

# Structured light 3D scanning

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**This lecture is being  
livestreamed and recorded  
(hopefully)**

**Two feedback persons**

# Learning objectives

After this lecture you should be able to:

- explain laser line scanning
- analyse and use Gray code encoding
- analyse and use phase shift encoding

# Presentation topics

Photogrammetry

Structured light

- Laser line scanning

- Encoding surfaces

- Gray code encoding

- Phase shift encoding

Notes on laser/projector calibration

Exercise: structured light

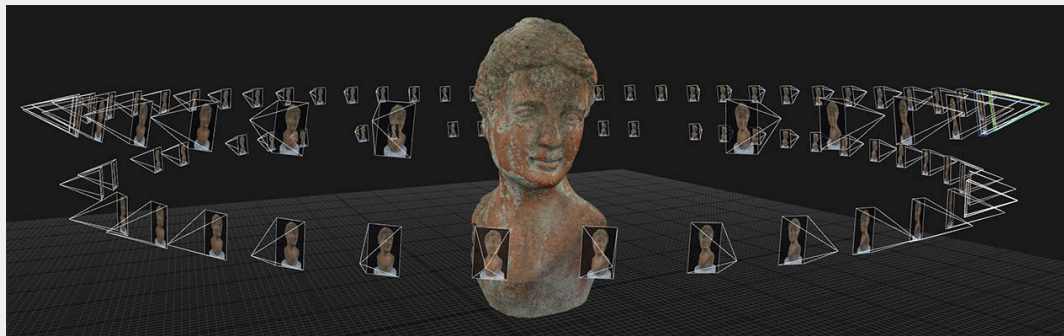
Exam information

# Photogrammetry

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# Photogrammetry

Take a lot of pictures of a scene and use SLAM to find camera positions and 3D points. Algorithms for dense estimation of 3D points can be applied to get a full 3D scene.



# Photogrammetry

Great:

- Works in daylight
- Handles textured objects

Bad:

- Requires good illumination
- Requires textured objects



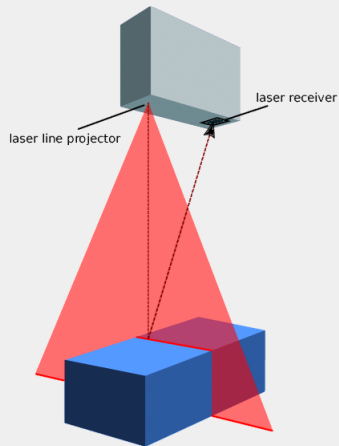
# Structured light

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# Laser line scanning

The first structured light technique.

- Laser projects 3D plane of light
- Camera sees the projected line
- Laser projector and camera are calibrated



# Laser line scanning

Example laser line scanner triangulation:

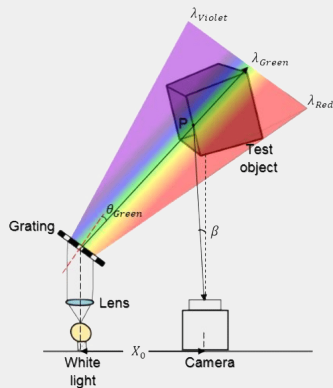
1. detect laser line in image
2. triangulate 3D point as intersection of pixel and the laser plane
3. move laser line and goto 1

Robust method, with a few drawbacks

- Requires laser calibration.
- A slow method; one triangulation line per image

# Encoding surfaces

Can we encode a surface?



Yes we can!

# Encoding surfaces

Possibilities:

- Continuous encoding
  - Color or intensity gradient
  - Sinusoidal (phase) shifting
- Discrete encoding
  - Binary monochrome
  - ternary RGB encoding
  - quaternary CMYK encoding
- Other encoding schemes

# Encoding surfaces

- Colored encodings have problems with colored surfaces
- Intensity codings have problems with textured objects
- Continuous encoding
  - **Sinusoidal (phase) shifting**
- Discrete encoding
  - **Binary monochrome**

# Continuous encoding schemes

1. For each pixel in the camera, identify the code/color
2. For each code, identify the corresponding light plane
3. Triangulate using pixel rays and the “laser plane”

Can get a 3D point for **each pixel** in the camera

Not always robust.

# Discrete encoding schemes

1. For each pixel in the camera, identify the code/color
2. For each **code border**, identify the corresponding plane
3. Triangulate using pixel rays and the “laser plane”

Only 3D points at **code-borders**, but usually more robust.



## Binary encoding – single frame

Frame:



Inverted frame:



Frame + inverted frame makes us robust towards ambient light and varying object albedo.

Binary test:  $\tau(\mathbf{p}, \mathbf{p}_i) = 1$  if  $\mathbf{p} > \mathbf{p}_i$  else 0.

Single test; two regions; one border

## Binary encoding – two frames

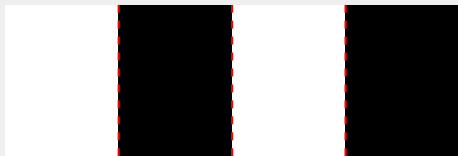
Frame 1:



Inverted frame 1:



Frame 2:

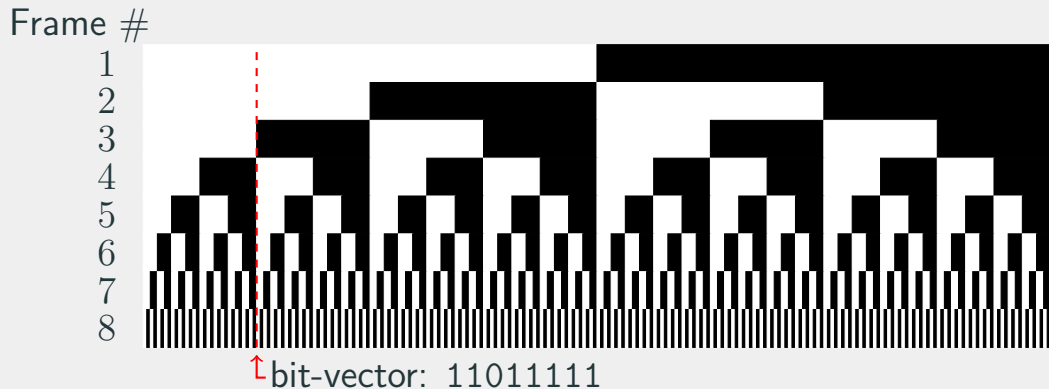


Inverted frame 2:



Two tests; four regions; three borders.

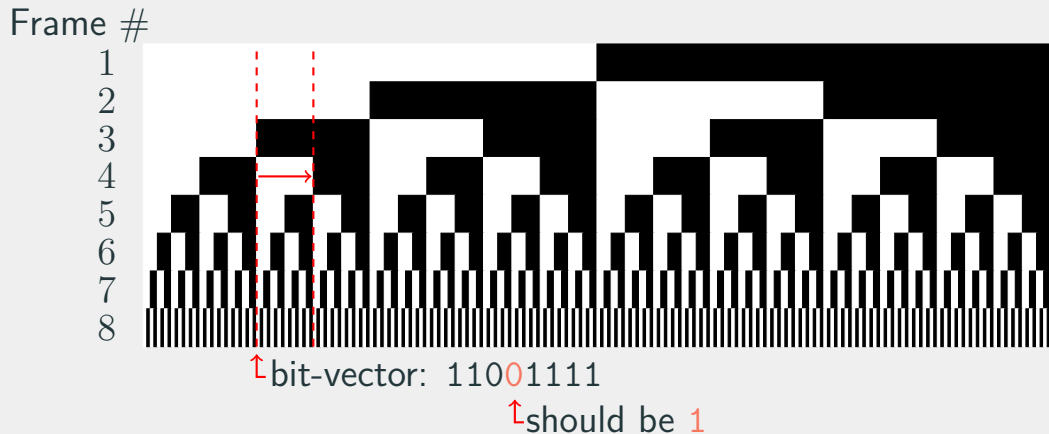
# Binary encoding – multiple frames



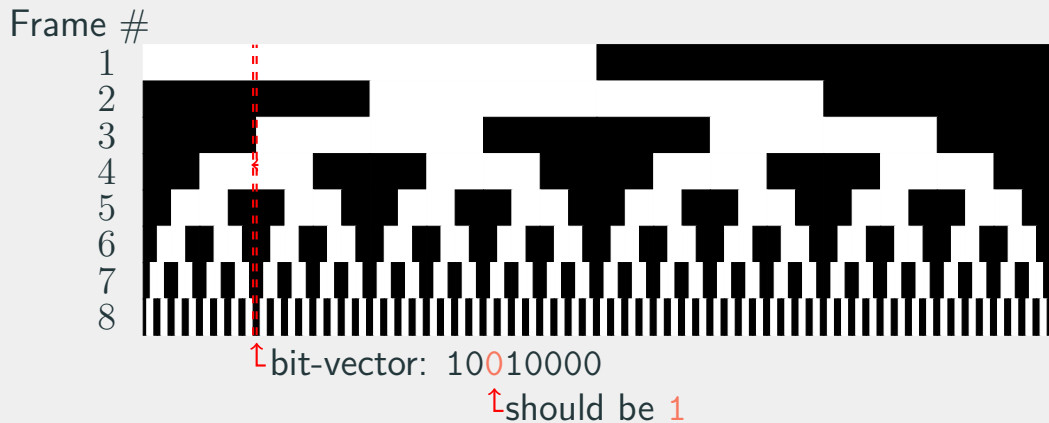
# Binary encoding

- For every frame we **subdivide the 3D volume**.
- For  $N$  frames we get  $2^N$  **unique regions**.
- For  $N$  frames we get  $2^N - 1$  **unique borders**.
- If a projector is  $W = 1920$  pixels wide, we are limited to  $N \leq \log_2(W) \approx 10.9$ . That is a max of 10 frames in total or, 20 in total with inverted frames.

# Binary encoding – border problems



# Gray code encoding



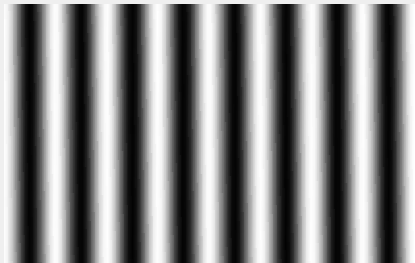
# Gray codes

- Only one bit flip at code borders; very robust.
- Uses same number of frames as binary patterns.

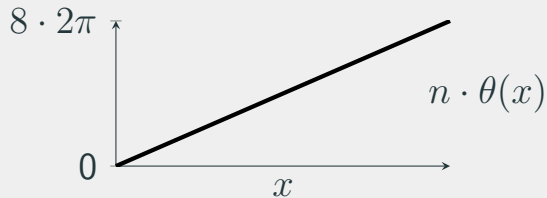
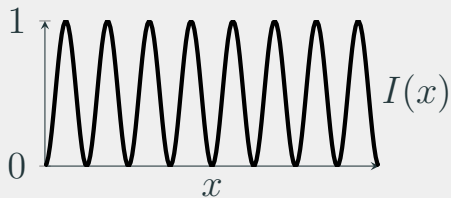
# Phase shift encoding



# Sinusoidal waves



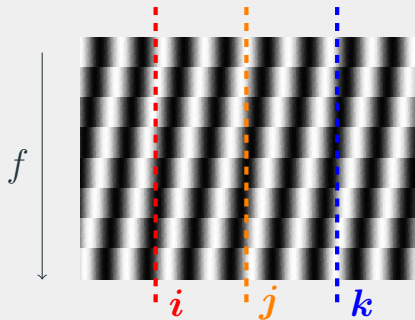
$$I(x, y) = \frac{1}{2} + \frac{1}{2} \cos(n \cdot \theta(x))$$



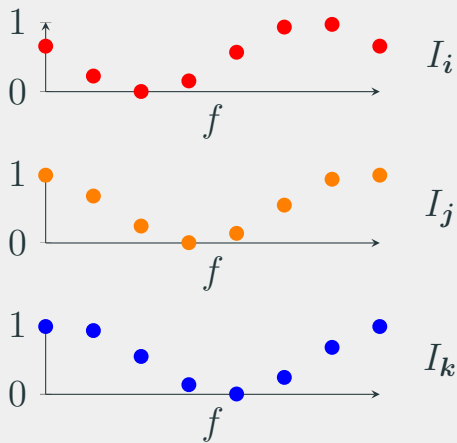
# Phase as a unique code

- The pattern is monochrome; good for colored objects.
- The phase is continuous; each point in space has a unique phase-plane.
- Even with a discrete intensity projector, the pattern is approximately continuous.
- $\theta(\cdot)$  is a function of the  $x$ -coordinate of the projector
  - From now on  $\theta$  is the  $x$ -coordinate of the projector (from 0 to  $2\pi$ )

# Phase shifting



$$I(f, \theta) = \frac{1}{2} + \frac{1}{2} \cos \left( n \cdot \theta + 2\pi \frac{f}{s} \right)$$



When projecting sinusoids and shifting them, **each pixel is a sinusoid** as a function of the pattern

# Phase shifting method

- Phase shift exactly one wavelength in  $s$  steps.
- The phase  $\theta$  corresponds to a unique projector plane.
- We can find  $n \cdot \theta$  for a single pixel by fitting a sinusoid to it

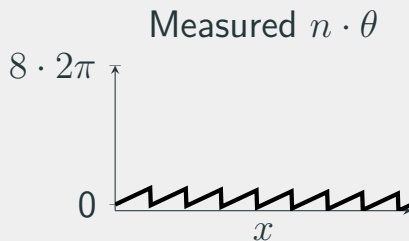
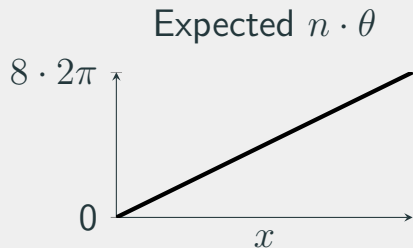
# Phase shifting method

- Phase shift exactly one wavelength in  $s$  steps.
- The phase  $\theta$  corresponds to a unique projector plane.
- We can find  $n \cdot \theta$  for a single pixel by fitting a sinusoid to it
- This can be done with least squares (slow) or the fast Fourier transform (FFT) (fast).

$$\text{FFT}_f[I(f, \theta)] = \left\{ \frac{s}{2}, \frac{s}{2}e^{i\theta}, 0, \dots, 0 \right\}$$

The second element of the FFT is a complex number with  $\theta = \text{angle}(\text{FFT}_2)$ .

# Phase wrapping



The phase  $n \cdot \theta = \text{angle}(\text{FFT}_2)$  is wrapped to  $0 \leq n \cdot \theta \leq 2\pi$ .

We need to **unwrap** the recovered phase!

# Heterodyne principle

Use two sinusoids:

$$\theta_1 = n_1 \cdot \theta \mod 2\pi \quad (\text{primary pattern})$$

$$\theta_2 = n_2 \cdot \theta \mod 2\pi \quad (\text{secondary pattern})$$

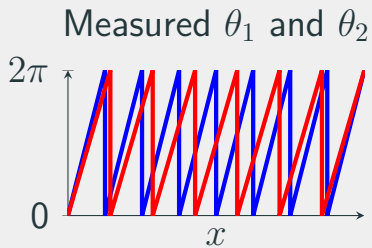
If we choose  $n_2 = n_1 + 1$  we can recover  $\theta$  by subtracting the primary phase from the secondary phase

$$\theta_2 - \theta_1 = n_2 \cdot \theta - n_1 \cdot \theta = \theta \mod 2\pi$$

This is the heterodyne principle, and gives us the **phase cue** ( $\theta_c$ ).

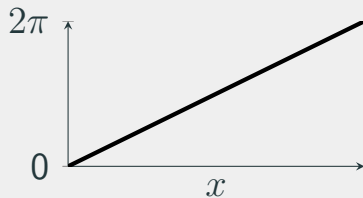


# Heterodyne principle



Looks great! 😊

$$\theta_c = \text{mod}(\theta_2(x) - \theta_1(x), 2\pi)$$



**Questions? Short break**

# Unwrapping

- If the measurements of  $\theta_1$  and  $\theta_2$  are noise free, the phase cue  $\theta_c$  is exactly equal to  $\theta$ .
- All measurements have noise, but in this case we can improve the handling of noise substantially.

# Unwrapping

To make the system more robust to noise in the measurements we can compute  $\theta$  using the phase cue and the primary phase  $\theta_1$ .

The **order** counts how many times  $\theta_1$  has wrapped around

$$o_1 = \left\lfloor \frac{n_1 \cdot \theta_c - \theta_1}{2\pi} \right\rfloor$$

The rounding  $\lfloor \cdot \rfloor$  makes it robust to noise. We can now estimate  $\theta$

$$\theta_{\text{est}} = \frac{2\pi o_1 + \theta_1}{n_1} \mod 2\pi$$

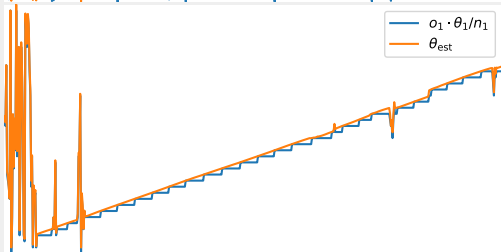
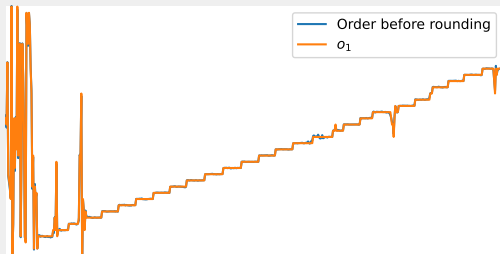
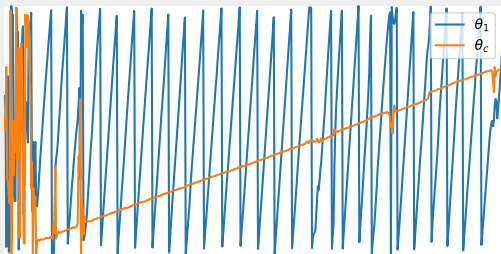
# Unwrapping and phase cue – Motivation

- Why not just use the phase cue?
- $\theta_1 = \theta_1^{\text{true}} + \epsilon_1$
- $\theta_2 = \theta_2^{\text{true}} + \epsilon_2$
- $\theta_c = \theta^{\text{true}} - \epsilon_1 + \epsilon_2$

# Unwrapping and phase cue – Motivation

- Why not just use the phase cue?
- $\theta_1 = \theta_1^{\text{true}} + \epsilon_1$
- $\theta_2 = \theta_2^{\text{true}} + \epsilon_2$
- $\theta_c = \theta^{\text{true}} - \epsilon_1 + \epsilon_2$
- The error of the phase cue is linear in the errors of  $\theta_1$  and  $\theta_2$
- $\theta$  has an error of  $\frac{\epsilon_1}{n_1}$ , which is much lower

# Unwrapping – examples from today's exercise.



Examples from row 400 of camera 0.

# Phase shift encoding

1. Project two sets of sinusoidals.
2. For each pixel, find the wrapped phases  $\theta_1$  and  $\theta_2$ .
3. Calculate the phase cue  $\theta_c = \theta_2 - \theta_1 \bmod 2\pi$ .
4. Calculate the primary order  $o_1 = \left\lfloor \frac{n_1 \cdot \theta_c - \theta_1}{2\pi} \right\rfloor$
5. Calculate the theta  $\theta_{\text{est}} = \frac{2\pi o_1 + \theta_1}{n_1}$
6. For each phase, find the corresponding projector plane.
7. Triangulate pixel rays and the projector plane.



# Phase shift encoding

- Very robust since the FFT is also a low-pass filter.
- Potentially one triangulation per camera pixel.
- Easy to make more precise; more projected frames gives a higher precision.

# Notes on laser/projector calibration

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# Laser/projector calibration

- Is needed for many structured light methods.
- Requires correspondences between the laser/projector and the real world.
- Often we use a calibrated camera to relate projected lines/pixels to world coordinates.
- Not ideal for projectors, as they usually have poor quality lenses.

However, do we need to calibrate the laser/projector?

## “Passive” structured light

- Use a stereo camera set up and a laser/projector.
- The laser/projector encodes the object surface, but is not calibrated.
  - Accurately calibrating a projector is harder than calibrating a camera
- Instead of laser/projector plane triangulation, we use epipolar lines in the cameras.
- Requires that the projected planes are not parallel with the epipolar planes.

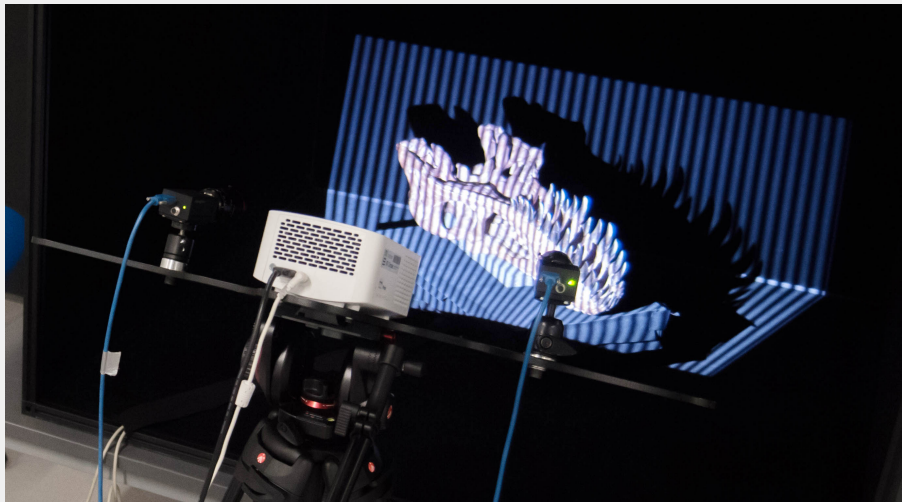
# Exercise: structured light

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# Structured light exercise

- Scan using phase shifting
- You will perform:
  - Image rectification
  - Phase decoding (and unwrapping)
  - Masking
  - Matching
  - Triangulation

# Casper the baby T-Rex



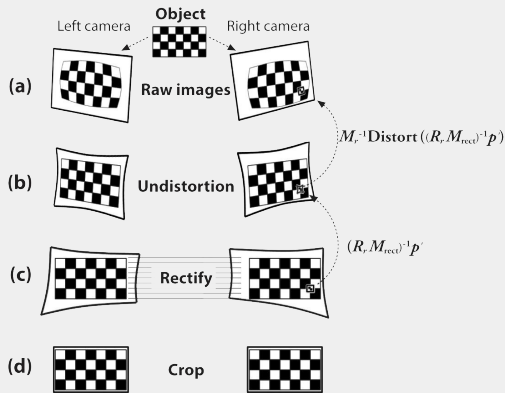
# Casper the baby T-Rex





# Rectified cameras

Cameras are (virtually) made parallel to each other.



# Masking

We need to only match phases, which is efficient and robust.

With rectified images, epipolar lines are the corresponding rows.

**Live demo[ish]**

## Further courses

- Are you interested in working more with images?
- 02506 Advanced Image Analysis (Spring)
- 02516 Introduction to Deep Learning in Computer Vision (Fall)
- 02501 Advanced Deep Learning in Computer Vision (Spring)

# Learning objectives

After this lecture you should be able to:

- explain laser line scanning
- analyse and use Gray code encoding
- analyse and use phase shift encoding

# Exam information

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# Exam information

Exam time and place: [www.eksamensplan.dtu.dk](http://www.eksamensplan.dtu.dk)

- Multiple choice exam
  - No negative points for wrong answers
- Questions are a mix of understanding and calculation in Python.
  - You can use your computer and all notes.
  - No internet access during exam.
  - No use of LLMs/generative AI.
  - You can [download](#) the documentation for OpenCV to your computer.

# Quiz awards



**Exercise time!**