surface data by a raytracer program.

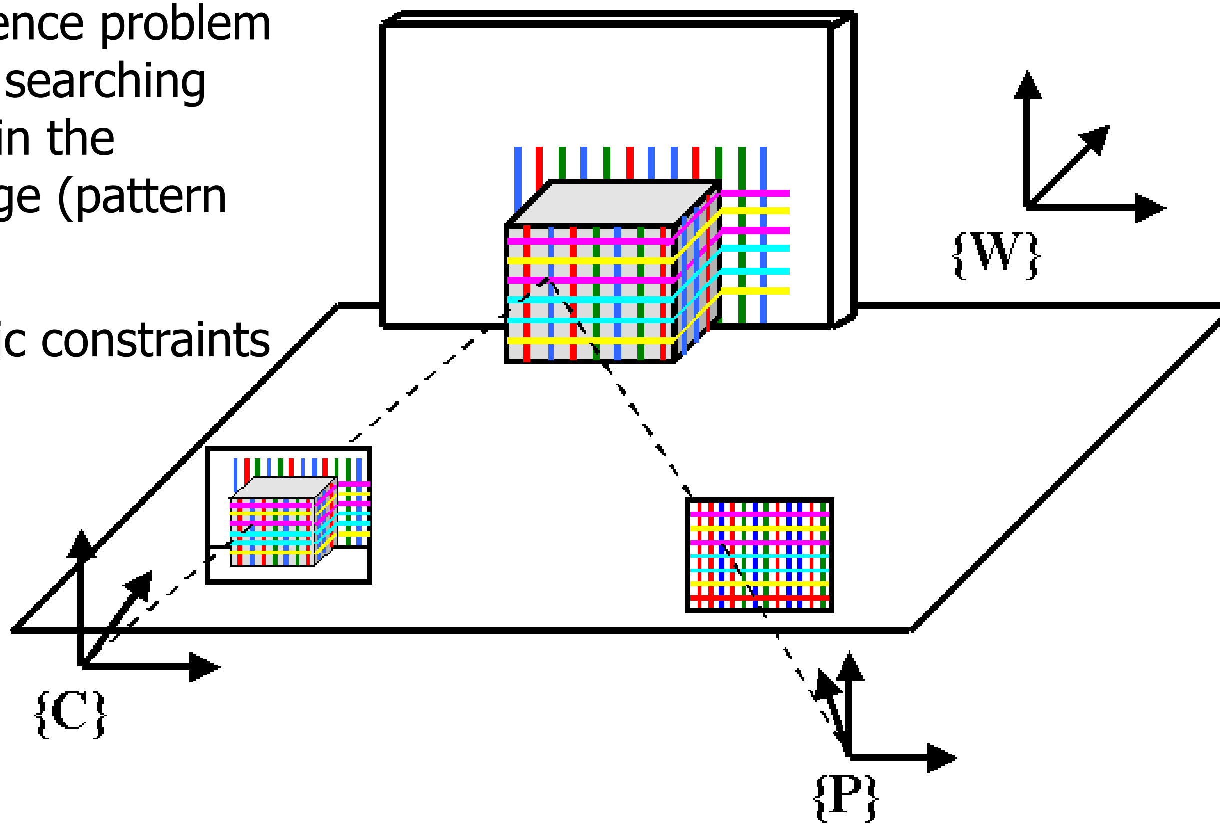
Figure 6: Beethoven - grid Model

Figure 7: Beethoven - Isoline plot

Figure 8: Beethoven - Photorealistic visualization

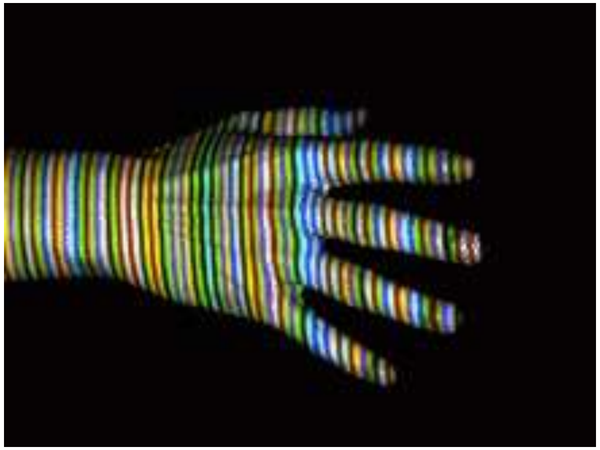
Active triangulation: Structured light

- 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?

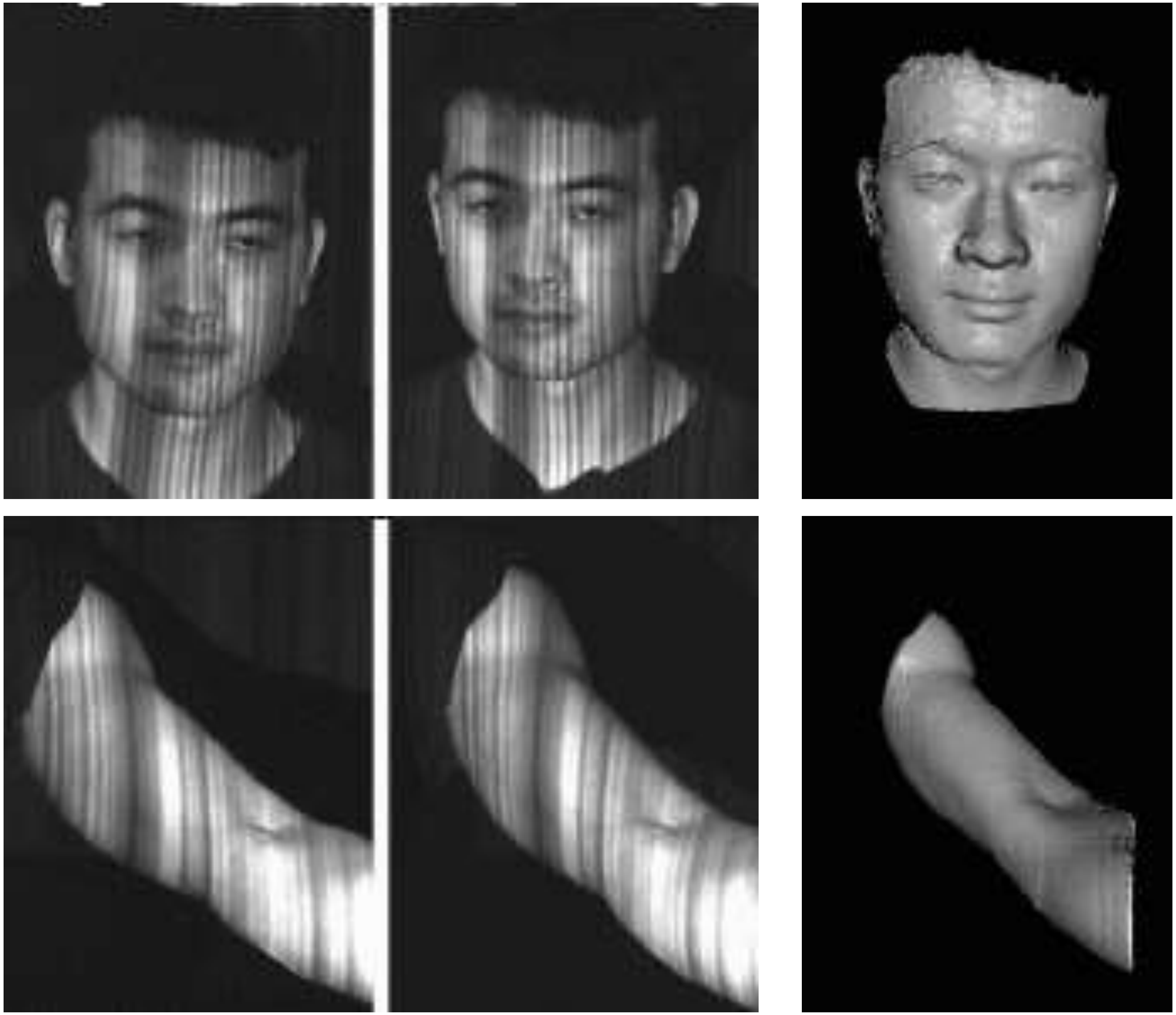
- Project multiple stripes/patterns simultaneously.
- Correspondence problem: which stripe/pattern is which? How to uniquely identify patterns?




Zhang 2002: Works in real-time and on dynamic scenes

Space-time stereo

Zhang, Curless and Seitz, CVPR'03



Coded structured light

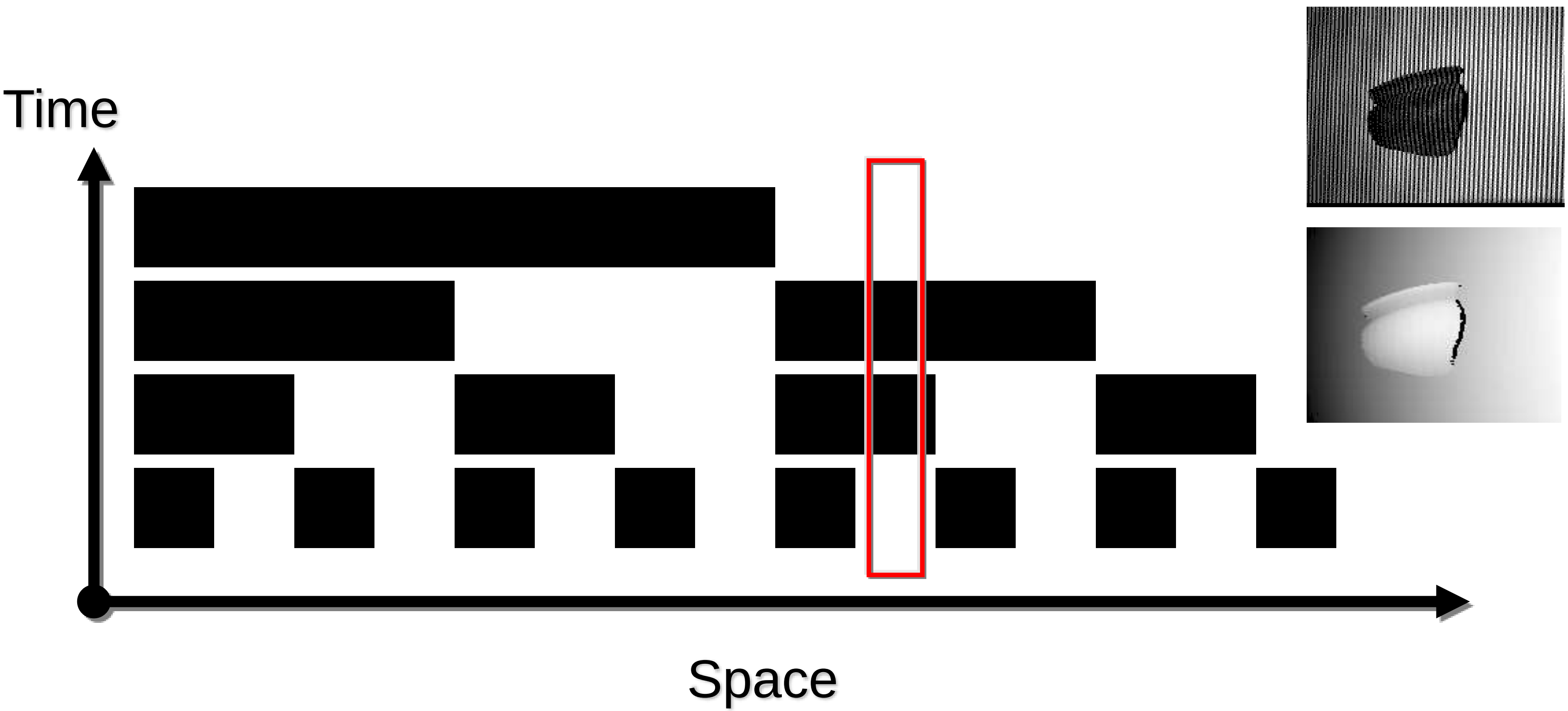
- Correspondence without need for geometrical constraints
- For dense correspondence, we need many light planes:
  - Move the projection device
  - Project many stripes at once: needs encoding
- Each pixel set is distinguishable by its encoding
- Codewords for pixels:
  - Grey levels
  - Color
  - Geometrical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

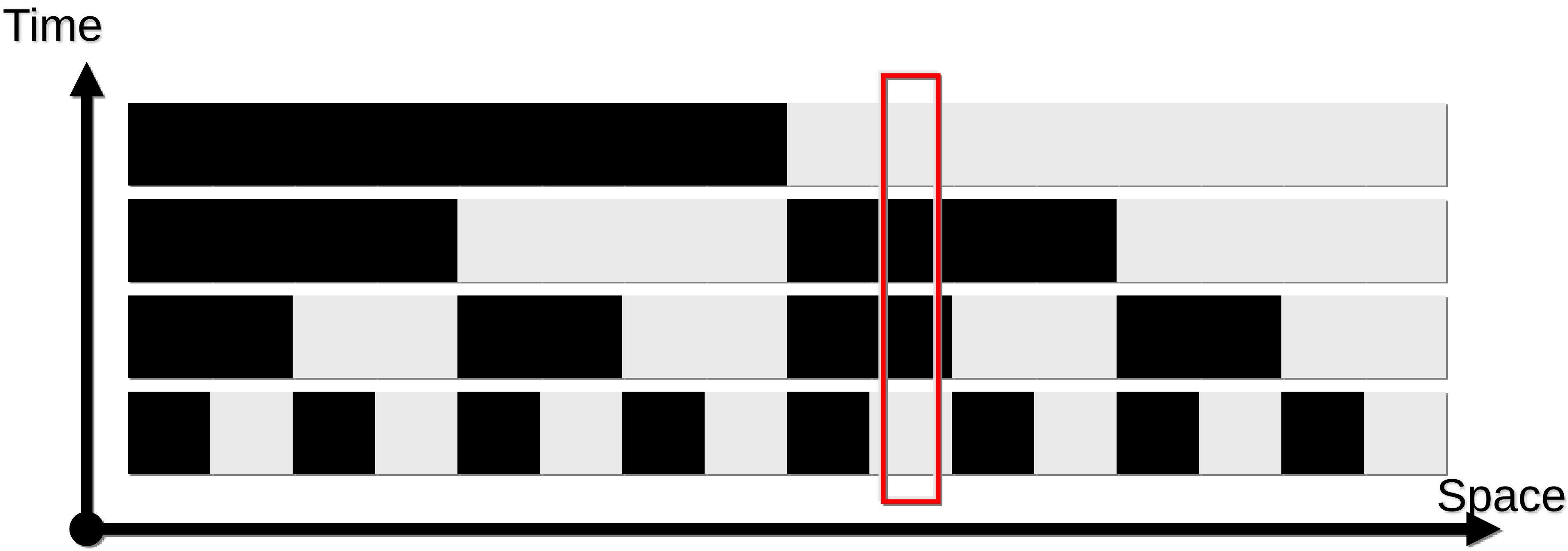
Time-Coded Light Patterns

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



Binary Coding: Bit Plane Stack

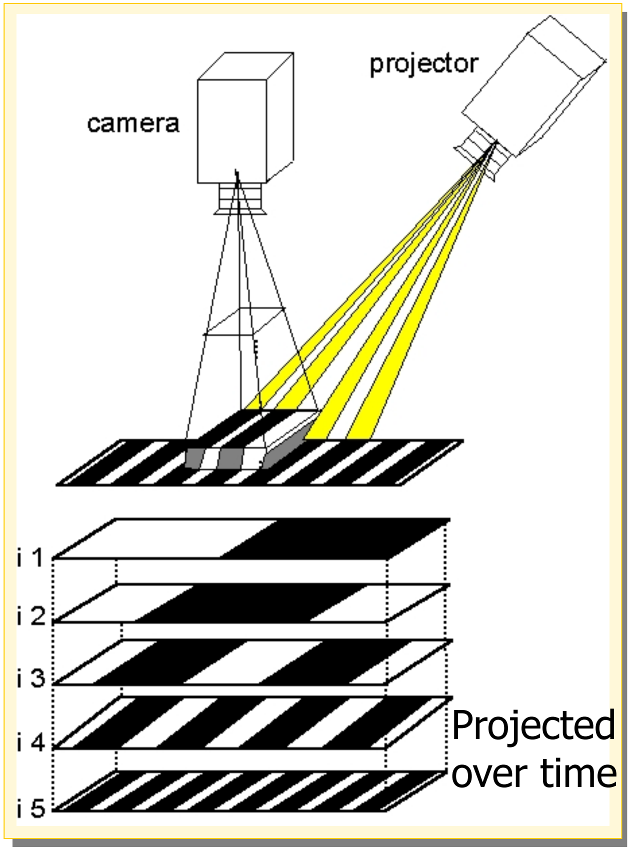
- Assign each stripe a unique illumination code over time [Posdamer 82]



1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
1	1	1	1	0	0	0	0	1	1	1	1	0	0	0	0
1	1	0	0	1	1	0	0	1	1	0	0	1	1	0	0
1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0

Time Multiplexing

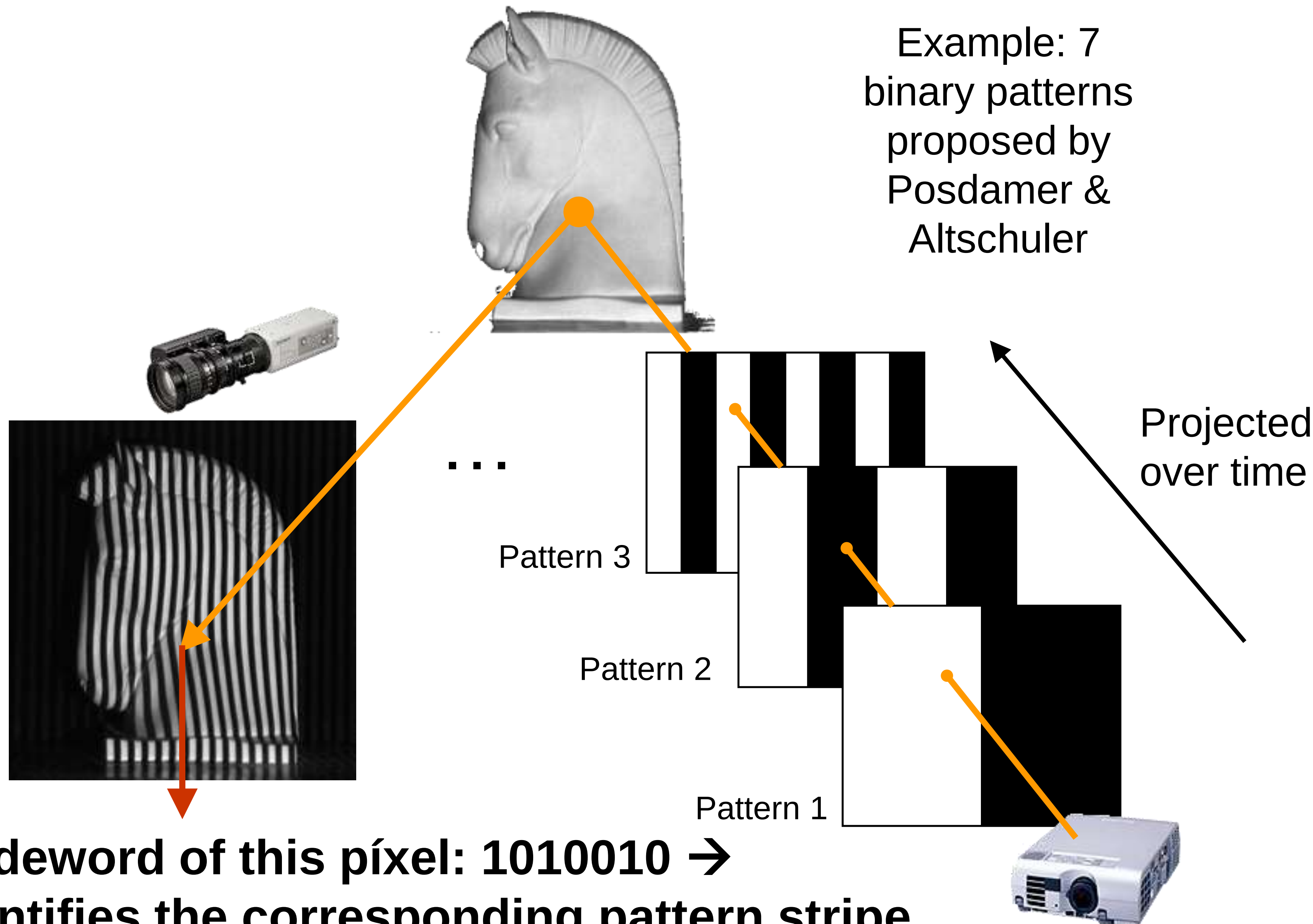
- A set of patterns are successively projected onto the measuring surface, codeword for a given pixel is formed by a sequence of patterns.
- The most common structure of the patterns is a sequence of stripes increasing its width by the time → single-axis encoding
- **Advantages:**
  - high resolution → 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

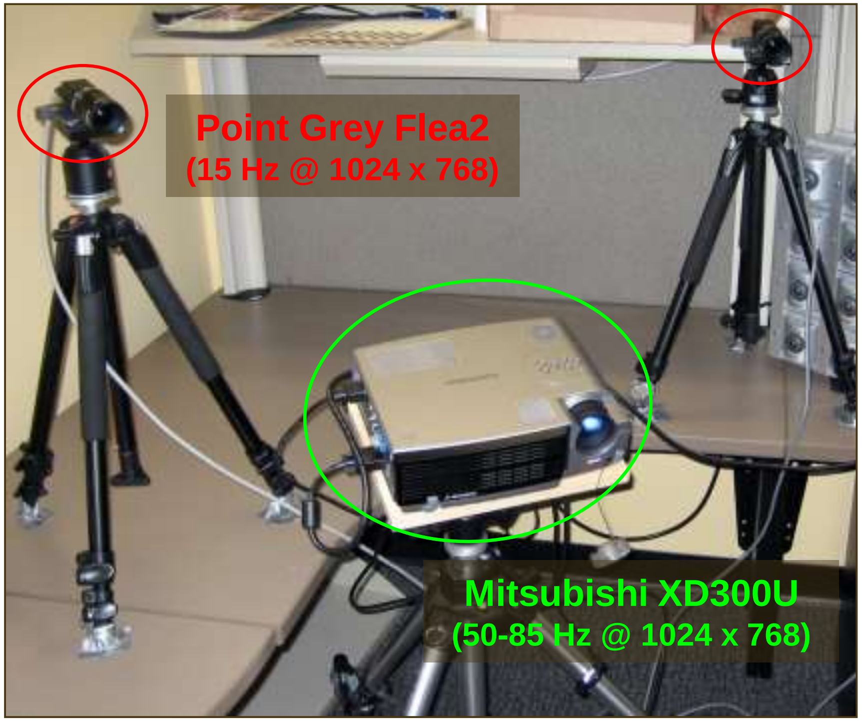
Binary Coding

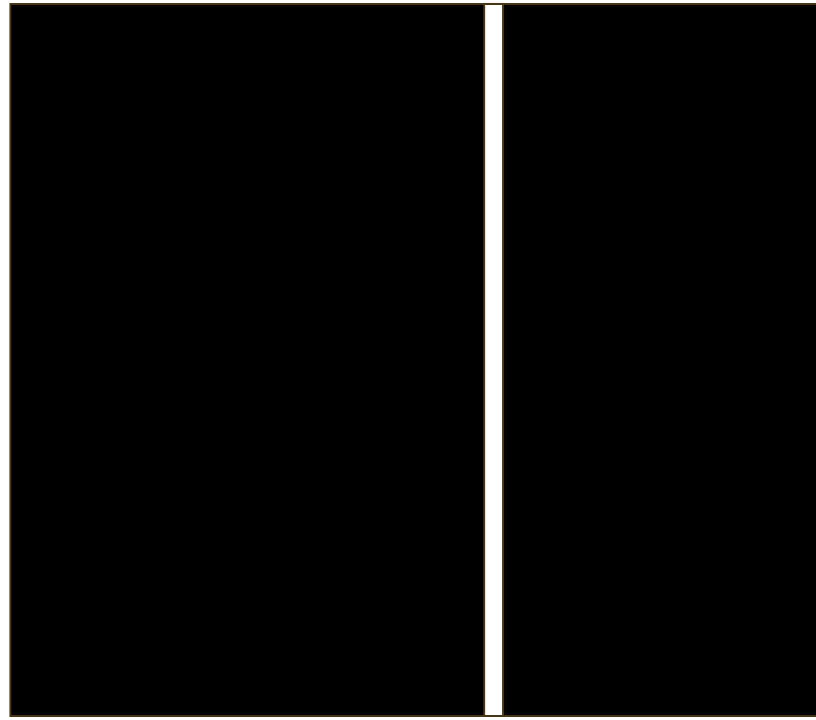
Example: 7 binary patterns proposed by Posdamer & Altschuler



Codeword of this píxel: 1010010 → identifies the corresponding pattern stripe

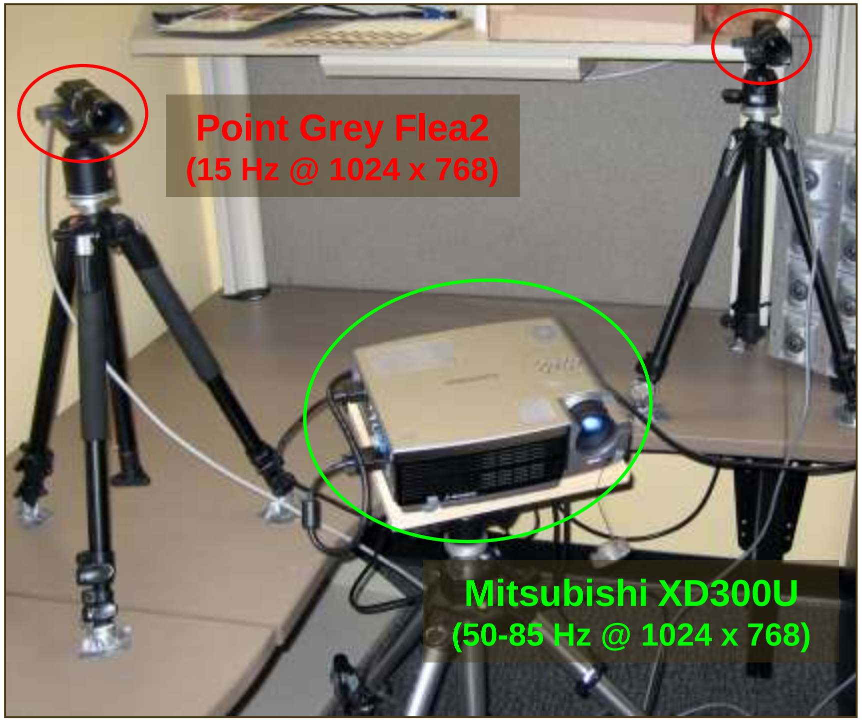
Structured Lighting: Swept-Planes Revisited

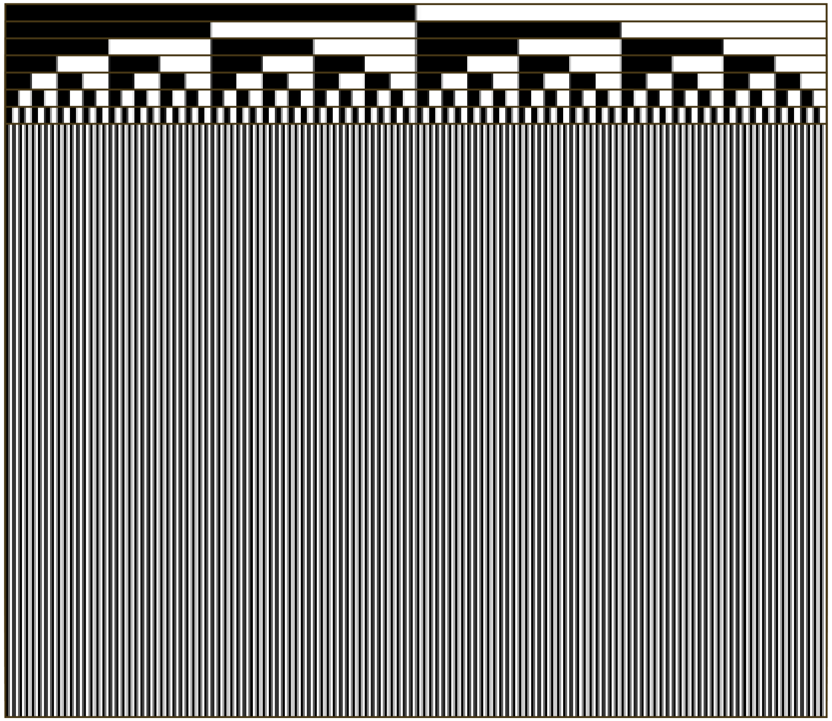




- Swept-plane scanning recovers 3D depth using ray-plane intersection
- Use a data projector to replace manually-swept laser/shadow planes
- How to assign correspondence from projector planes to camera pixels?
- Solution: Project a spatially- and temporally-encoded image sequence
- **What is the optimal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

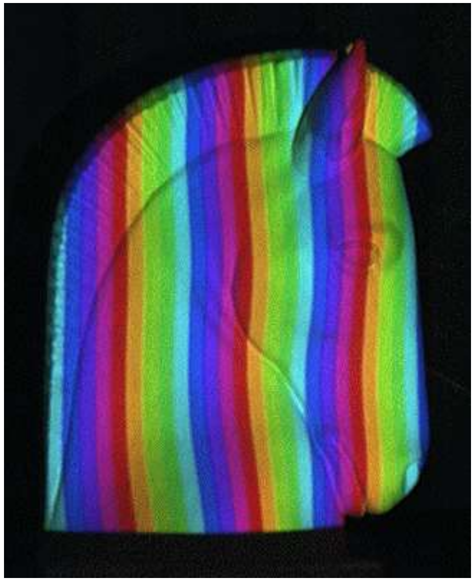
Towards higher precision and real time scanning

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)



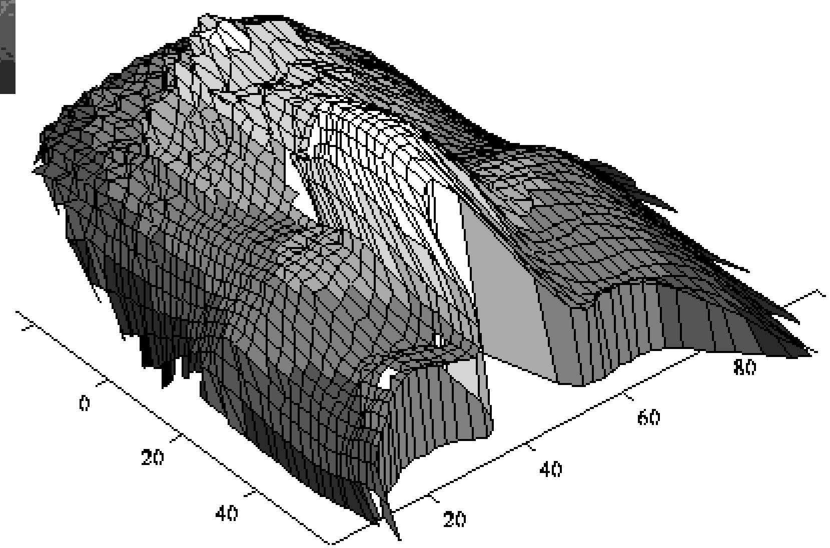
T. Sato patterns capable of cancelling the object colour by projecting three shifted patterns

(it can be implemented with an LCD projector if few colours are projected)

Rainbow Pattern

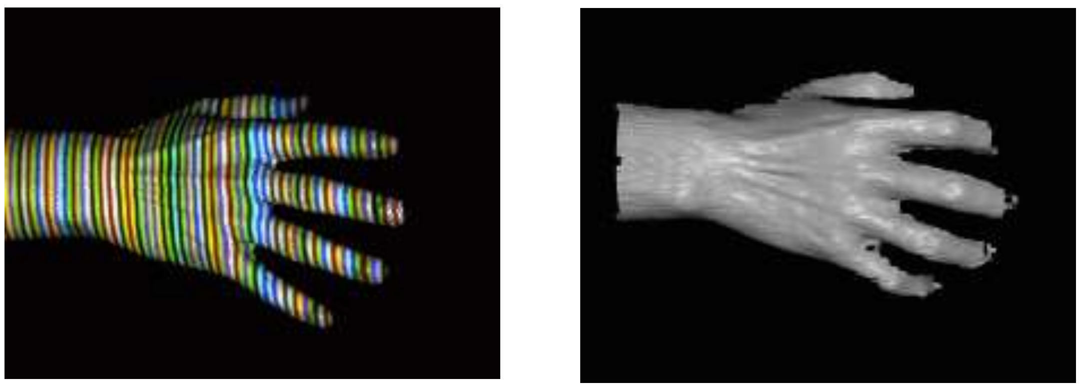
http://cmp.felk.cvut.cz/cmp/demos/RangeAcquisition.html

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

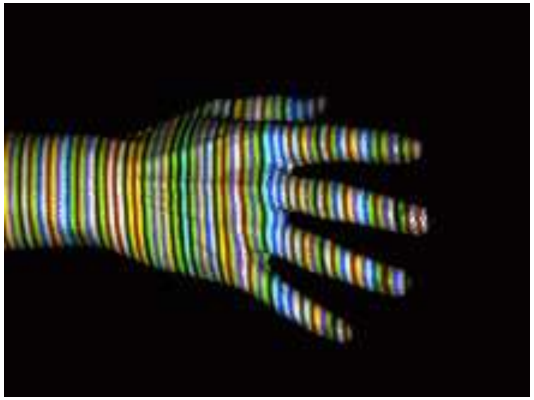
Zhang et al

De Bruijn Sequences

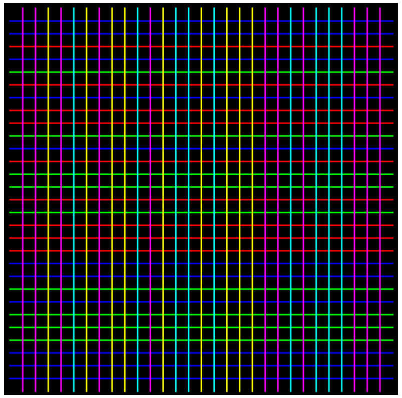
- A De Bruijn sequence (or pseudorandom sequence) of order m over an alphabet of n symbols is a circular string of length n^m that contains every substring of length m exactly once (in this case the windows are one-dimensional).

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

- 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



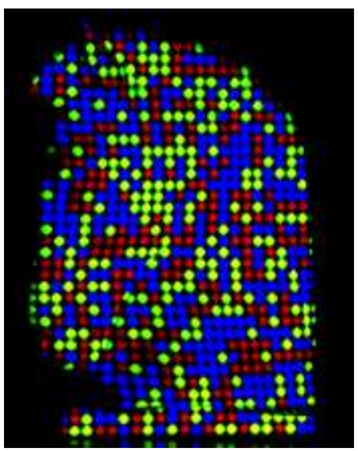
Salvi et al.: grid of 29×29 where a De Bruijn sequence of 3 colors and window size of 3 slits is used to encode the vertical and horizontal slits

M-Arrays

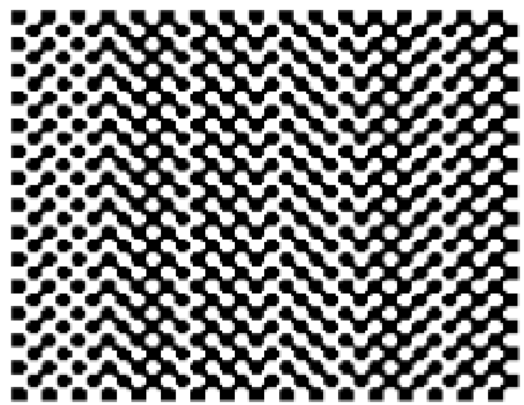
- An m-array is the bidimensional extension of a De Bruijn sequence. Every window of w×h units appears only once. The window size is related with the size of the m-array and the number of symbols used

0	0	1	0	1	0
0	1	0	1	1	0
1	1	0	0	1	1
0	0	1	0	1	0

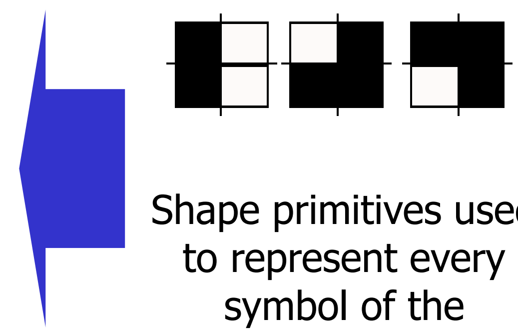
Example: binary m-array of size 4×6 and window size of 2×2



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

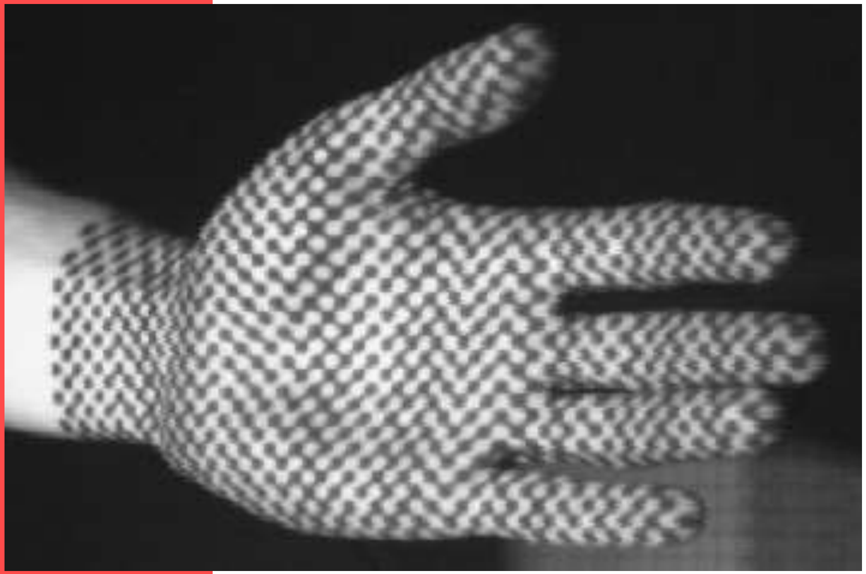


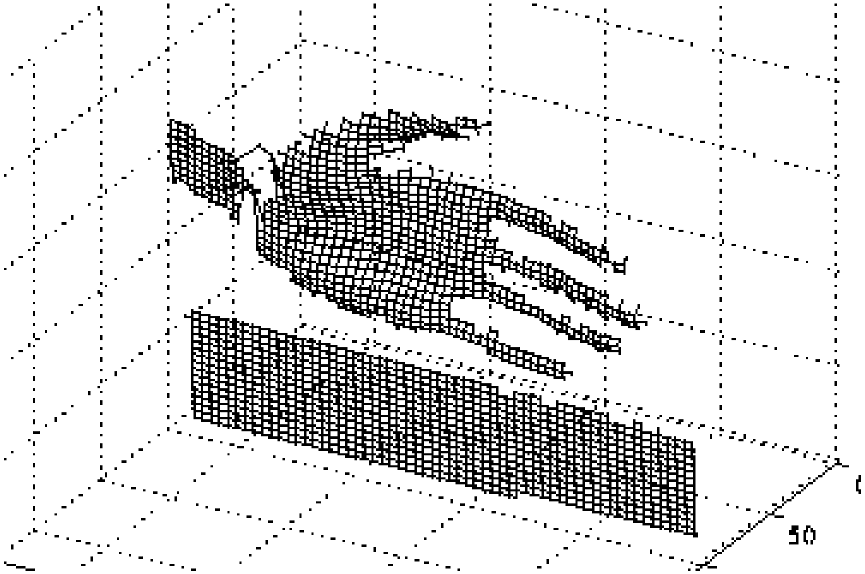
M-array proposed by Vuylsteke et al. Represented with shape primitives



Shape primitives used to represent every symbol of the alphabet

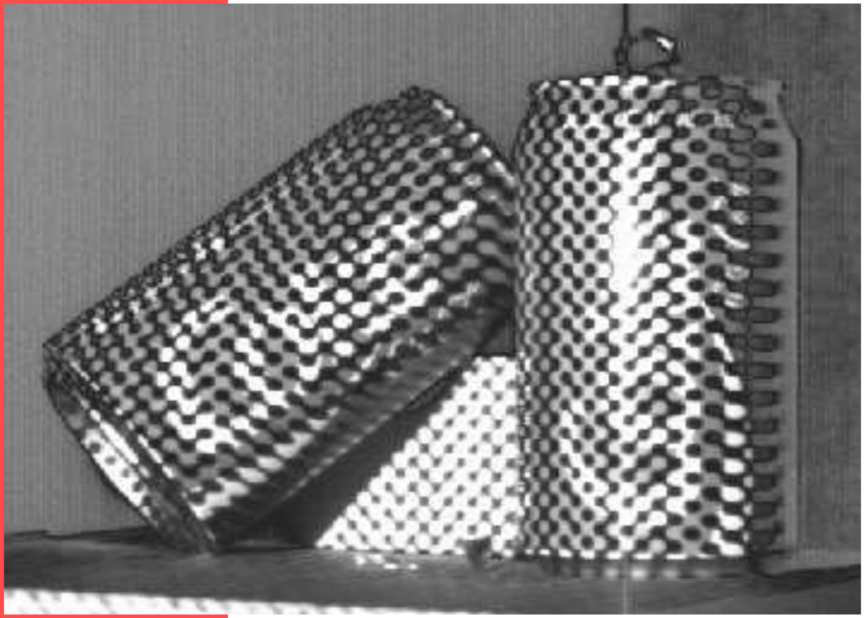
Binary spatial coding

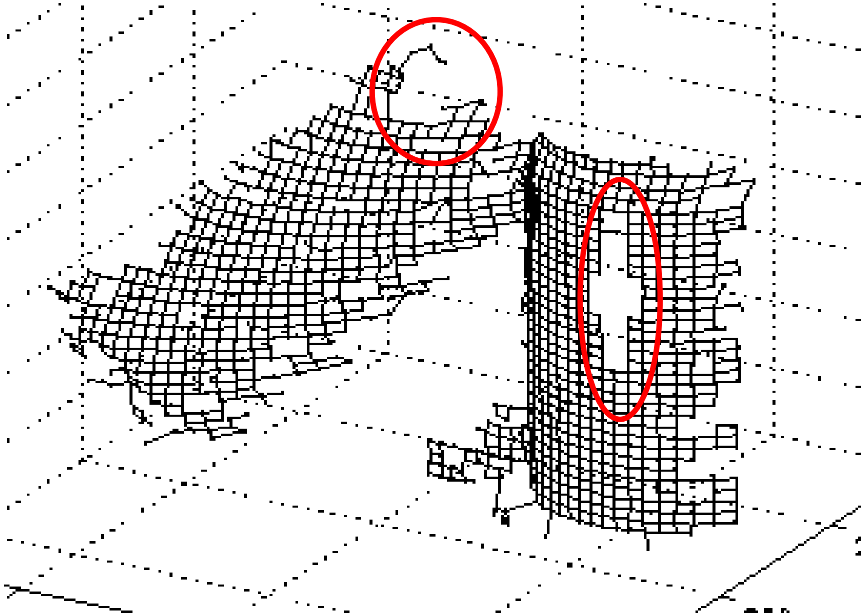




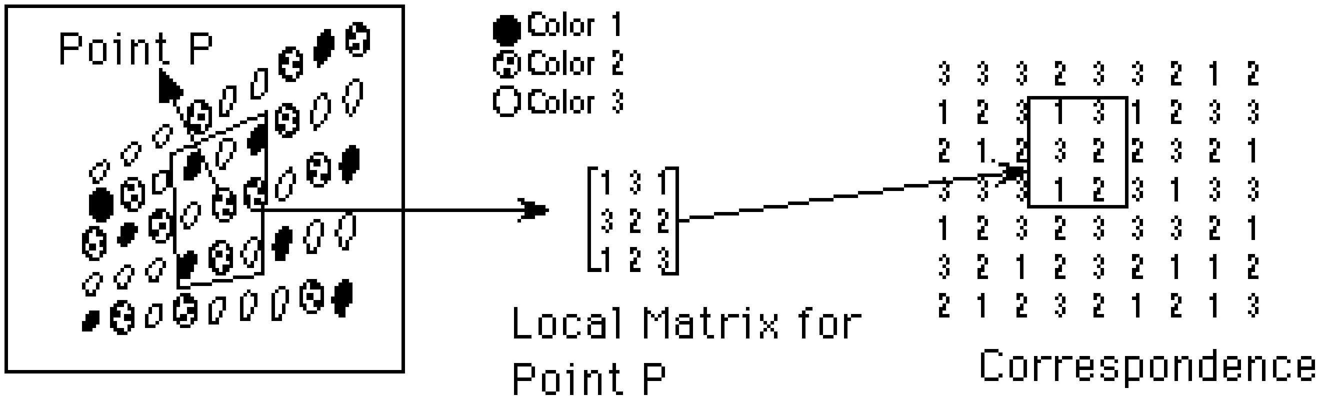
http://cmp.felk.cvut.cz/cmp/demos/RangeAcquisition.html

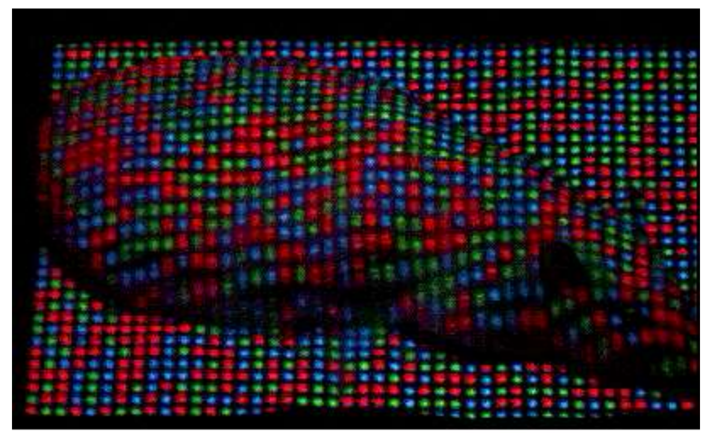
Problems in recovering pattern





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

Experimental results

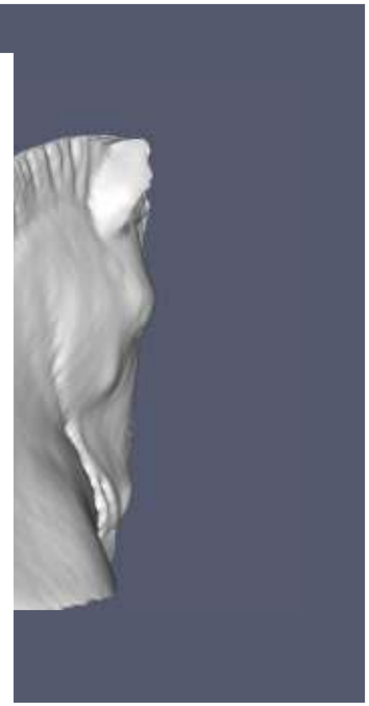
s)

4 stripes)

Gühring

De Bruijn

Time-
multipl



Morano (45x45 dot array)

Spat
codific

Direct
codification

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
  - …..

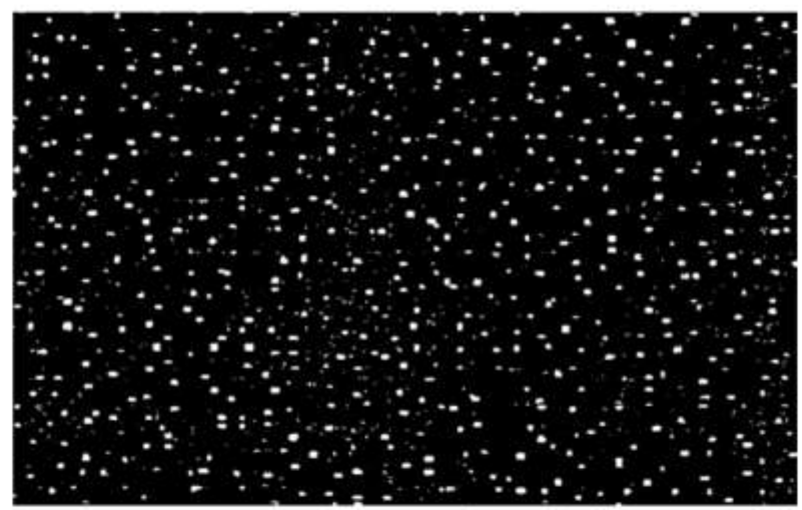
Microsoft Kinect

Microsoft Kinect

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

Stage 1: The depth map is constructed by analyzing a speckle pattern of infrared laser light

The Kinect uses infrared laser light, with a speckle pattern

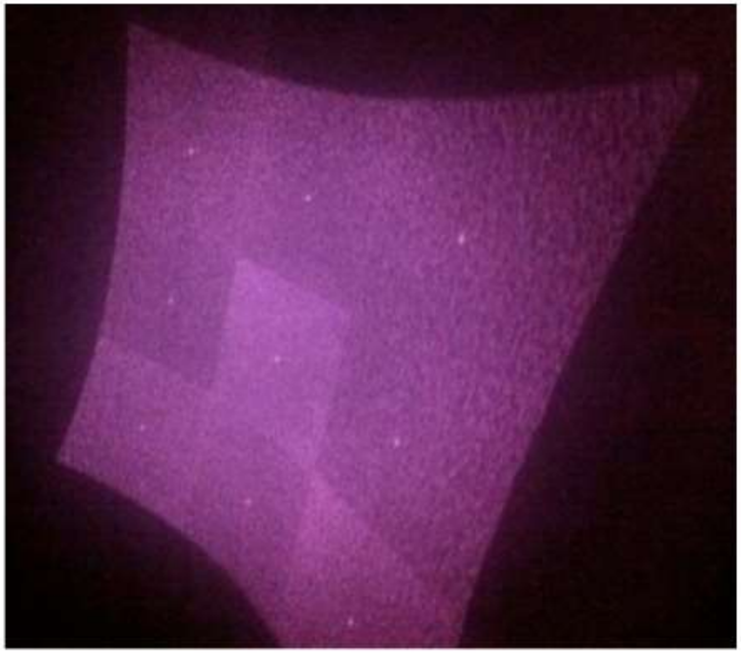


Shpunt et al, PrimeSense patent application US 2008/0106746

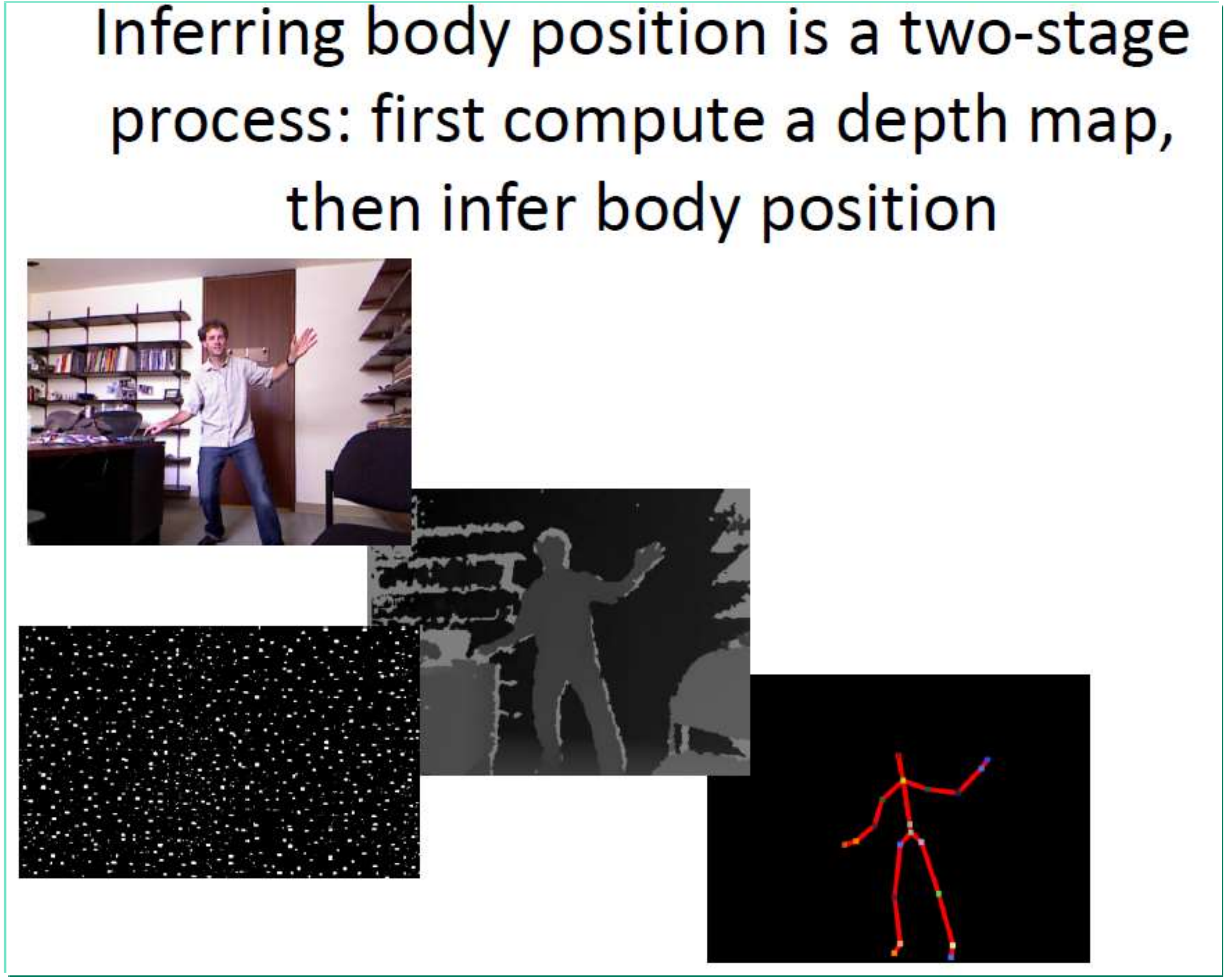
http://users.dickinson.edu/~jmac/selected-talks/kinect.pdf

Consumer application

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



Microsoft Kinect



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

Conclusions

Types of techniques		
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

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