Visual Perception

Lecture 5

Pattern Projection Techniques

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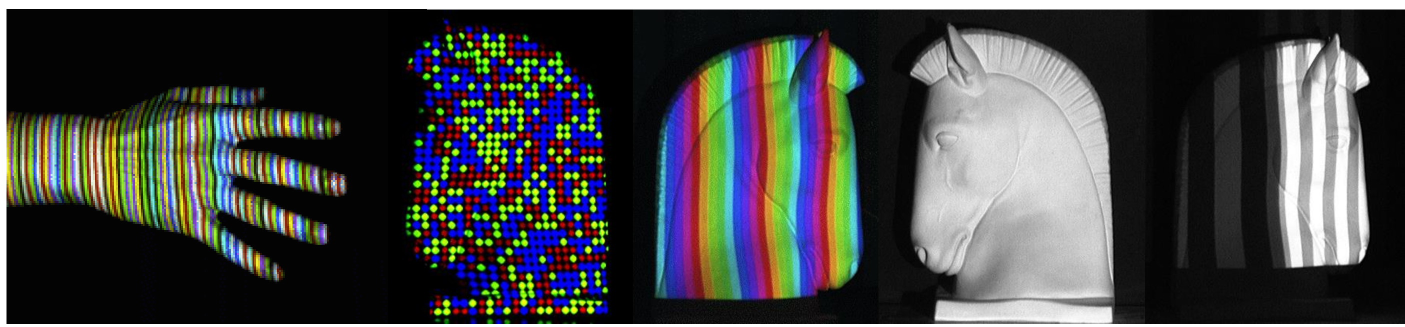

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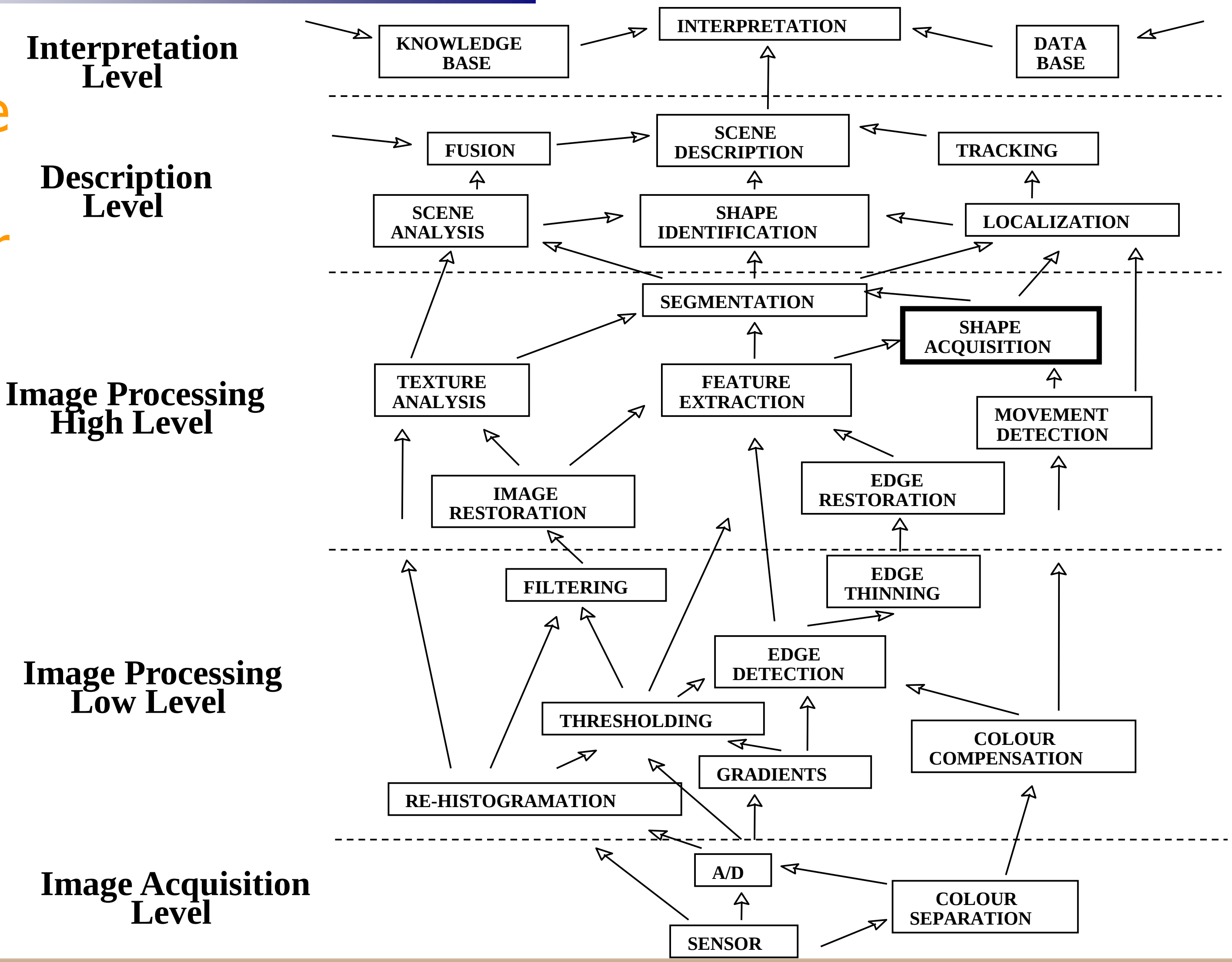
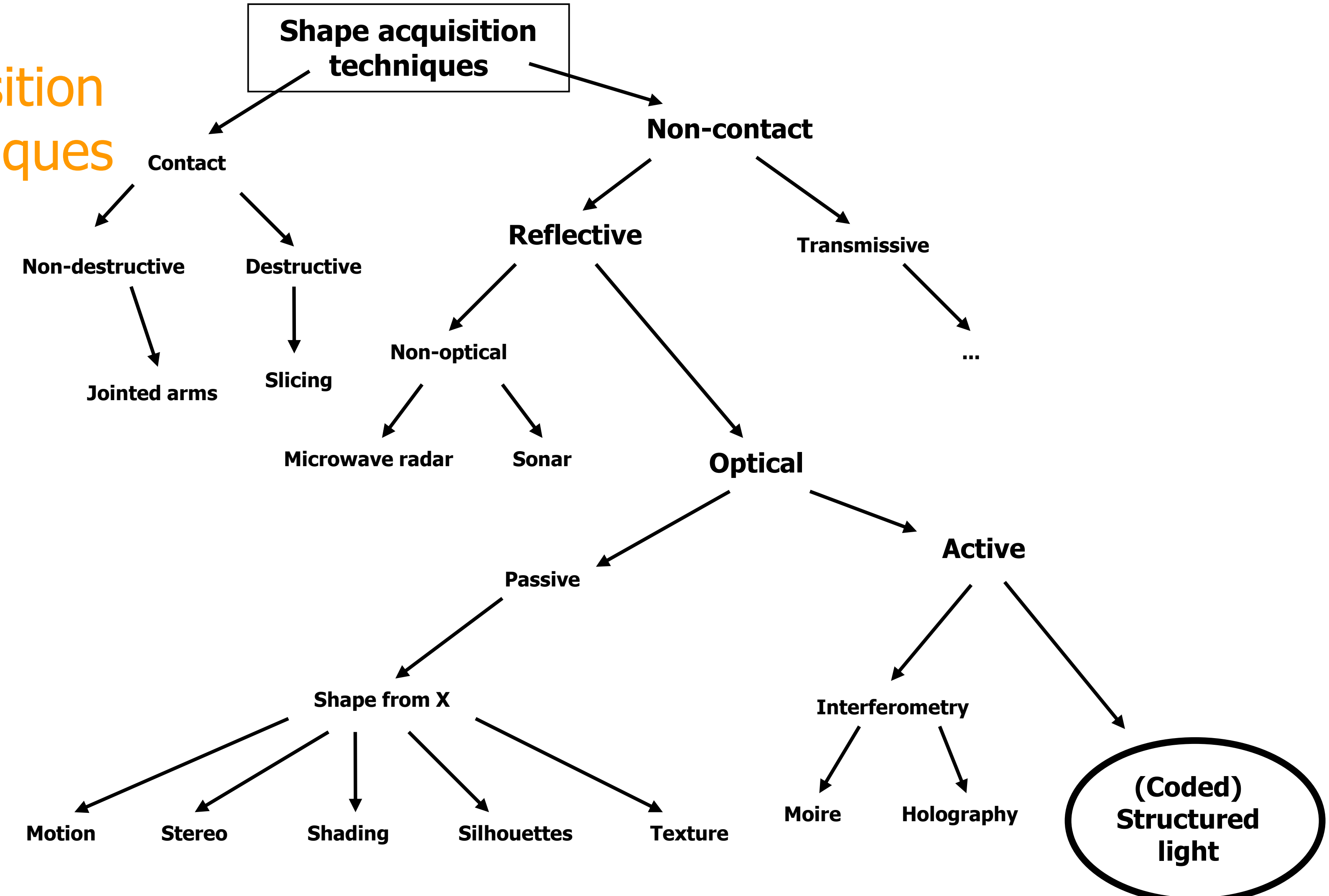
5.1 Passive vs active stereo

The Challenge of Computer Vision



5.1 Passive vs active stereo

Shape Acquisition Techniques



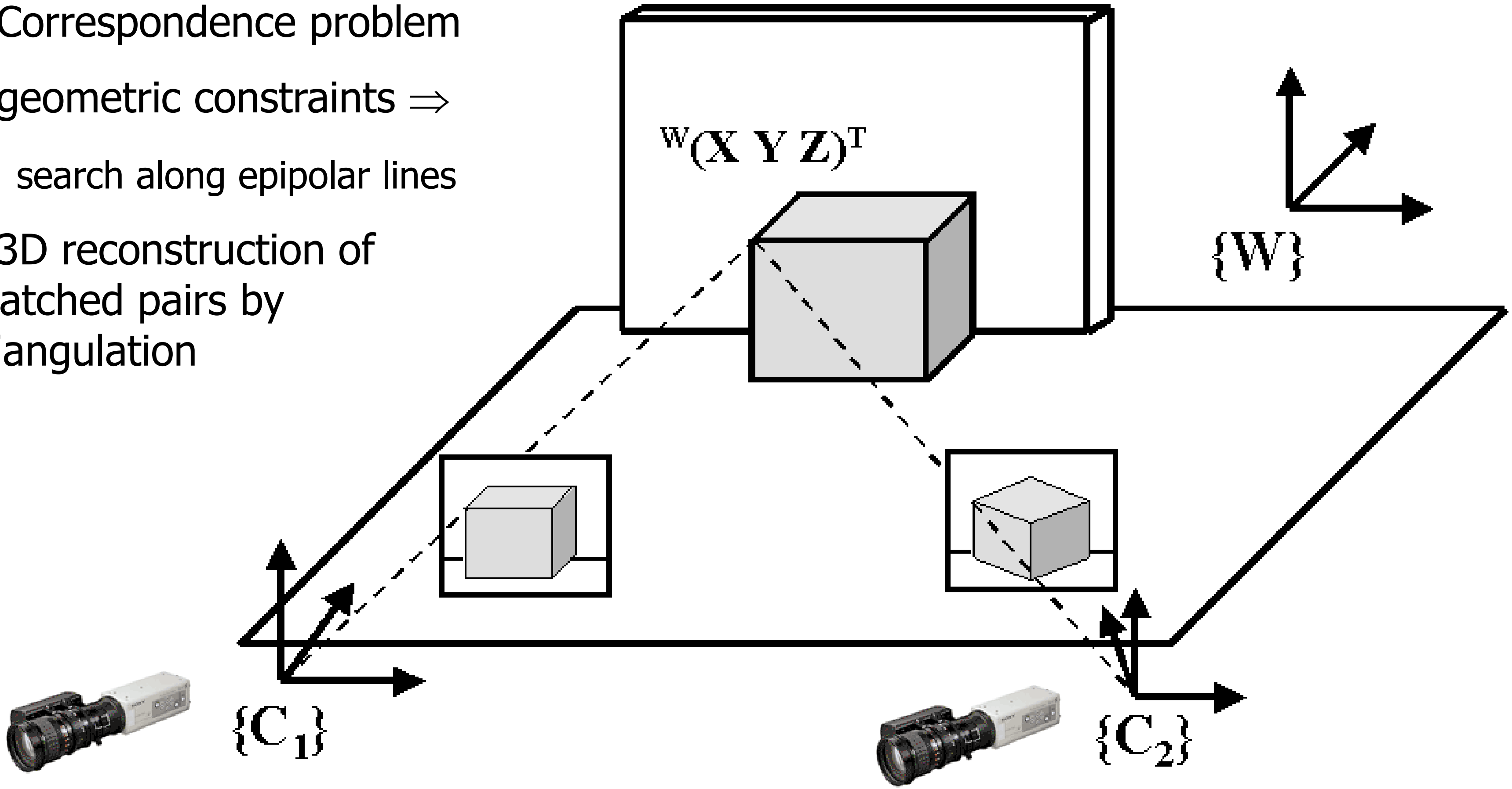
Source: Brian Curless

5.1 Passive vs active stereo

Passive Stereo

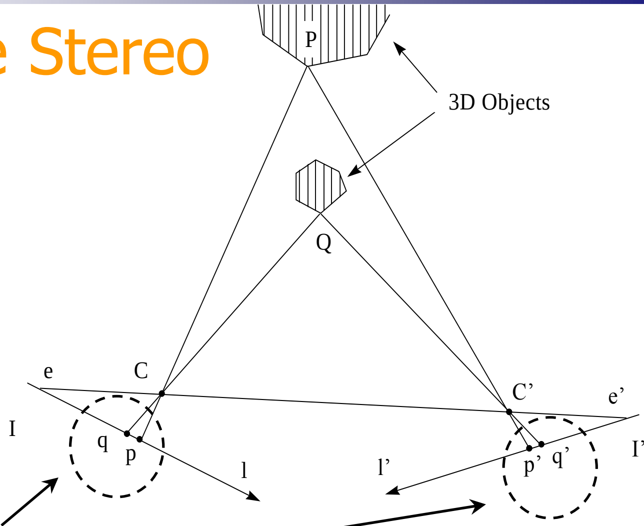
- Correspondence problem
- geometric constraints ⇒

  search along epipolar lines
- 3D reconstruction of matched pairs by triangulation

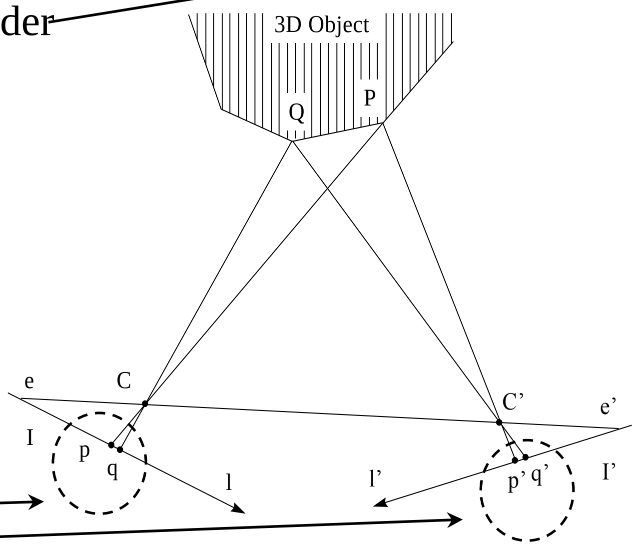


5.1 Passive vs active stereo

Passive Stereo



Direct order



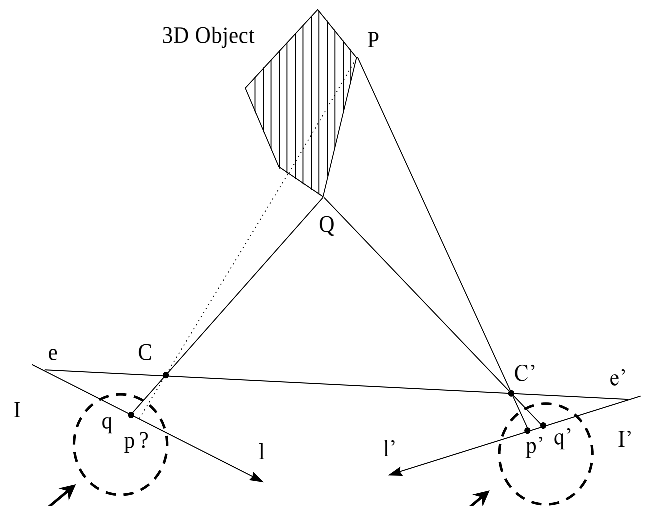
Inverse order

Arrange correspondence points

- Ordered Projections
- Projections bad order

Occlusions

- Points without homologue

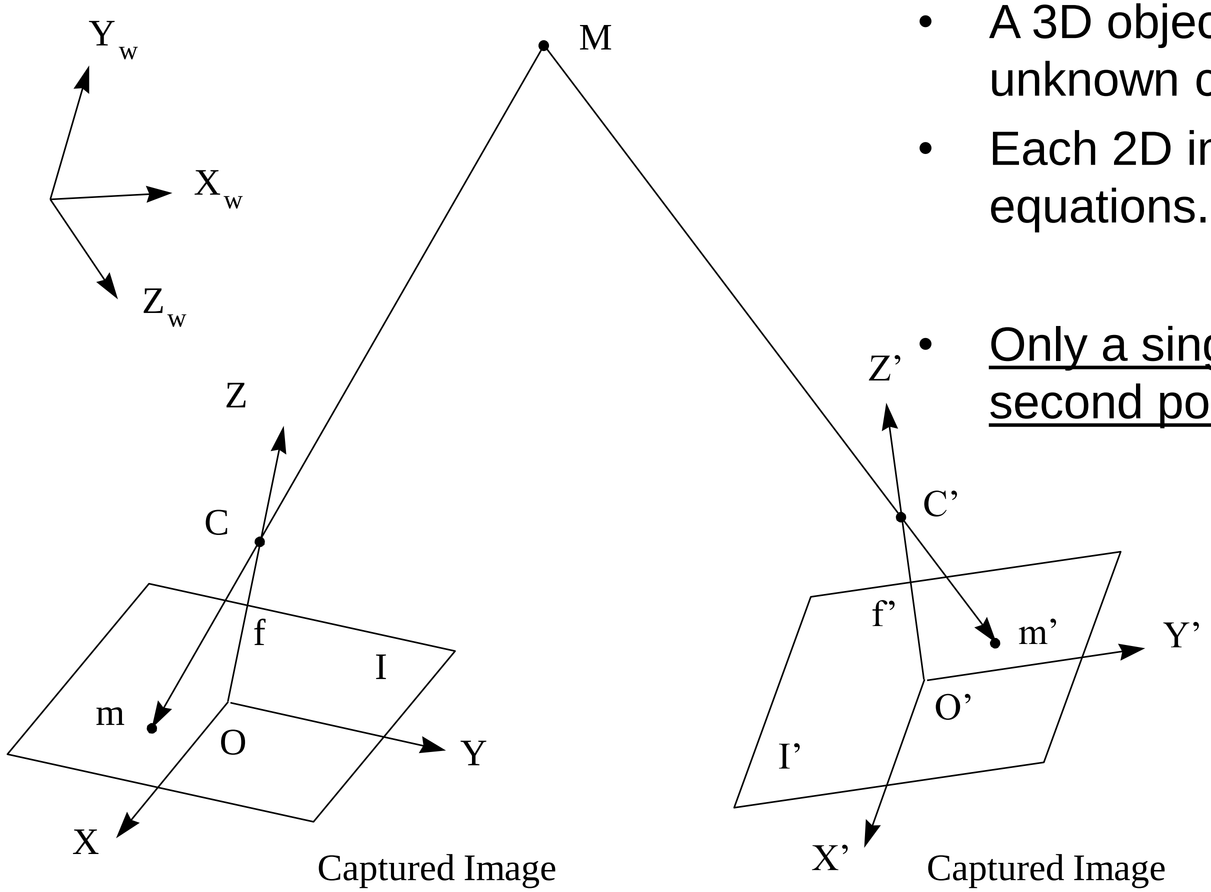


Surface occlusion

Point without homologue

5.1 Passive vs active stereo

Passive Stereo

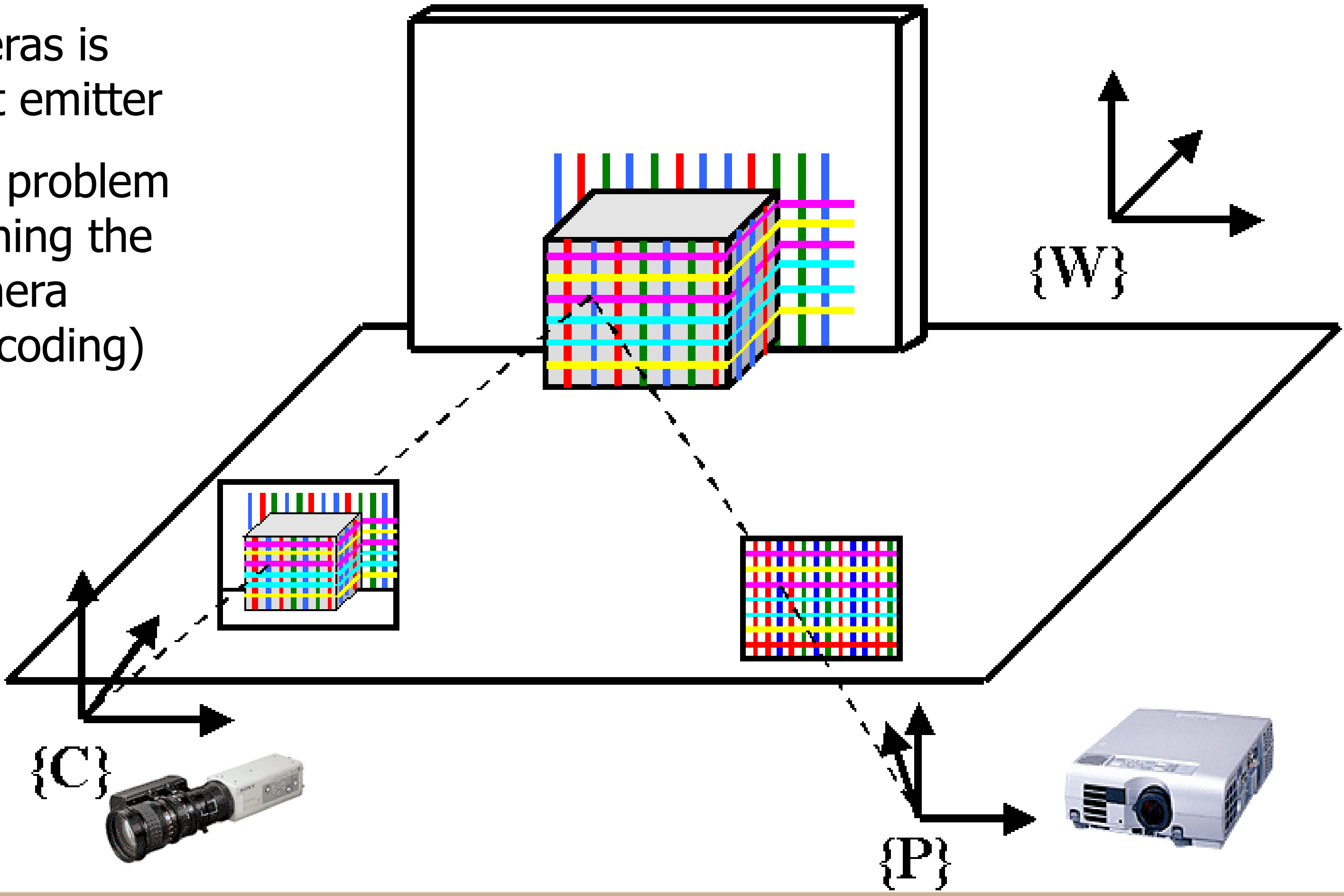


- We need at least two cameras.
- A 3D object point has three unknown co-ordinates.
- Each 2D image point gives two equations.
- <u>Only a single component of the second point is needed.</u>

5.1 Passive vs active stereo

Active Stereo

- One of the cameras is replaced by a light emitter
- Correspondence problem is solved by searching the pattern in the camera image (pattern decoding)



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5.2 Coded structured light

- The correspondence problem is reduced :

  – Single dot :
    - No correspondence problem.
    - Scanning both axis.

  – Single slit :
    - No correspondence problem.
    - Scanning the axis orthogonal to the slit.

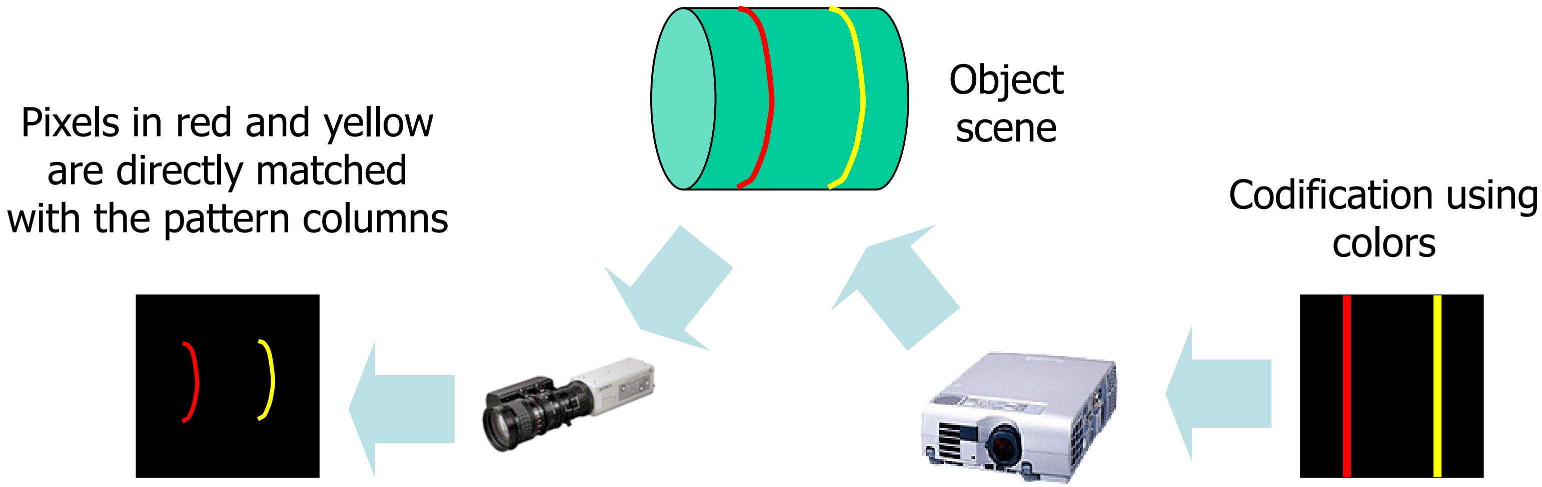
  – Stripe patterns :
    - No scanning.
    - Correspondence problem among slits.

  – Grid, multiple dots :
    - No scanning.
    - Correspondence problem among all the imaged features (points, dots, segments,…).

- The matching between the projected pattern and the captured one can be uniquely solved codifying the pattern.

5.2 Coded structured light

- 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

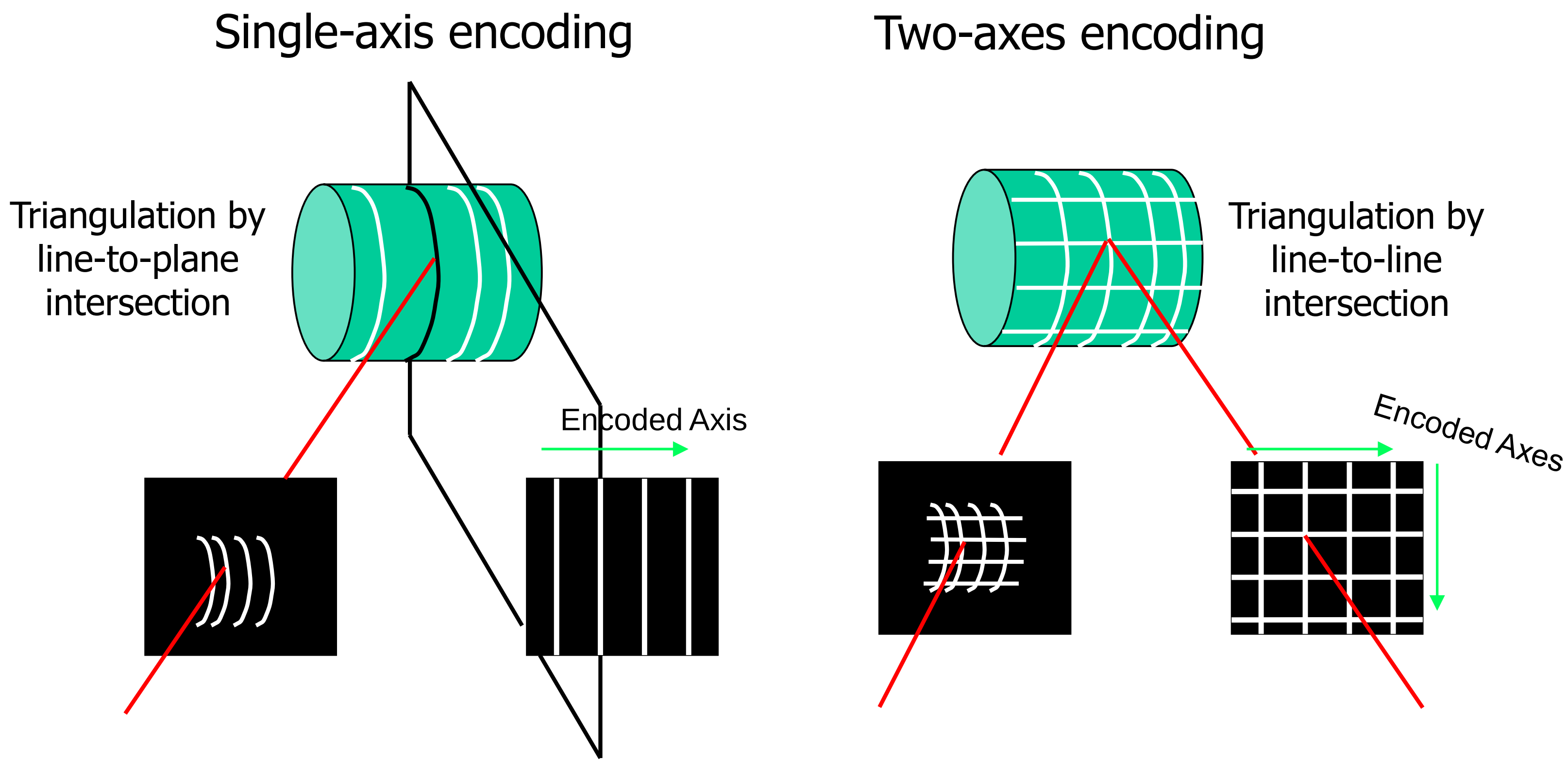


- The process of matching an image region with its corresponding pattern region is known as pattern decoding → similar to searching correspondences

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

5.2 Coded structured light

- Two ways of encoding the correspondences: single axis and two axes 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

5.2 Coded structured light

AXIS CODIFICATION

- Single Axis
  - Row-coded patterns
  - Column-coded patterns
- Both Axes

SCENE APPLICABILITY

- Static Scenes
  - Projection of a set of patterns.
- Moving Scenes
  - Projection of a unique pattern.

PIXEL DEPTH

- Binary
- Grey Levels
- Colour

CODING STRATEGY

- Periodical
  - The codification of the tokens is repeated periodically.
- Absolute
  - Each token is uniquely encoded

5.2 Coded structured light

TIME-MULTIPLEXING	Binary codes	Posdamer et al., Inokuchi et al., Minou et al., Trobina, Valkenburg and McIvor, Skocaj and Leonardis, Rocchin et al., …
	n-ary codes	Caspi et al., Horn and Kiryati, Osawa et al.,…
	Gray code + Phase shifting	Bergmann, Sansoni et al., Wiora, Gühring, …
	Hybrid methods	K. Sato, Hall-Holt and Rusinkiewicz, Wang et al., …
SPATIAL CODIFICATION	Non-formal codification	Maruyama and Abe, Durdle et al., Ito and Ishii, Boyer and Kak, Chen et al., …
	De Bruijn sequences	Hügli and Maître, Monks et al., Vuylsteke and Oosterlinck, Salvi et al. Lavoi et al., Zhang et al., …
	M-arrays	Morita et al., Petriu et al., Kiyasu et al., Spoelder et al., Griffin and Yee, Davies and Nixon, Morano et al., …
DIRECT CODIFICATION	Grey levels	Carrihill and Hummel, Chazan and Kiryati, Hung, …
	Colour	Tajima and Iwakawa, Smutny and Pajdla, Geng, Wust and Capson, T. Sato, …

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5.3 Classification: Time multiplexing

TIME-MULTIPLEXING	**Binary codes**	**Posdamer et al., Inokuchi et al., Minou et al., Trobina, Valkenburg and McIvor, Skocaj and Leonardis, Rocchin et al., …**
	n-ary codes	**Caspi et al., Horn and Kiryati, Osawa et al.,…**
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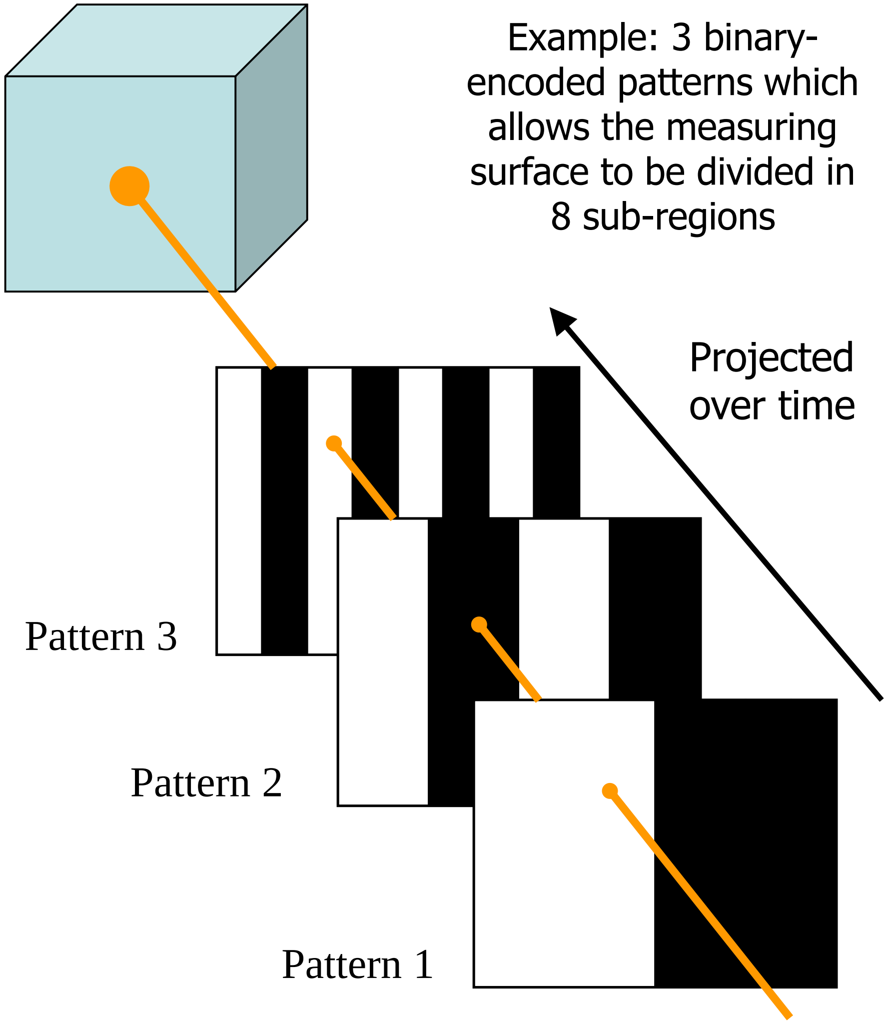
	Colour	**Tajima and Iwakawa, Smutny and Pajdla, Geng, Wust and Capson, T. Sato, …**

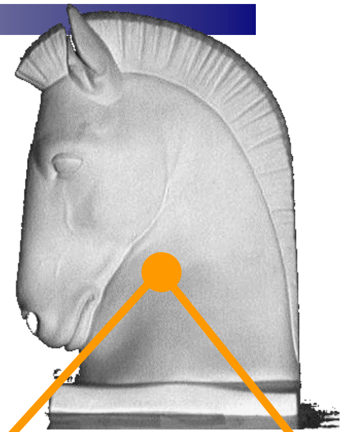
5.3 Time multiplexing

- The time-multiplexing paradigm consists in projecting a series of light patterns so that every encoded point is identified with the sequence of intensities that receives
- The most common structure of the patterns is a sequence of stripes increasing its length by the time → single-axis encoding
- **Advantages:**
  - high resolution → a lot of 3D points
  - High accuracy (order of μm)
  - Robustness against colorful objects (using binary patterns)
- **Drawbacks:**
  - Static objects only
  - Large number of patterns → High computing time

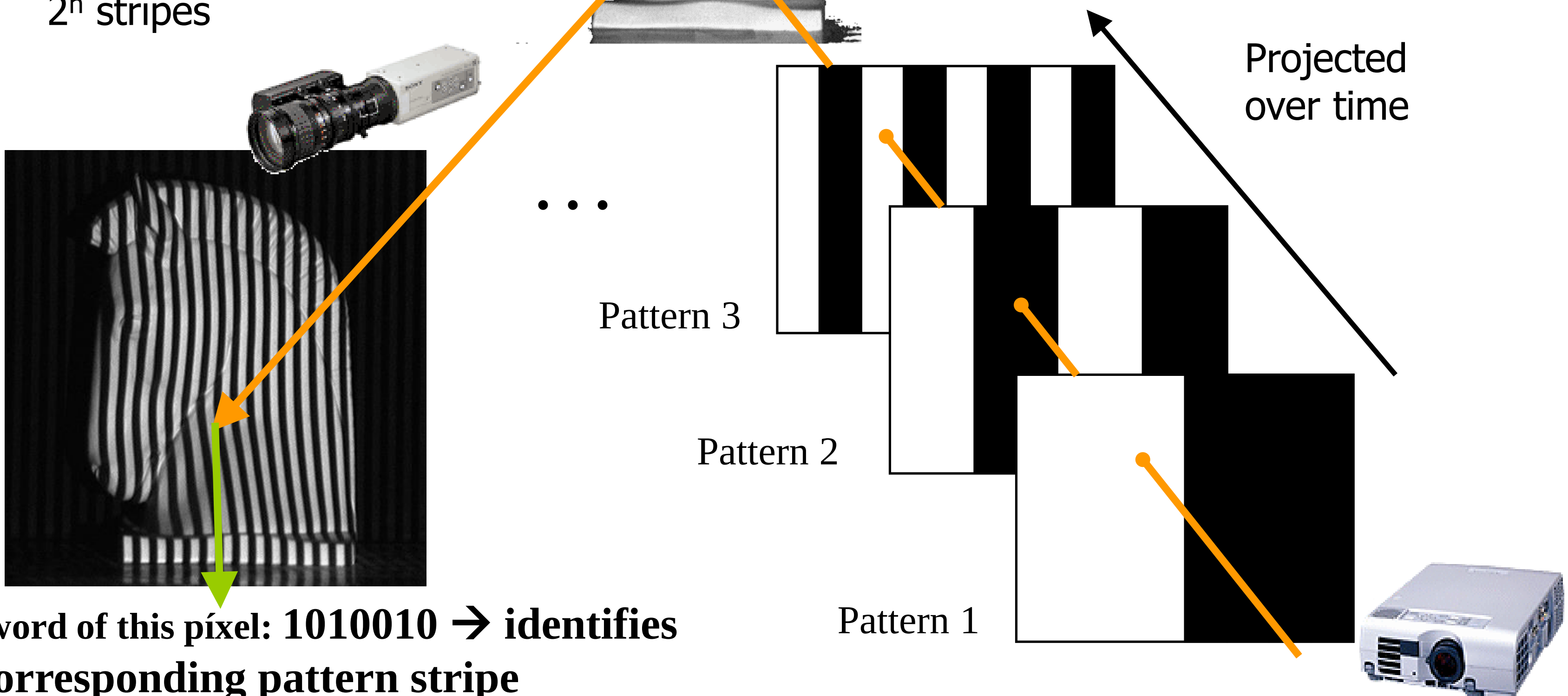


5.3 Time-multiplexing: Binary codes (I)

- Every encoded point is identified by the sequence of intensities that receives
- n patterns must be projected in order to encode 2^n stripes



Example: 7 binary patterns proposed by Posdamer & Altschuler



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

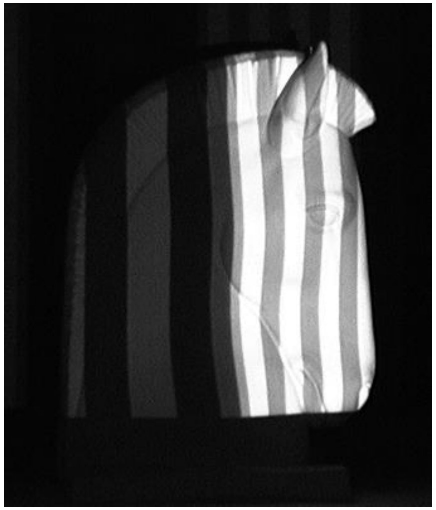
5.3 Time-multiplexing: Binary codes (II)

- **Coding redundancy**: every edge between adjacent stripes can be decoded by the sequence at its left or at its right

		Scene applicability: Static	Scene applicability: Moving	Pixel depth: Binary	Pixel depth: Grey levels	Pixel depth: Colour	Coding strategy: Periodical	Coding strategy: Absolute
Binary codes	**Posdamer et al.**	√		√				√
	Inokuchi et al.	√		√				√
	Minou et al.	√		√				√
	Trobina	√		√				√
	Valkenburg and McIvor	√		√				√
	Skocaj and Leonardis	√		√				√
	Rocchini et al.	√				√		√

5.3 Time-multiplexing: N-ary codes (I)

- n-ary codes reduce the number of patterns by increasing the number of projected intensities (grey levels/colours) → increases the basis of the code
- The number of patterns, the number of grey levels or colours and the number of encoded stripes are strongly related → fixing two of these parameters the reamaining one is obtained



Using a 4-ary code, 3 patterns are used to encode 64 stripes (Horn & Kiryati)

Using a binary code, 6 patterns are necessary to encode 64 stripes

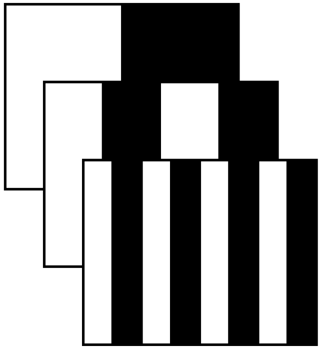
5.3 Time-multiplexing: N-ary codes (II)

- n-ary codes reduce the number of patterns by increasing the number of projected intensities (grey levels/colours)

		Scene applicability: Static	Scene applicability: Moving	Pixel depth: Binary	Pixel depth: Grey levels	Pixel depth: Colour	Coding strategy: Periodical	Coding strategy: Absolute
N-ary codes	**Caspi et al.**	√				√		√
	Horn and Kiryati	√			√			√
	Osawa et al.	√			√			√

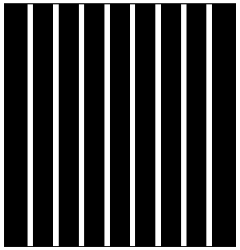
5.3 Time-multiplexing: Gray code+Phase shifting (I)

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



Example: three binary patterns divide the object in 8 regions

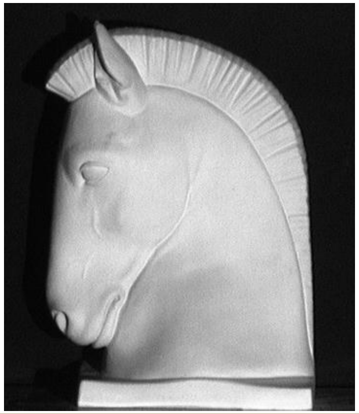
- An additional periodical pattern is projected



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

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

Gühring's line-shift technique



Every slit always falls in the same region

5.3 Time-multiplexing: Gray code+Phase shifting (II)

- A periodical pattern is shifted and projected several times in order to increase the resolution of the measurements
- The Gray encoded patterns permit to differentiate among all the periods of the shifted pattern

Gray Code + Phase Shift	Scene applicability: Static	Scene applicability: Moving	Pixel depth: Binary	Pixel depth: Grey levels	Pixel depth: Colour	Coding strategy: Periodical	Coding strategy: Absolute
Bergmann	√			√			√
Sansoni et al.	√		√				√
Wiora	√			√			√
Gühring	√		√				√

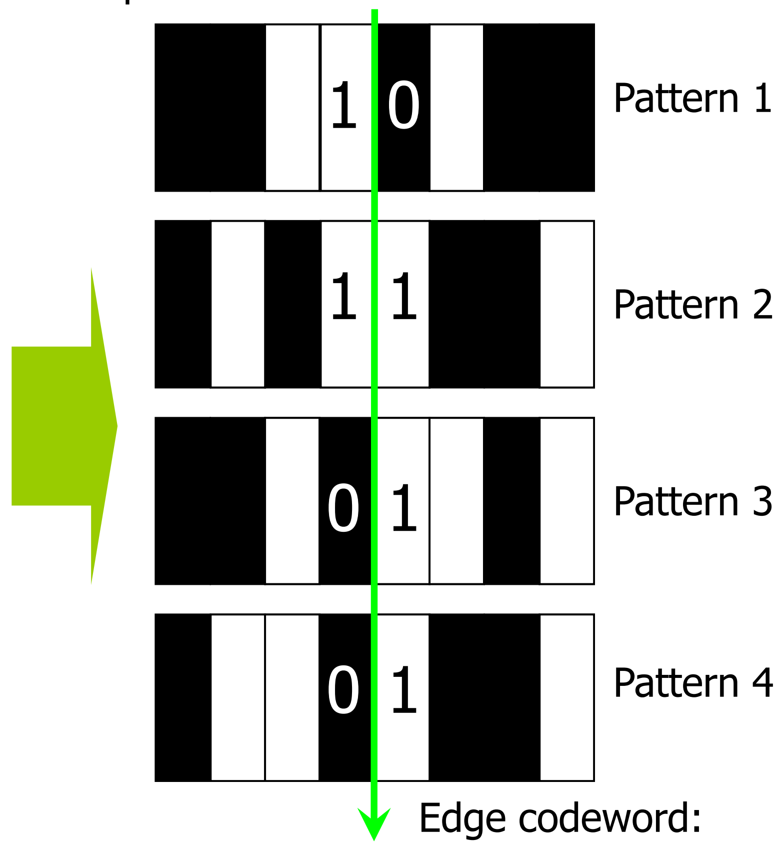
5.3 Time-multiplexing: Hybrid methods (I)

- In order to decode an illuminated point it is necessary to observe not only the sequence of intensities received by such a point but also the intensities of **few** (normally 2) adjacent points
- The number of projected patterns reduces thanks to the spatial information that is taken into account

Hall-Holt and Rusinkiewicz technique:

4 patterns with 111 binary stripes

Edges encoding: 4x2 bits (every adjacent stripe is a bit)



Edge codeword: 10110101

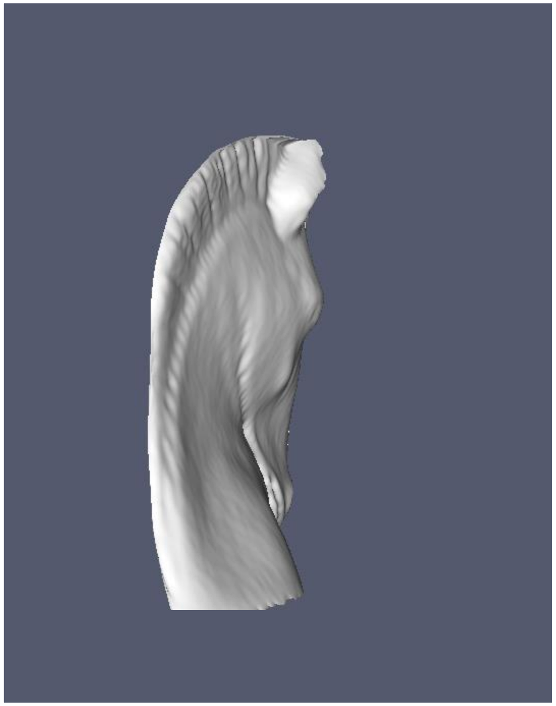
5.3 Time-multiplexing: Hybrid methods (II)

Hybrid methods	Scene applicability		Pixel depth			Coding strategy	
	Static	Moving	Binary	Grey levels	Colour	Periodical	Absolute
K. Sato	√		√				√
Hall-Holt and Rusinkiewicz	√		√				√
Wang et al.	√		√				√

5.3 Time-multiplexing: Results

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

Gühring



5.3 Time-multiplexing: Conclusions

Types of techniques		
Time-multiplexing	• Highest resolution • High accuracy • Easy implementation	• Large number of patterns • Only motionless objects

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5.4 Spatial Codification

TIME-MULTIPLEXING	Binary codes	Posdamer et al., Inokuchi et al., Minou et al., Trobina, Valkenburg and McIvor, Skocaj and Leonardis, Rocchin et al., …
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	De Bruijn sequences	**Hügli and Maître, Monks et al., Vuylsteke and Oosterlinck, Salvi et al. Lavoi et al., Zhang et al., …**
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5.4 Spatial Codification

- Spatial codification paradigm encodes a set of points with the information contained in a **neighborhood** (called **window**) around them
- 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 $\Rightarrow$ moving objects can be measured

Advantages:

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

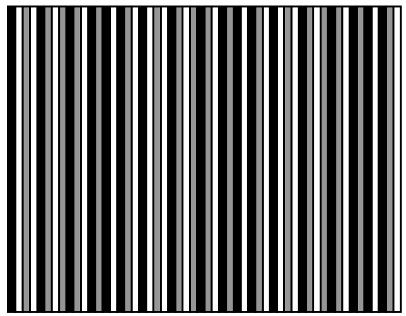
Drawbacks:

- 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 non-neutral coloured surfaces

5.4 Spatial Codification: Non-formal codification (I)

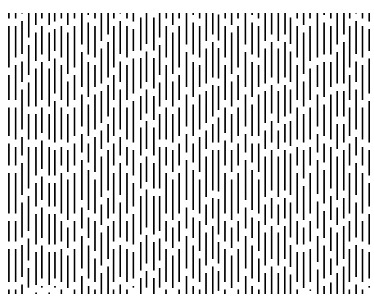
- The first group of techniques that appeared used codification schemes with no mathematical formulation.
- Drawbacks:

  - the codification is not optimal and often produces ambiguities since different regions of the pattern are identical



Durdle et al. → periodic pattern

  -the structure of the pattern is too complex for a good image processing



Maruyama and Abe → complex structure based on slits containing random cuts

5.4 Spatial Codification: Non-formal codification (II)

Non-formal codification	**Maruyama and Abe**		√	√			√	
	Durdle et al.		√		√		√	
	Ito and Ishii		√		√			√
	Boyer and Kak		√			√		√
	Chen et al.		√			√		√

Scene applicability	**Static**	
	Moving	
Pixel depth	**Binary**	
	Grey levels	
	Colour	
Coding strategy	**Periodical**	
	Absolute	

5.4 Spatial Codification: De Bruijn sequences (I)

- A De Bruijn sequence (or pseudorrandom 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 unidimensional).

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

- Formulation:

Given $P=\{1,2,\ldots,p\}$ set of colours.

- We want to determine $S=\{s_1,s_2,\ldots s_n\}$ sequence of coloured slits.

Node: $\{ijk\} \in VR_p^3$

Number of nodes: p^3 nodes.

Transition $\{ijk\} \curlywedge \{rst\} \Rightarrow j = r, k = s$

m = 3 (window size)

n = p (alphabet symbols)

- The problem is reduced to obtain the path which visits all the nodes of the graph only once (a simple variation of the Salesman's problem).
  - Backtracking based solution.
  - Deterministic and optimally solved by Griffin.

5.4 Spatial Codification: De Bruijn sequences (II)

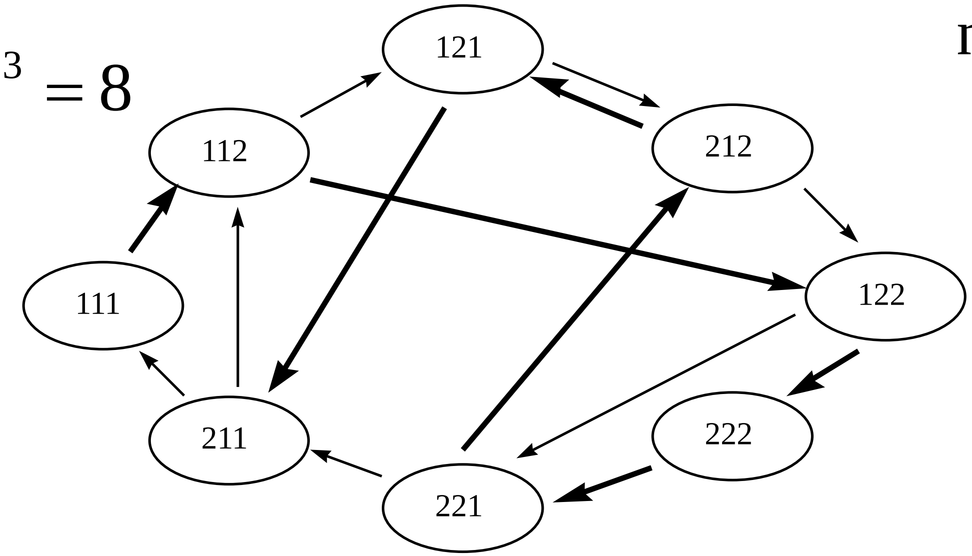
Example:

$p = 2$

$VR^{3}_{p=2} = 2^3 = 8$

m = 3

n = 2



Path: (111),(112),(122),(222),(221),(212),(121),(211).

Slit colour sequence:111,2,2,2,1,2,1,1 $\Rightarrow$ Maximum 10 slits.

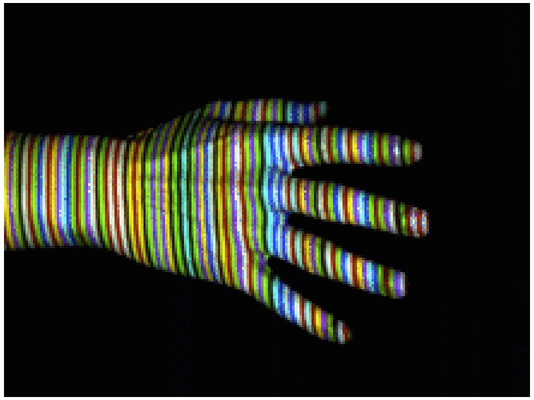
'1' → Red

'2' → Green

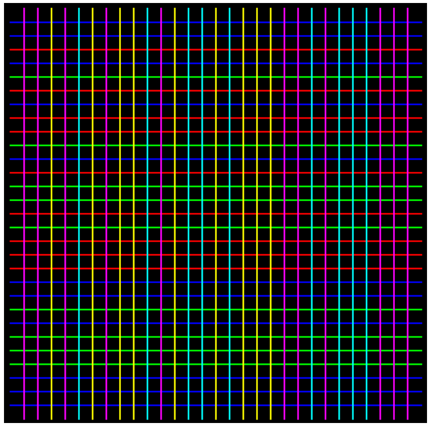
5.4 Spatial Codification: De Bruijn sequences (III)

• The De Bruijn sequences are used to define coloured 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



Zhang et al.: 125 slits encoded with a De Bruijn sequence of 5 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

5.4 Spatial Codification: De Bruijn sequences (IV)

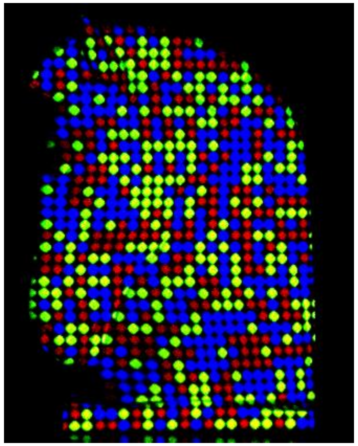
	Method	Scene applicability: Static	Scene applicability: Moving	Pixel depth: Binary	Pixel depth: Grey levels	Pixel depth: Colour	Coding strategy: Periodical	Coding strategy: Absolute
De Bruijn sequences	**Hügli and Maître**		√			√		√
	Monks et al.		√			√		√
	Salvi et al.		√			√		√
	Lavoie et al.		√			√		√
	Zhang et al.		√			√		√

5.4 Spatial Codification: M-arrays (I)

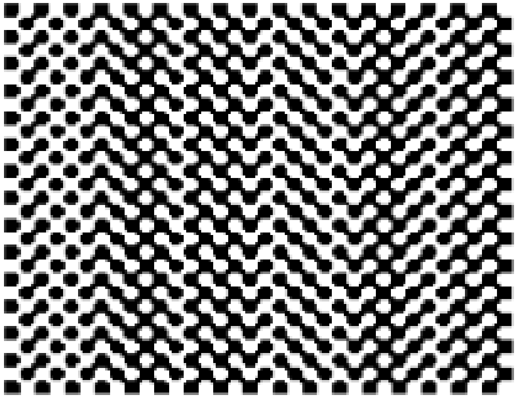
- An m-array is the bidimensional extension of a De Bruijn sequence. Every window of w×h units appears only once. The window size is related with the size of the m-array and the number of symbols used

$$\begin{matrix} 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 1 & 0 \\ 1 & 1 & 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 0 & 1 & 0 \end{matrix}$$

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

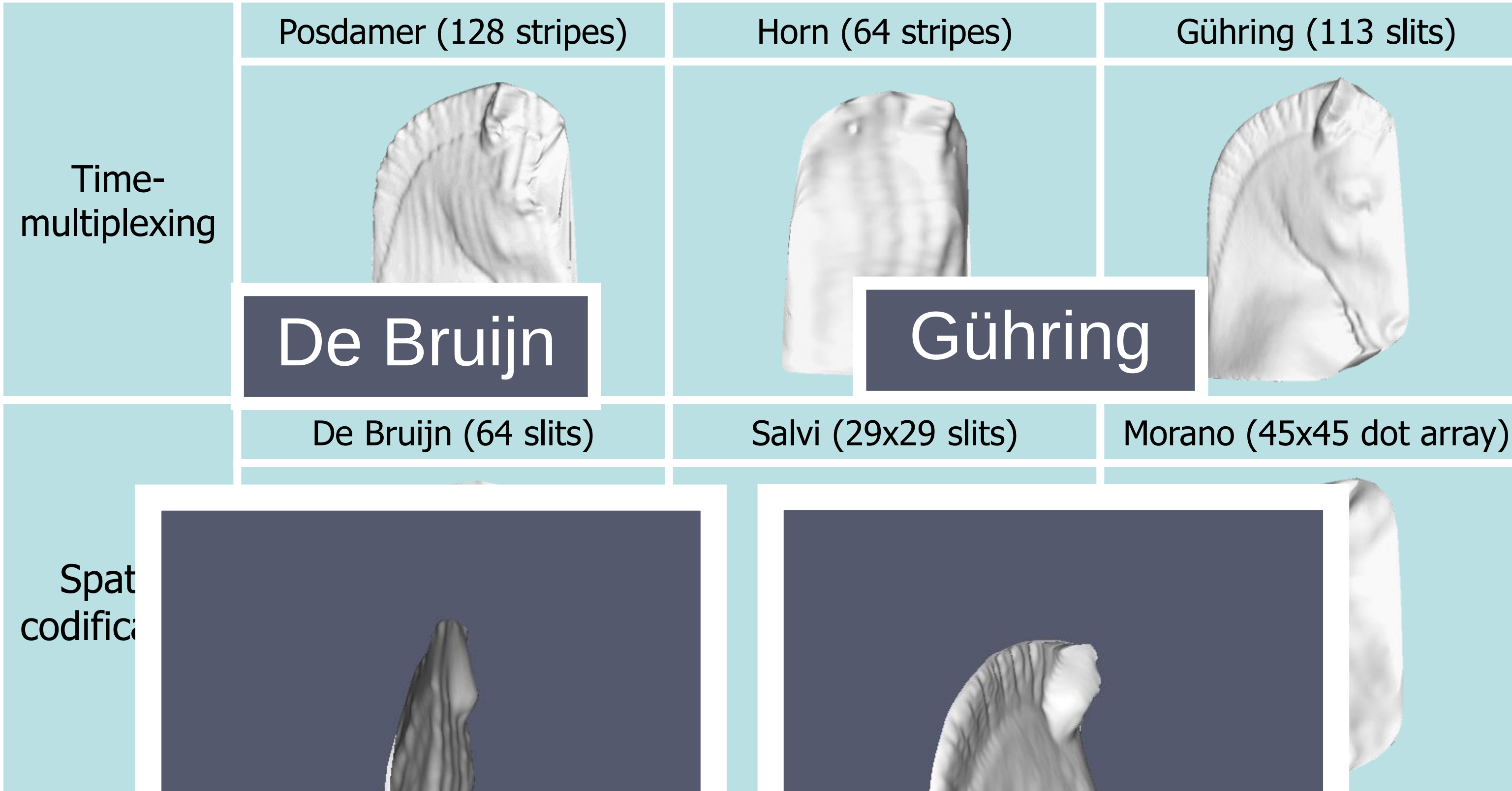


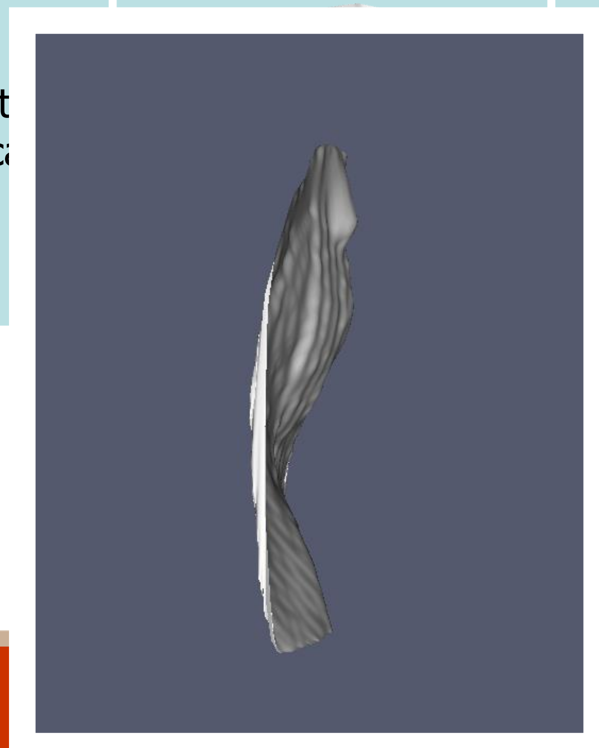
M-array proposed by Vuylsteke et al. Represented with shape primitives

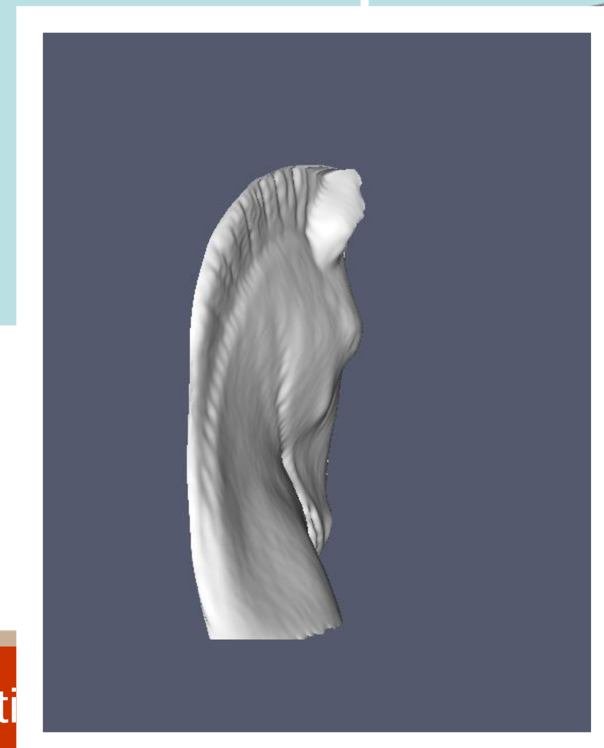
5.4 Spatial Codification: M-arrays (II)

		Scene applicability: Static	Scene applicability: Moving	Pixel depth: Binary	Pixel depth: Grey levels	Pixel depth: Colour	Coding strategy: Periodical	Coding strategy: Absolute
M-arrays	**Morita et al.**	√		√				√
	Petriu et al.		√	√				√
	Vuylsteke and Oosterlinck		√	√				√
	Kiyasu et al.		√	√				√
	Spoelder et al.		√	√				√
	Griffin and Yee		√	√		√		√
	Davies and Nixon		√			√		√
	Morano et al.	√		√		√		√

5.4 Spatial Codification: Results







5.4 Spatial Codification: Results

Types of techniques		
Time-multiplexing	• Highest resolution • High accuracy • Easy implementation	• Large number of patterns • Only motionless objects
Spatial codification	• A unique pattern is required • Can measure moving objects	• Lower resolution than time-multiplexing • More complex decoding stage • Occlusions problem

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5.5 Direct Codification

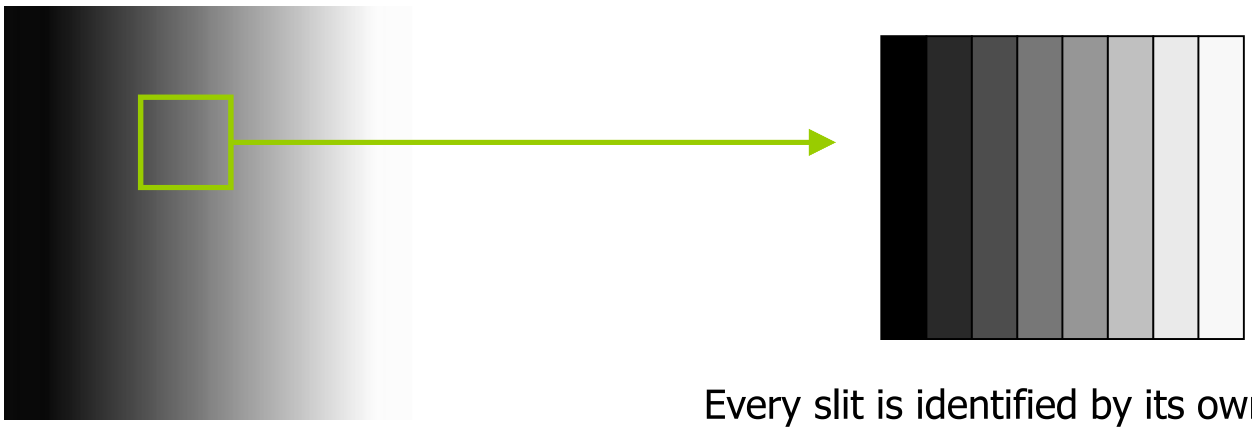
TIME-MULTIPLEXING	Binary codes	Posdamer et al., Inokuchi et al., Minou et al., Trobina, Valkenburg and McIvor, Skocaj and Leonardis, Rocchin et al., …
	n-ary codes	Caspi et al., Horn and Kiryati, Osawa et al.,…
	Gray code + Phase shifting	Bergmann, Sansoni et al., Wiora, Gühring, …
	Hybrid methods	K. Sato, Hall-Holt and Rusinkiewicz, Wang et al., …
SPATIAL CODIFICATION	Non-formal codification	Maruyama and Abe, Durdle et al., Ito and Ishii, Boyer and Kak, Chen et al., …
	De Bruijn sequences	Hügli and Maître, Monks et al., Vuylsteke and Oosterlinck, Salvi et al. Lavoi et al., Zhang et al., …
	M-arrays	Morita et al., Petriu et al., Kiyasu et al., Spoelder et al., Griffin and Yee, Davies and Nixon, Morano et al., …
DIRECT CODIFICATION	**Grey levels**	**Carrihill and Hummel, Chazan and Kiryati, Hung, …**
	Colour	**Tajima and Iwakawa, Smutny and Pajdla, Geng, Wust and Capson, T. Sato, …**

5.5 Direct Codification

- Every encoded pixel is identified by its own intensity/colour
- Since the codification is usually condensed in a unique pattern, the **spectrum** of intensities/colours used is very large
- Additional **reference patterns** must be projected in order to differentiate among all the projected intensities/colours:
    - Ambient lighting (black pattern)
    - Full illuminated (white pattern)
    - …
- **Advantages**:
  - Reduced number of patterns
  - High resolution can be teorically achieved (all points are coded)
- **Drawbacks**:
  - Very noisy in front of reflective properties of the objects, non-linearities in the camera spectral response and projector spectrum $\Rightarrow$ non-standard light emitters are required in order to project **single wave-lengths**
  - Low accuracy (order of 1 mm)

5.5 Direct Codification: Grey levels (I)

- Every encoded point of the pattern is identified by its intensity level



Every slit is identified by its own intensity

Carrihill and Hummel Intensity Ratio Sensor: fade from black to white

Requirements to obtain high resolution

- Every slit must be projected using a single wave-length
- Cameras with large depth-per-pixel (about 11 bits) must be used in order to differentiate all the projected intensities

5.5 Direct Codification: Grey levels (II)

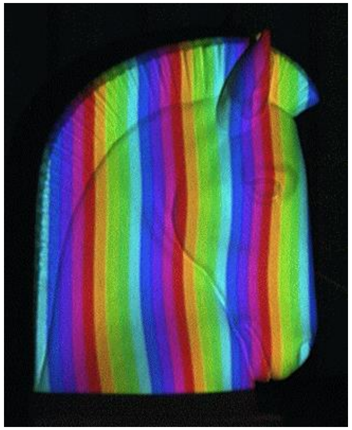
Grey levels	Static	Moving	Binary	Grey levels	Colour	Periodical	Absolute
	Scene applicability		Pixel depth			Coding strategy	
Carrihill and Hummel	√			√			√
Chazan and Kiryati	√			√			√
Hung		√		√		√	

5.5 Direct Codification: Colour (I)

- 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

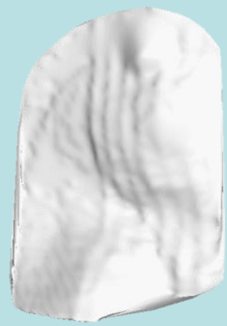
(it can be implemented with an LCD projector if few colours are projected → drawback: the pattern becomes periodic in order to maintain a good resolution)

5.5 Direct Codification: Colour (II)

		Static	Moving	Binary	Grey levels	Colour	Periodical	Absolute
Colour	**Tajima and Iwakawa**	√				√		√
	Smutny and Pajdla	√				√		√
	Geng		√			√		√
	Wust and Capson		√			√	√	
	T. Sato	√				√	√	

Scene applicability	**Static**
	Moving
Pixel depth	**Binary**
	Grey levels
	Colour
Coding strategy	**Periodical**
	Absolute

5.5 Direct Codification: 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	Sato (64 slits) 		

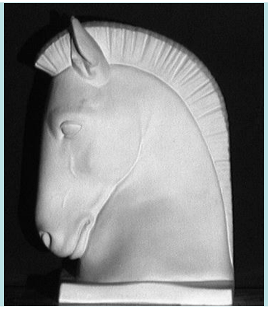
5.5 Direct Codification: Conclusions

Types of techniques	👍	👎
Time-multiplexing	• Highest resolution • High accuracy • Easy implementation	• Large number of patterns • Only motionless objects
Spatial codification	• A unique pattern is required • Can measure moving objects	• Lower resolution than time-multiplexing • More complex decoding stage • Occlusions problem
Direct codification	• High resolution • Few patterns	• Very sensitive to image noise → cameras with large depth-per-pixel required • Sensitive to limited bandwith of LCD projectors → special projector devices are usually required • Only motionless objects

Contents

Contents

Guidelines

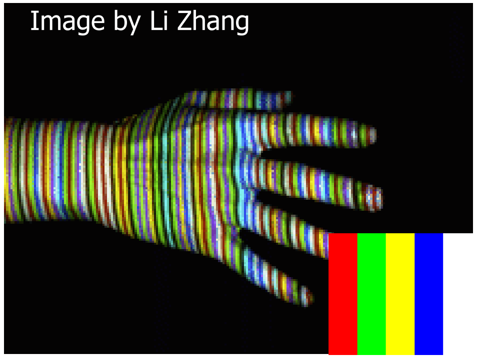
Requirements	Best technique	
• High accuracy • Highest resolution • Static objects • No matter the number of patterns	Phase shift + Gray code → Gühring's line-shift technique	
• High accuracy • High resolution • Static objects • Minimum number of patterns	N-ary pattern → Horn & Kiryati Caspi et al.	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

Presentation outline

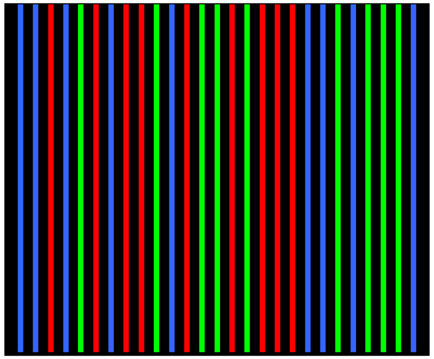
2.- An Optimised one-shot technique
- Typical one-shot patterns
- Optimal pattern
- A new coding strategy
- Implementation design
- Experimental results
- Conclusions

Typical one-shot patterns

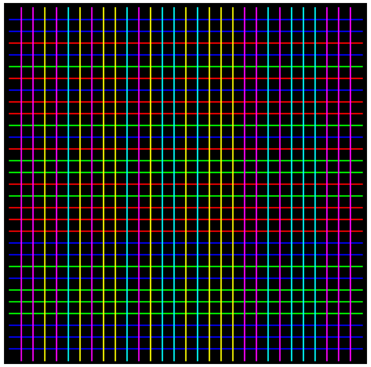
De Bruijn codification



Stripe pattern

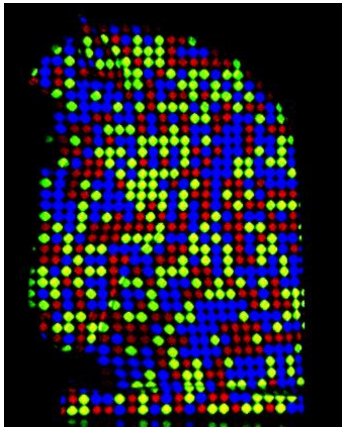


Multi-slit pattern

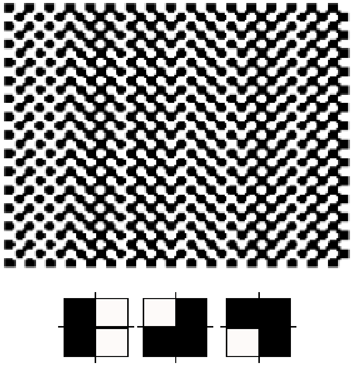


Grid pattern

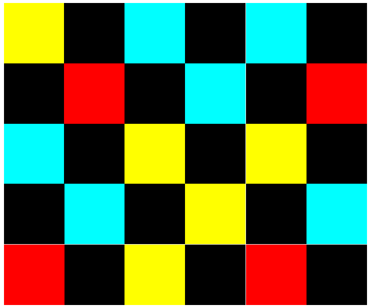
M-array codification



Array of dots



Array of shape primitives



Checkerboard pattern

Best one-shot patterns

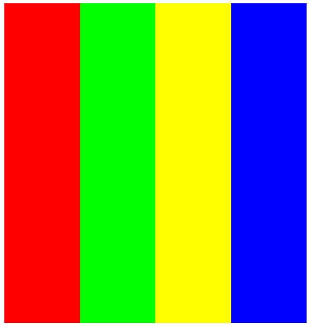
De Bruijn patterns	**Stripe patterns**	**High resolution and good accuracy**
	Multi-slit patterns	**High accuracy and good resolution**
	Grid patterns	Low resolution
M-array patterns	Array of dots	Low resolution and inaccurate sub-pixel localisation of the dots
	Shape primitives	Low accuracy and difficult sub-pixel localisation of shape primitives
	Checkerboard	Low resolution

Optimising De Bruijn patterns: interesting features

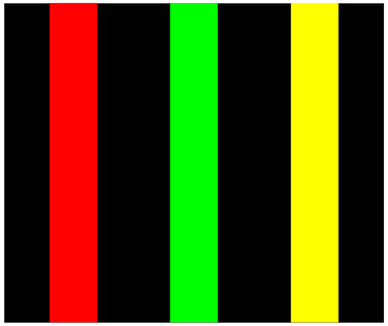
Optimisation	Advantages
Maximising resolution	Larger number of correspondences in a single shot
Maximising accuracy	Better quality in the 3D reconstruction
Minimising the window size	More robustness against discontinuities in the object surface
Minimising the number of colours	More robustness against non-neutral coloured objects and noise

Optimisation: maximising resolution

Ideal pattern: the one which downsamples the projector resolution so that all the projected pixels are perceived in the camera image → in fact only columns or rows must be identified in order to triangulate 3D points.



Stripe patterns: achieve maximum resolution since they are formed by adjacent bands of pixels.



Multi-slit patterns: the maximum resolution is not achieved since black gaps are introduced between the slits

Optimisation: maximising accuracy

Ideal pattern: multi-slit patterns allow intensity peaks to be detected with precise sub-pixel accuracy

Multi-slit pattern

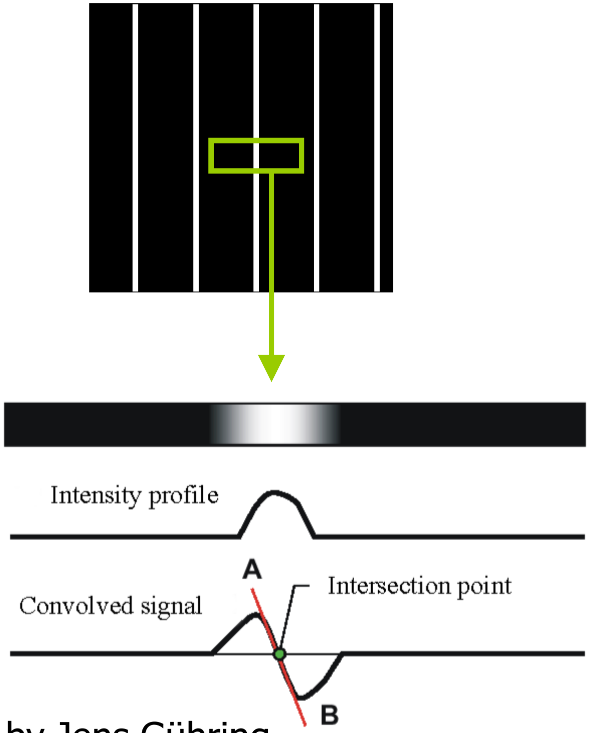
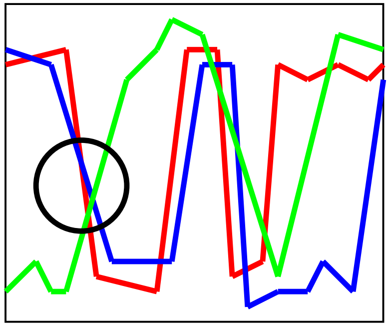


Figure by Jens Gühring

Stripe pattern

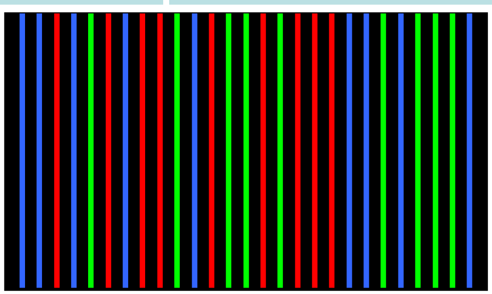
RGB channels intensity profile of a row of the image



Edge detection between stripes: need to find edges in the three RGB channels → the location of the edges does not coincide

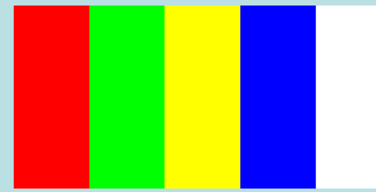
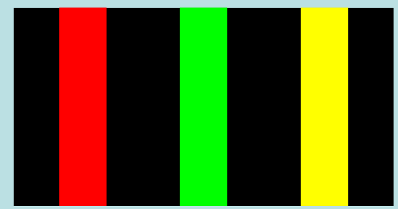
Optimisation: minimising the window size and the number of colours

	Maximising	**Minimising**
Number of colours	• Larger resolution • Smaller distance in the Hue space → more difficult colour identification	• Smaller resolution • Larger distance in the Hue space → Easier colour identification
Window size	• Larger resolution • Danger to violate the local smoothness assumption	• Smaller resolution • More robustness against surface discontinuities



If both the number of colours and the window size are minimised the resolution decreases

Optimising De Bruijn patterns: summary

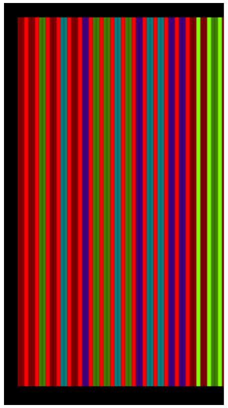
Optimisation	**Best pattern**
Maximising resolution	Stripe pattern 
Maximising accuracy	Multi-slit pattern 
Minimising the window size and the number of colours preserving a good resolution	Stripe pattern + multi-slit pattern

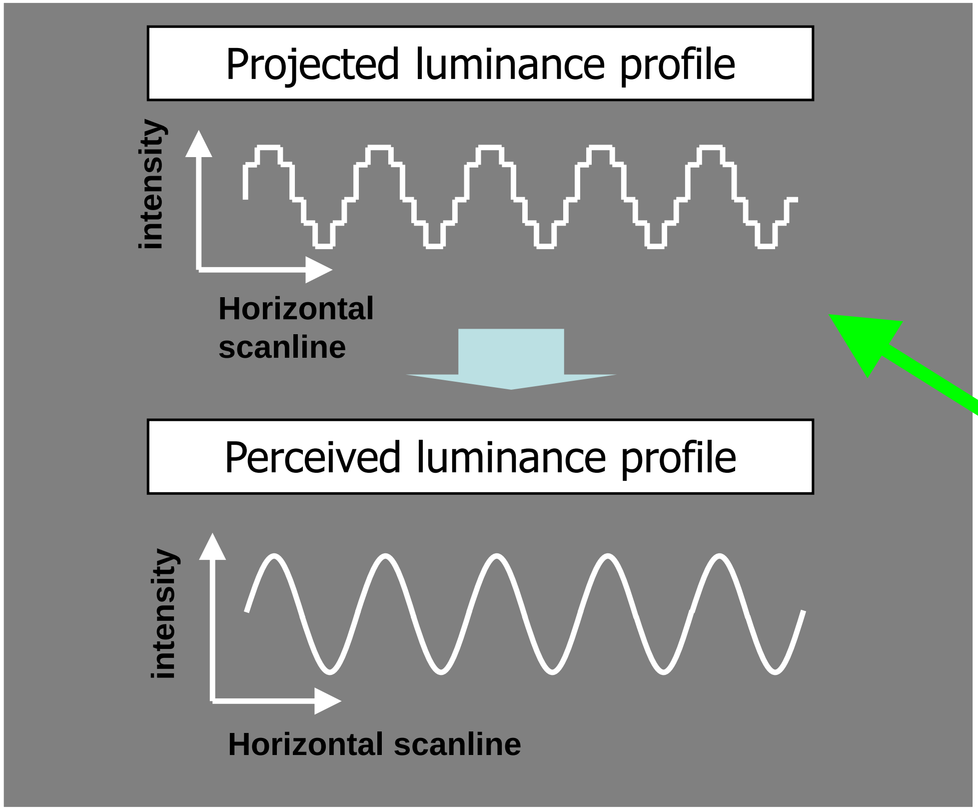
A new hybrid pattern

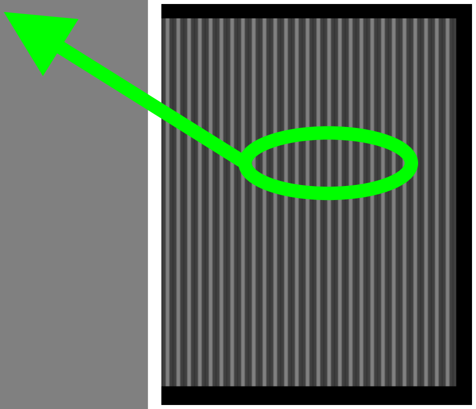
Combination of the
advantages of stripe patterns

Stripe

ern in the
channel







The new coding strategy

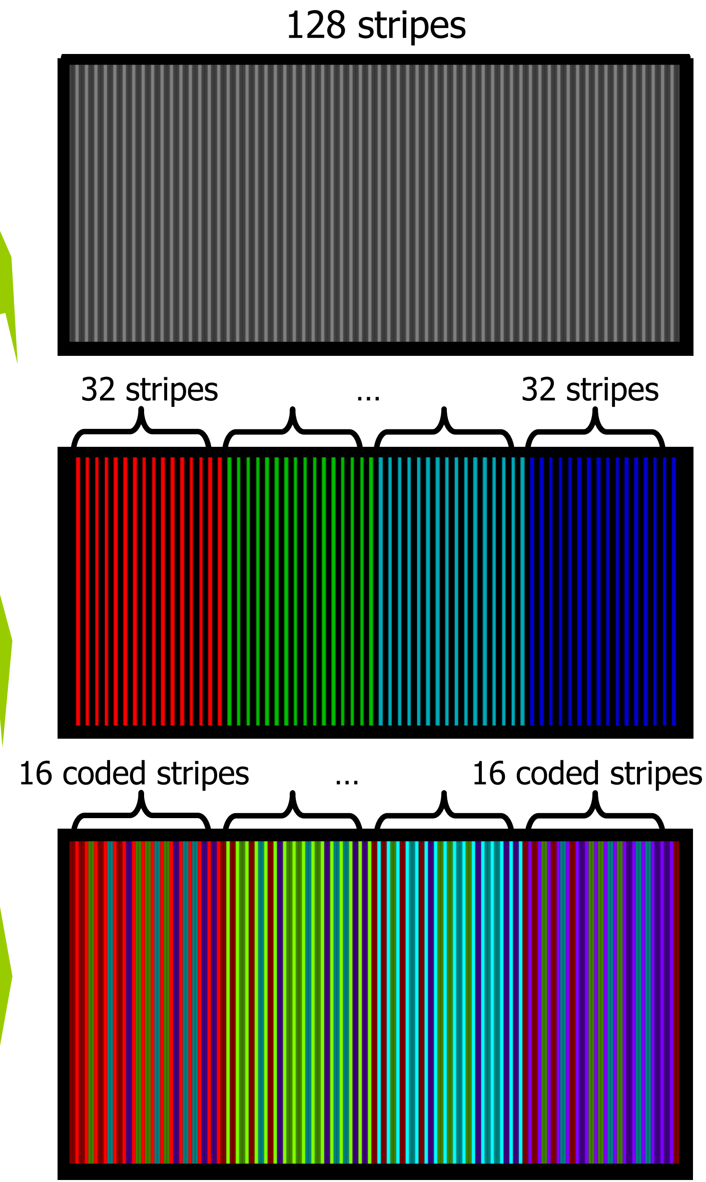
Example:
n=4, m=3

Given n different values of Hue and a window size of length m

A pattern with $2n^m$ stripes is defined with a square Luminance profile with alternating full-illuminated and half-illuminated stripes

The pattern is divided in n periods so that all the full-illuminated stripes of every period share the same Hue

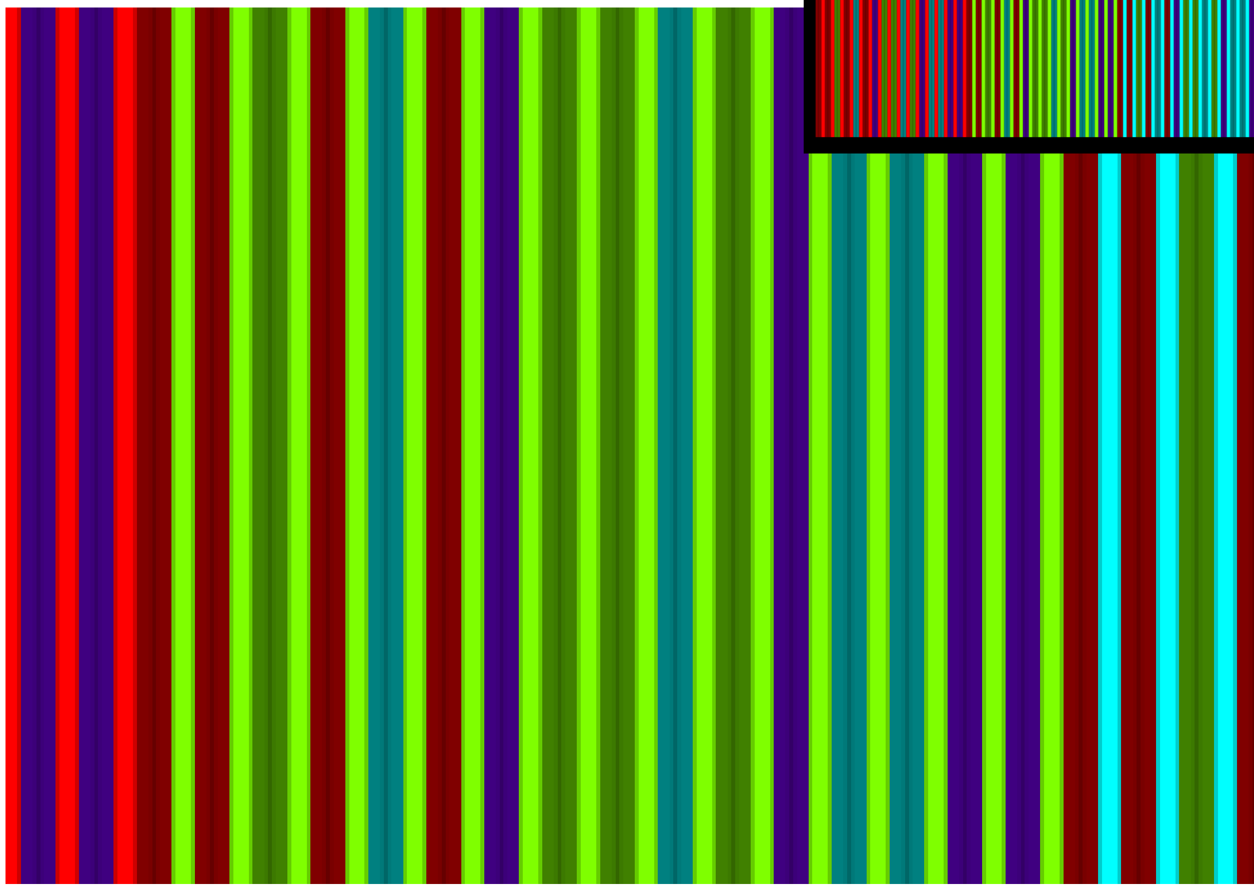
The half-illuminated stripes of every period are coloured according to a De Bruijn sequence of order m-1 and the same n Hue values

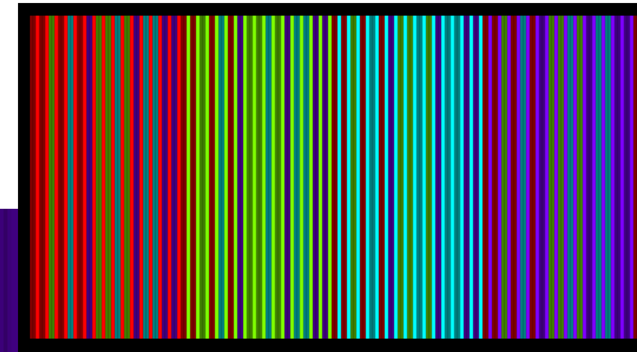


The new coding strategy

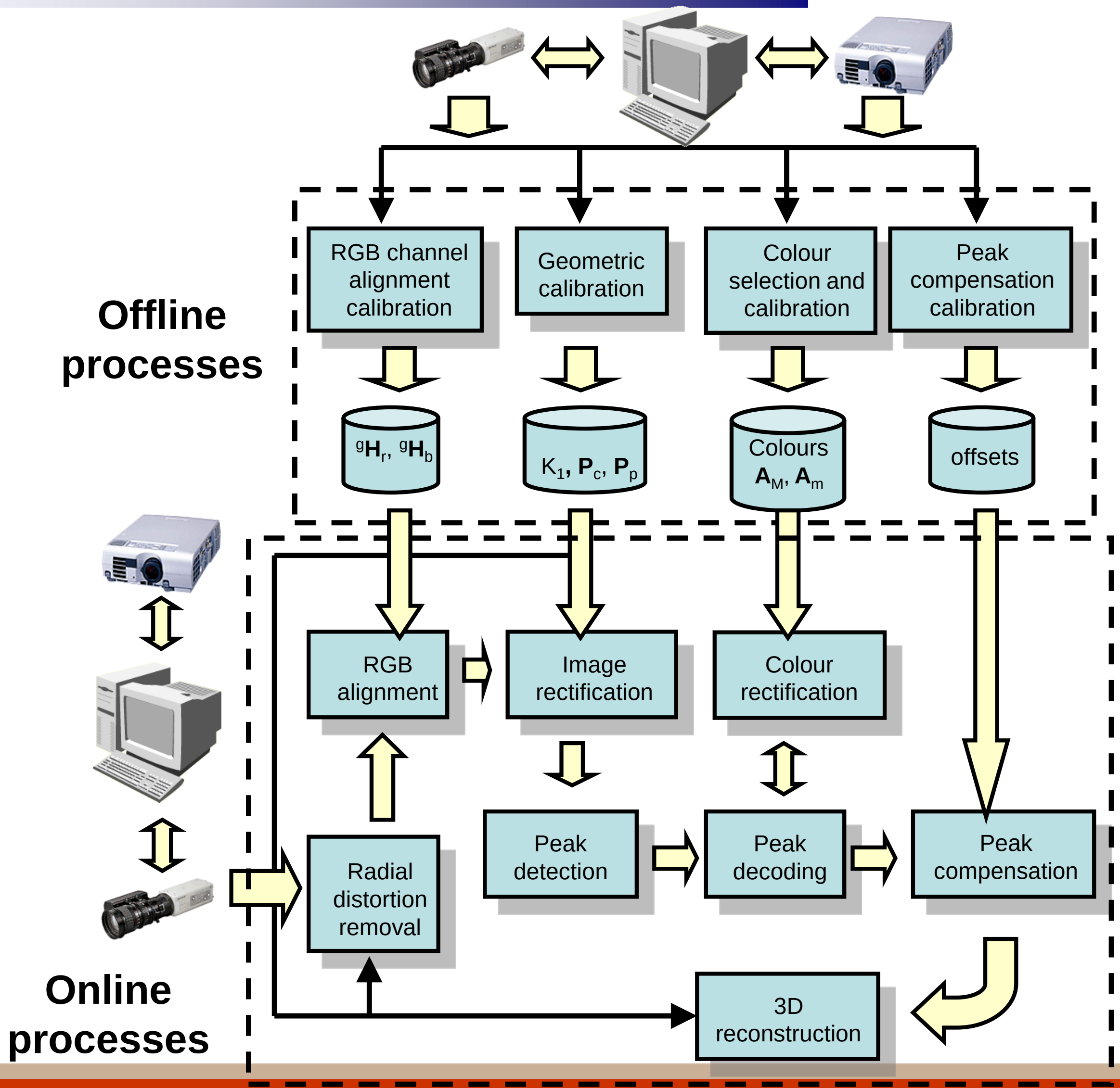
S={0010203112132233}

0=red; 1=green; 2=cyan; 3=blue



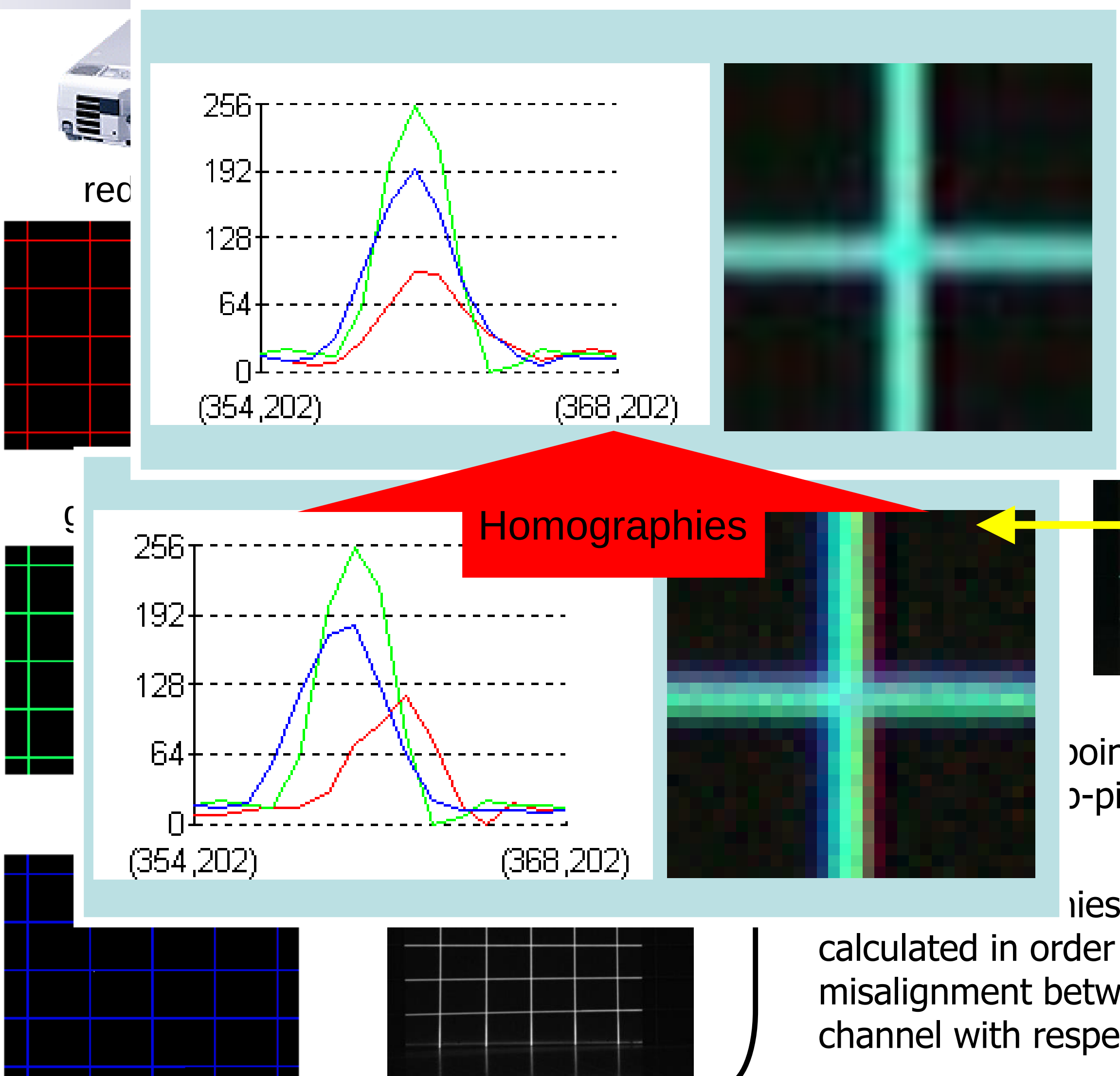


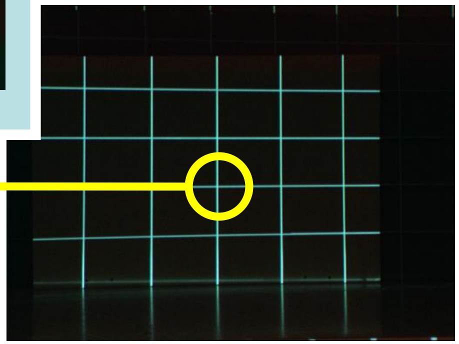
Implementation design of the coded structured light technique



Most of the processes of this schema are valid for any one-shot technique based on colour structured light

Offline processing: RGB channel misalignment calibration

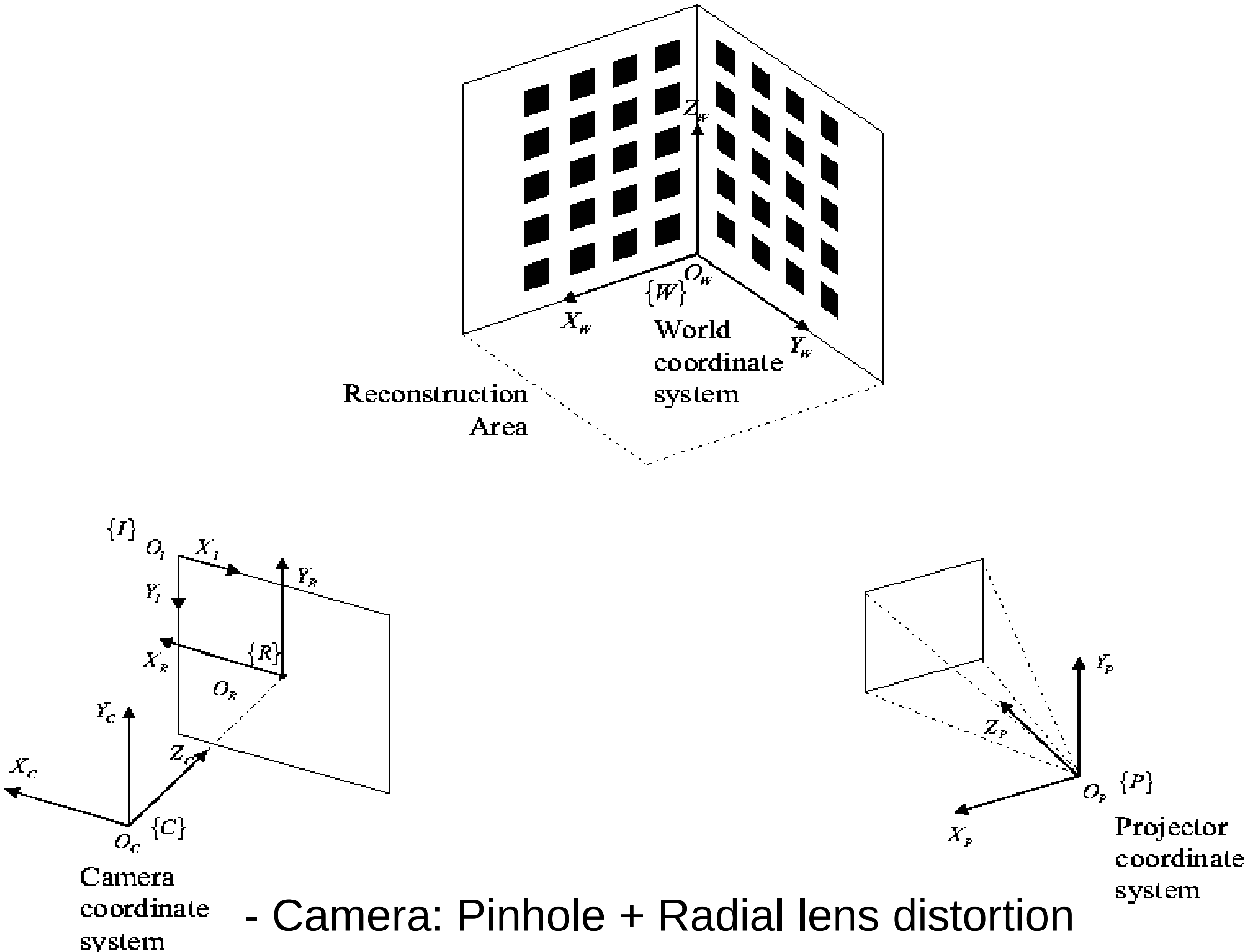




…oints coordinates are …-pixel accuracy in each RGB

…ies ^gH_r and ^gH_b are calculated in order to reduce the misalignment between the red and the blue channel with respect to the green.

Offiline processing: geometric calibration



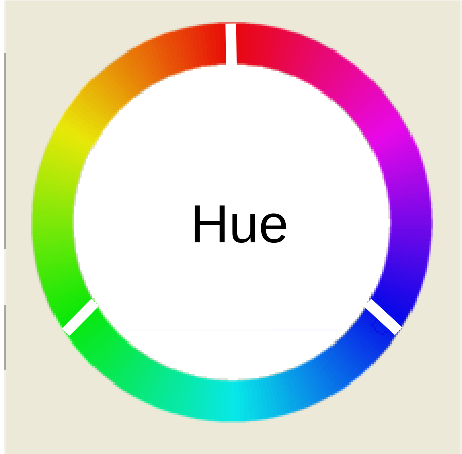
- Camera: Pinhole + Radial lens distortion
- Projector: like a reverse camera

Offline processing: colour selection (I)

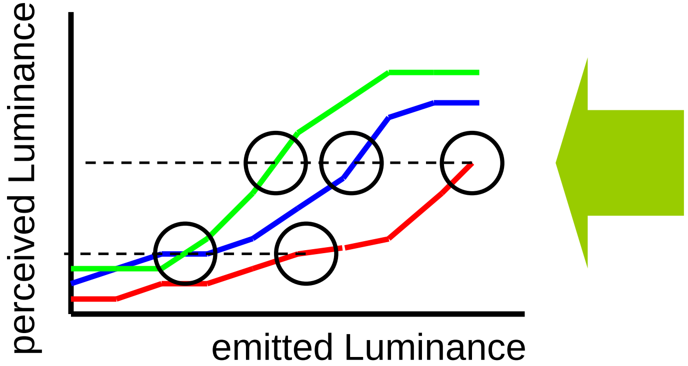
Each RGB channel has different sensitivity → the intensity perceived is in function of the projected Hue

Example: selection of n=3 colours

1) Select n equi-spaced Hue levels



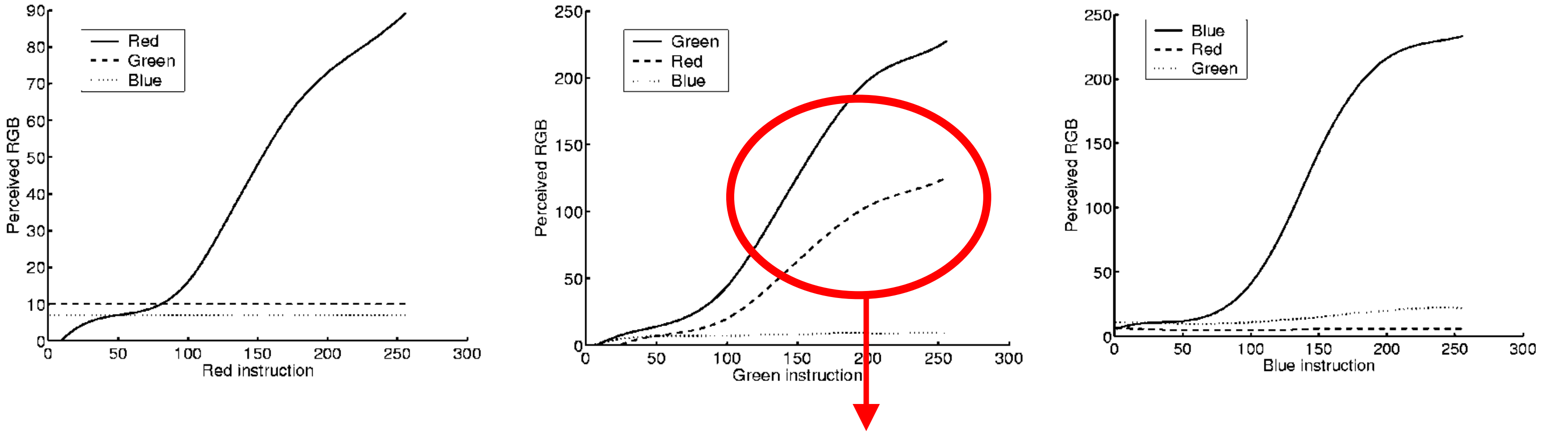
2) Project the n Hue values with different Luminance values and interpolate their response curve.



3) Given the maximum and minimum levels of luminances that we want to perceive → the corresponding projecting luminances for every Hue can be chosed

Offline processing: colour selection (II)

The projector-camera system introduces a strong colour cross-talk which makes colour identification difficult.



The highest cross-talk exists between the green and the red channel

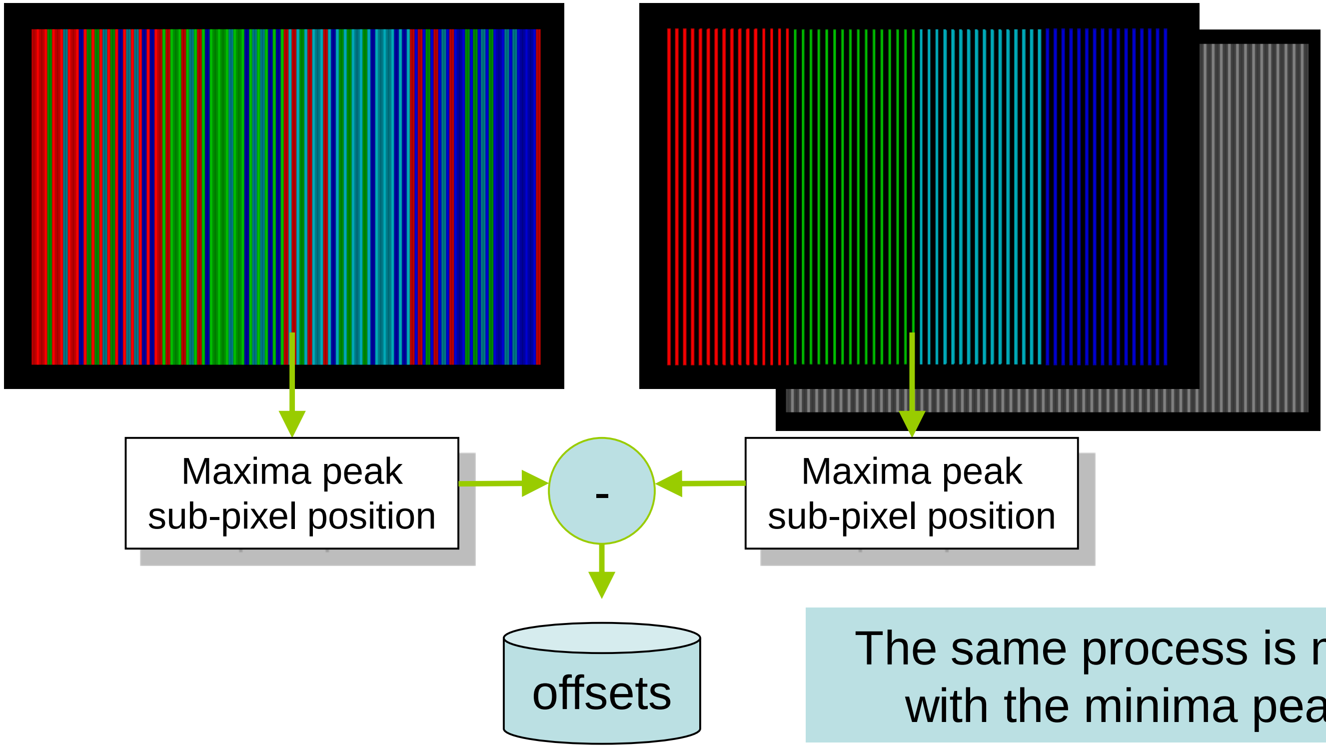
The cross-talk can be reduced with a calibration procedure:

- a pure red, green and blue patterns are projected over a colour-neutral panel.
- a linear mapping is calculated between the colour instructions and the perceived ones → a cross-talk matrix is obtained
- this matrix approximates the behaviour of the projector-camera system → This matrix will be used online to reduce the cross-talk.

Offline processing: peak compensation calibration

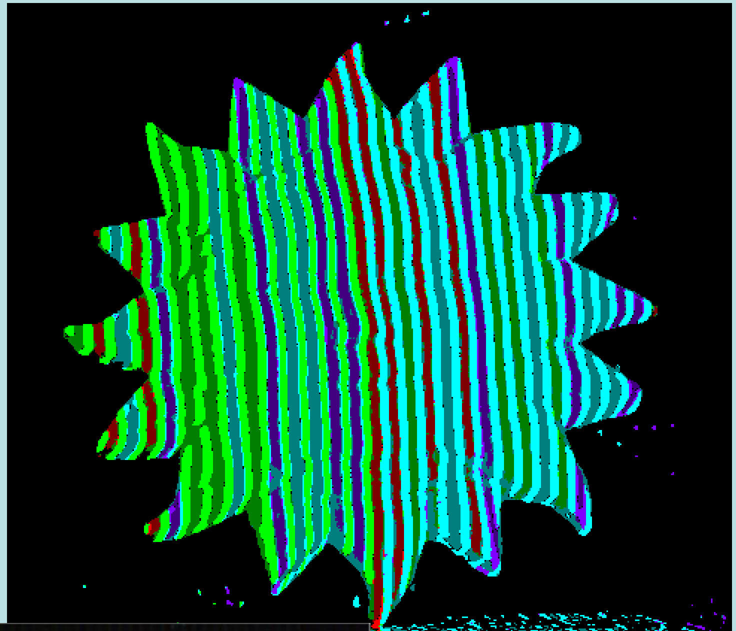
Every peak of luminosity is affected by the colours of the surrounding stripes → the detected peak position is affected by an offset

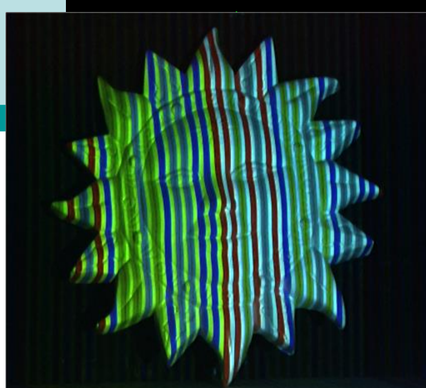
Peak compensation calibration: the pattern containing both full and half-illuminated stripes is projected and then the pattern only containing the full-illuminated stripes is also projected

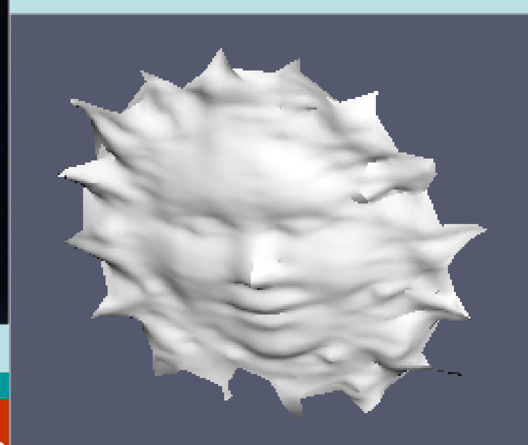


The same process is made with the minima peaks sing

Colour rectification by using the inverse of the calibrated cross-talk matrix







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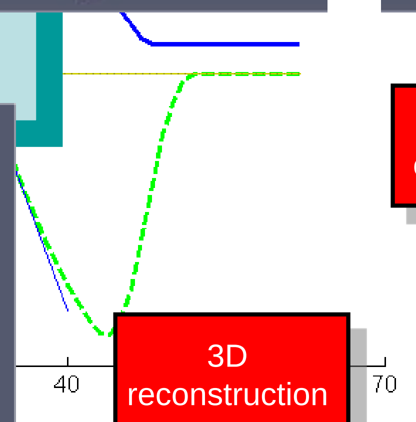
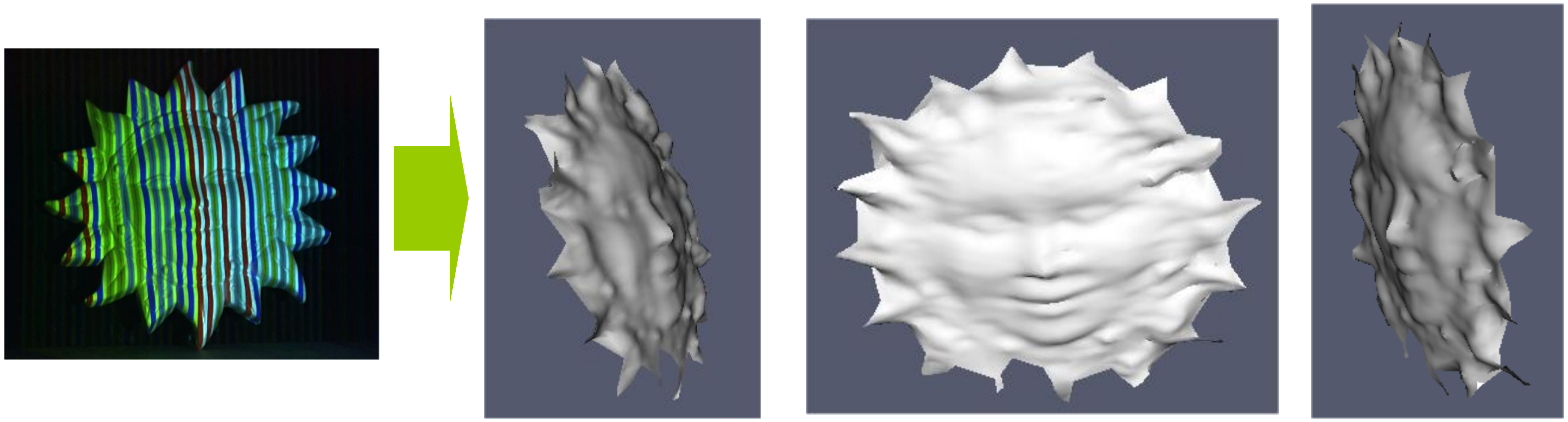
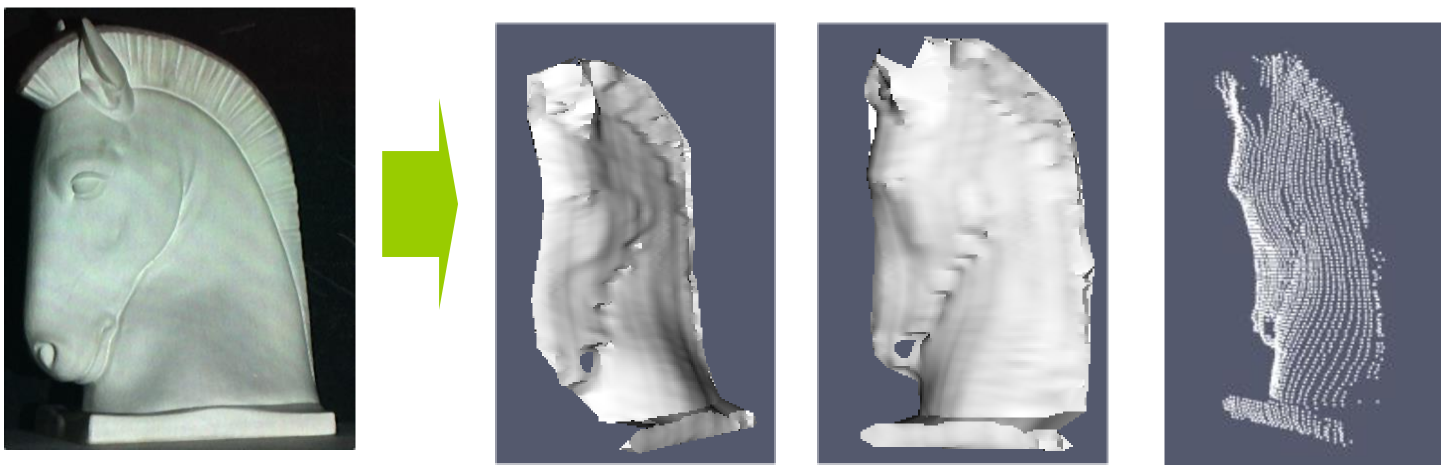


3D reconstruction

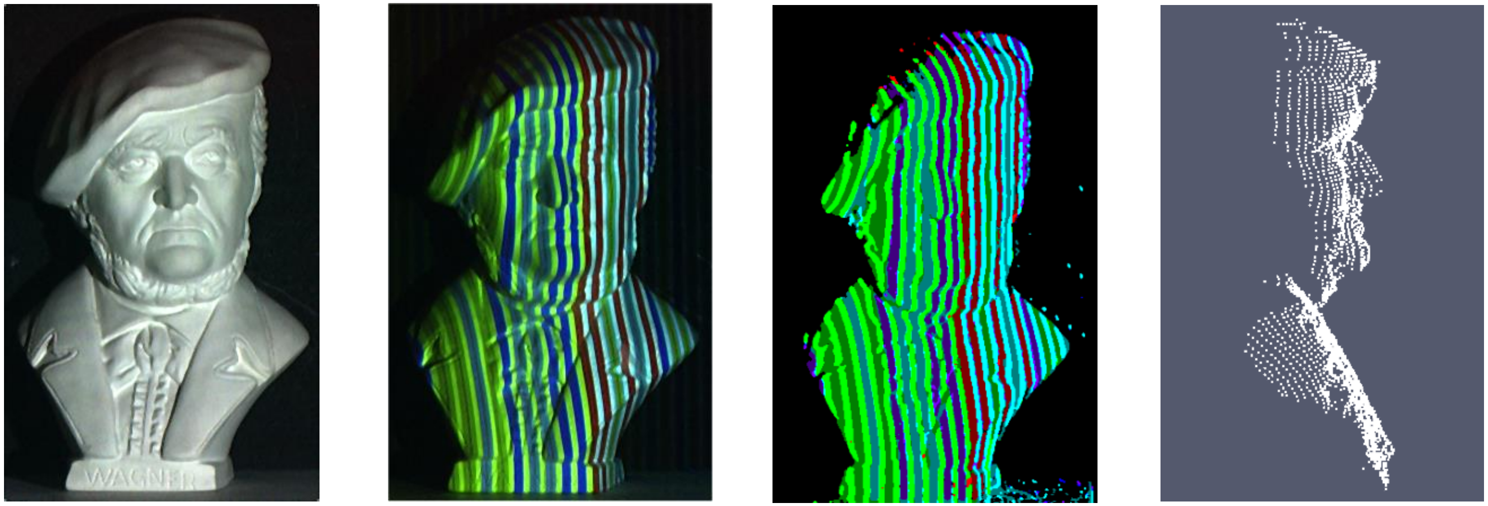
Peak compensation

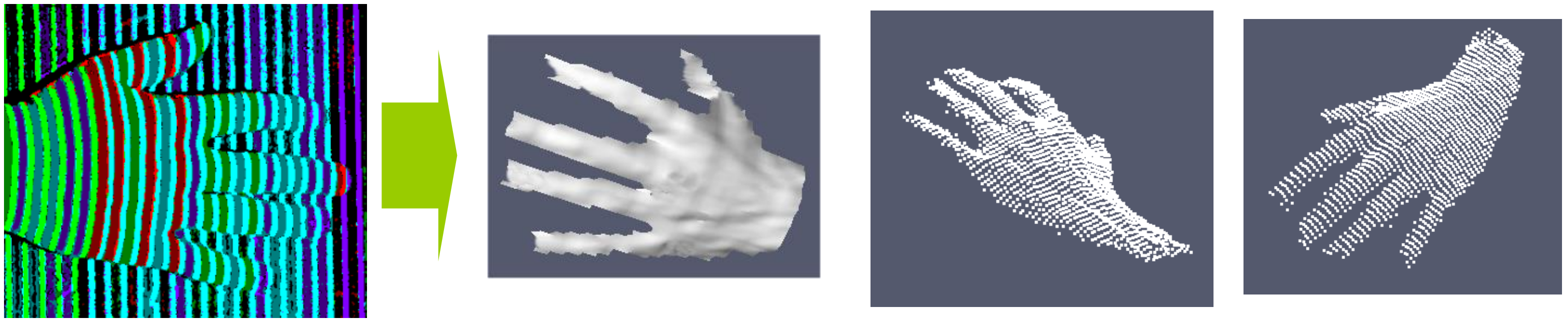
Experimental results (I)





Experimental results (II)





Conclusions

- A new coding strategy for one-shot patterns has been presented.
- The new pattern combines the high resolution of stripe-patterns and the high accuracy of multi-slit patterns.
- A pattern with $2n^m$ stripes is achieved with only n levels of Hue and a window property equal to m. (ex. $2*4^3 = 128$ stripes)
  - Given the same parameters, stripe-patterns encoded with classical De Bruijn sequences have a resolution of n^m (ex. $4^3 = 64$ stripes)
  - The resolution has been doubled.
- The pattern has a sinusoidal profile in the luminance channel so that maximum and minimum peaks can be accurately detected with classical peak detectors.

n = Number of colours (4),
m = Window size (3)

Published Material

Journals

- *J. Pagés, J. Salvi, J. Forest. Optimised De Bruijn patterns for one-shot shape acquisition. Image and Vision Computing. 23(8), pp 707-720, August 2005.*
- *J. Salvi, J. Pagés, J. Batlle. Pattern Codification Strategies in Structured Light Systems. Pattern Recognition 37(4), pp 827-849, April 2004.*
- *J. Batlle, E. Mouaddib and J. Salvi. A Survey: Recent Progress in Coded Structured Light as a Technique to Solve the Correspondence Problem. Pattern Recogniton 31(7), pp 963-982, July 1998.*
- *J. Salvi, J. Batlle and E. Mouaddib. A Robust-Coded Pattern Projection for Dynamic 3D Scene Measurement. Pattern Recognition Letters 19, pp 1055-1065, September 1998.*

Recent Conferences

- *J. Pagès, J. Salvi and J. Forest. Optimised De Bruijn Patterns for One-Shot Shape Acquisition. IEEE Int. Conf. on Pattern Recognition, ICPR 2004, Cambridge, Great Britain, 2004.*
- *J. Pagès, J. Salvi and C. Matabosch. Implementation of a robust coded structured light technique for dynamic 3D measurements. IEEE Int. Conf. on Image Processing, ICIP 2003, Barcelona, Spain, Septembre 2003.*
- *J. Pagès, J. Salvi, R. García and C. Matabosch. Overview of coded light projection techniques for automatic 3D profiling. IEEE Int. Conf. on Robotics and Automation, ICRA 2003, Taipei, Taiwan, May 2003.*

More Information: http://eia.udg.es/~qsalvi/