Structured light 3D scanning

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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

Photogrammetry

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:

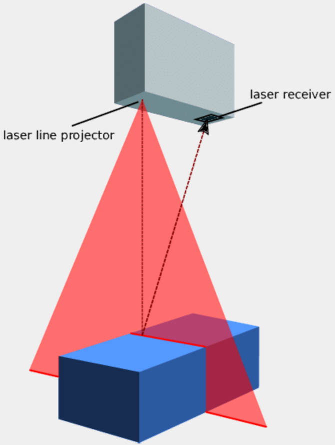
- Requires daylight
- Requires objects texture

Structured light

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:

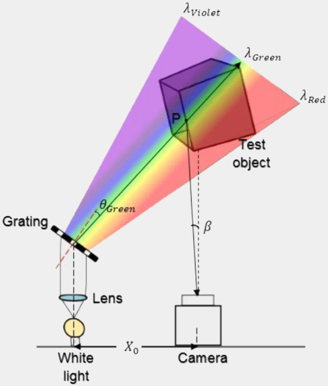
1. detect laser line in image
2. triangulate 3D point as intersection of pixel and the laser plane
3. move laser line and goto 1

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

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 pixel rays and the laser plane

Can get a 3D point for each pixel in the camera
Not always robust.

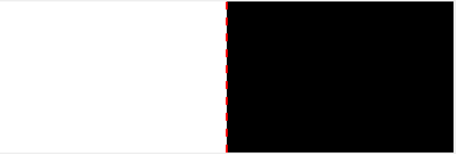
Discrete encoding schemes

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

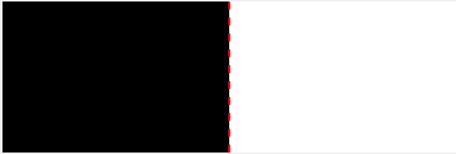
Only 3D points at code-borders, but usually more robust.

Binary encoding – single frame

Frame:



Inverted frame:

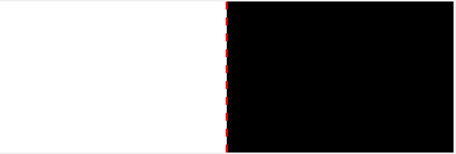


Binary test: $\tau(\boldsymbol{p}, \boldsymbol{p}_i) = 1$ if $\boldsymbol{p} > \boldsymbol{p}_i$ else 0.

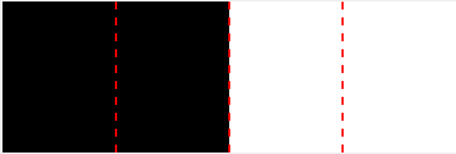
Single test; two regions; one border

Binary encoding – two frames

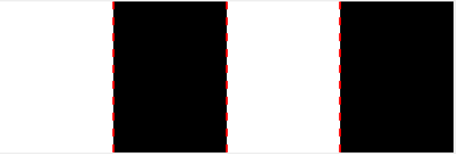
Frame 1:



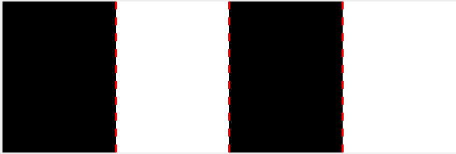
Inverted frame 1:



Frame 2:



Inverted frame 2:



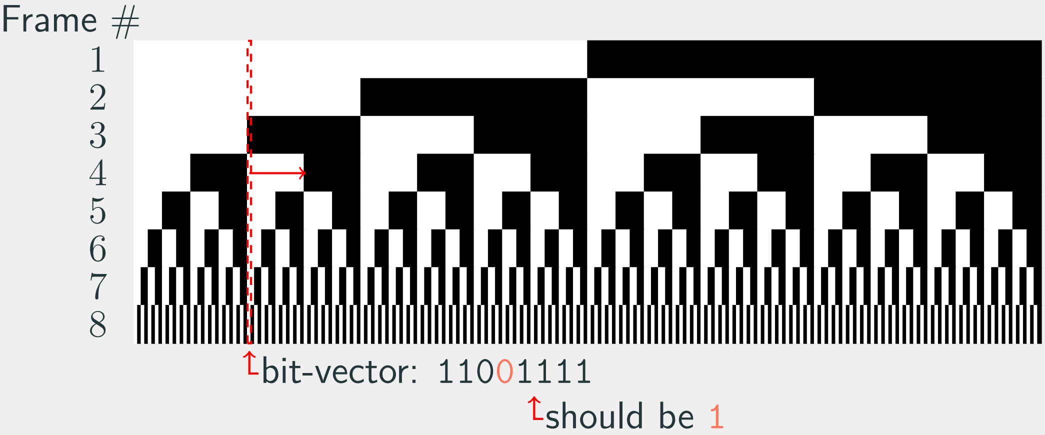
Two tests; four regions; three borders.

Binary encoding – multiple frames

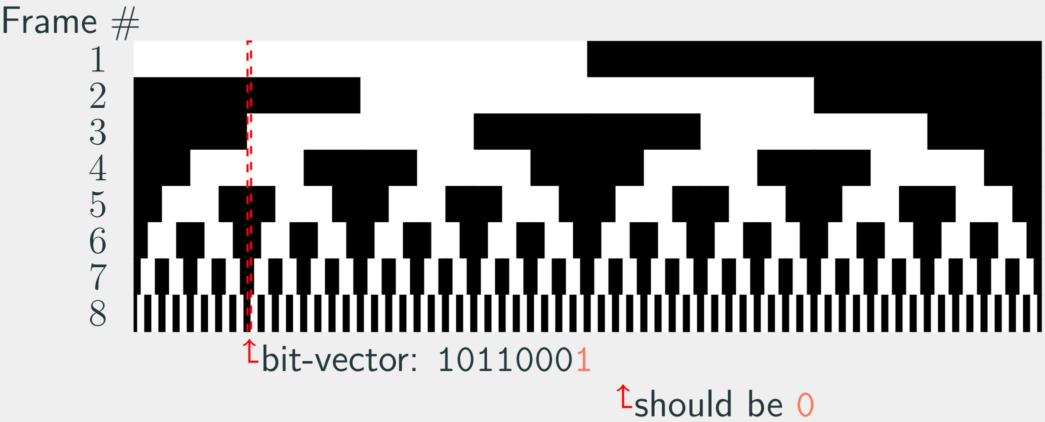
Binary encoding

- 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 $W = 1980$ pixels wide, we are limited to $N \leq \log_2(W) \approx 10$. That is a max of $10 - 2 = 8$ frames in total accounting for projector blur. Or, 16 in total with inverted frames.

Binary encoding – border problems



Gray code encoding

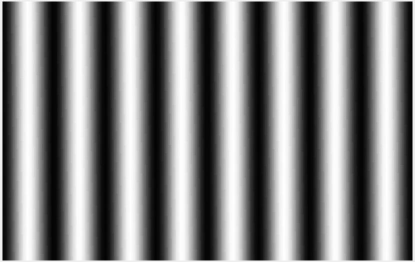


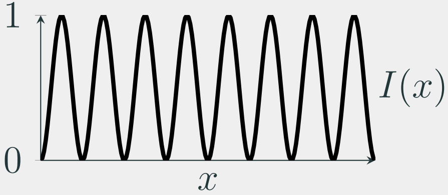
Gray codes

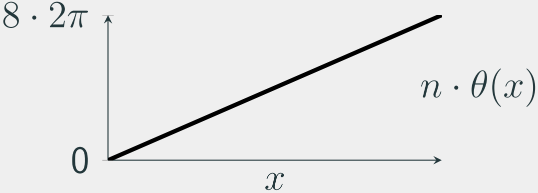
- Only one bit flip at code borders; very robust.
- Uses same number of frames as binary patterns.

Phase shift encoding

Sinusoidal waves





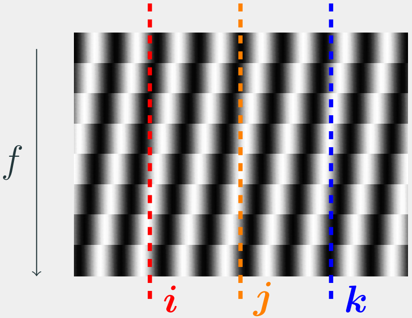


$$I(x, y) = \frac{1}{2} + \frac{1}{2}\cos(n \cdot \theta(x))$$

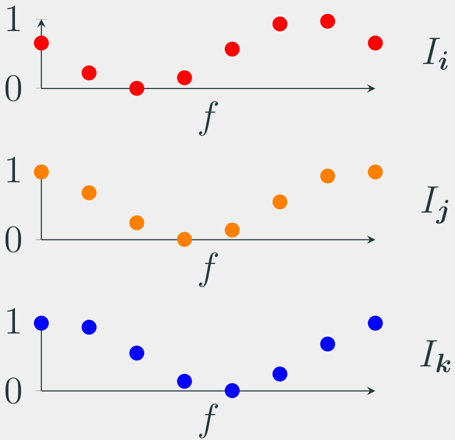
Phase as a unique code

- 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.

Phase shifting



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



Phase shifting method

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

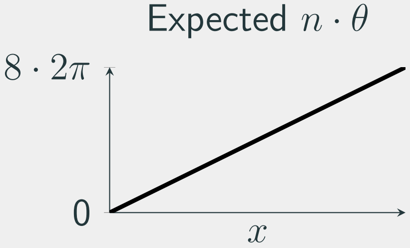
Phase shifting method

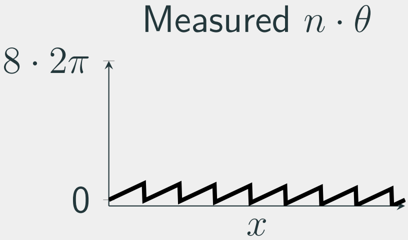
- Phase shift exactly one wave length in s steps.
- The phase θ corresponds to a unique projector plane.
- We can find $n \cdot \theta$ for a single pixel by fitting a sinusoid to it
- This can be done with least squares (slow) or the fast Fourier transform (FFT) (fast).

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

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

Phase wrapping





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

Heterodyne principle

Use two sinusoids:

$$\begin{aligned} \theta_1 =& n_1 \cdot \theta \mod 2\pi \text{(primary pattern)} \\ \theta_2 =& n_2 \cdot \theta \mod 2\pi \text{(secondary pattern)} \end{aligned}$$

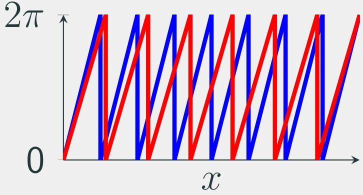
If we choose $n_2 = n_1 + 1$ we can recover θ by subtracting the secondary phase from the primary phase

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

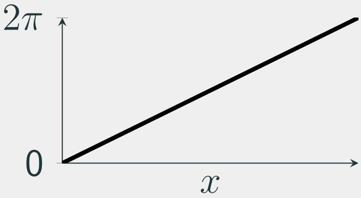
This is the heterodyne principle, and gives us the phase cue (θ_c).

Heterodyne principle

Measured θ_1 and θ_2



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



The phase cue θ_c is only equal to θ if there is no noise in the measurements of ϕ_1 and ϕ_2.

Unwrapping

To make the system more robust to noise in the measurements we can compute θ using the phase cue and the primary phase ϕ_1.

The order counts how many times θ_1 has wrapped around

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

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

$$\theta_{\text{est}} = \frac{2\pi o_1 + \phi_1}{n_1} \mod 2\pi$$

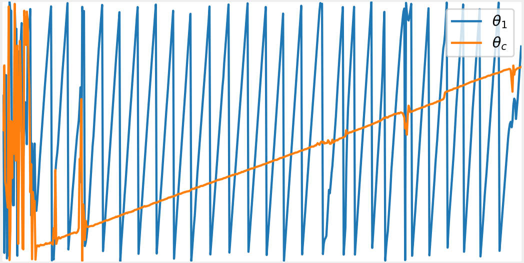
Unwrapping and phase cue – Motivation

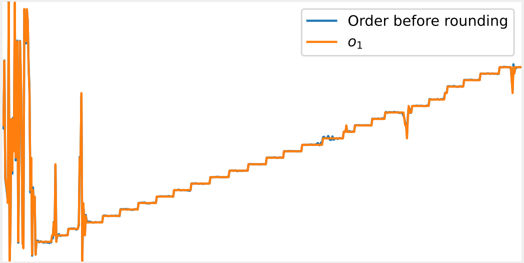
- Why not just use the phase cue?
- $\theta_1 = \theta_1^{\text{true}} + \epsilon_1$
- $\theta_2 = \theta_2^{\text{true}} + \epsilon_2$
- $\theta_c = \theta^{\text{true}} - \epsilon_1 + \epsilon_2$

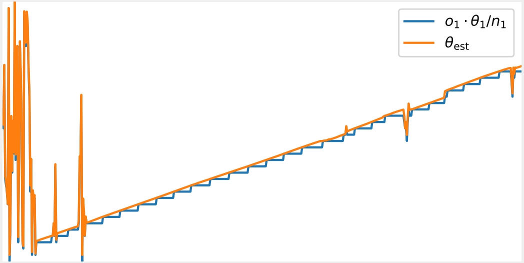
Unwrapping and phase cue – Motivation

- 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 θ_1 and θ_2
- θ 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 θ_1 and θ_2.
3. Calculate the phase cue $\theta_c = \theta_1 - \theta_2 \mod 2\pi$.
4. Calculate the primary order $o_1 = \left\lfloor \frac{n_1 \cdot \theta_c - \theta_1}{2\pi} \right\rceil$
5. Calculate the theta $\theta_{\text{est}} = \frac{2\pi o_1 + \phi_1}{n_1}$
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

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

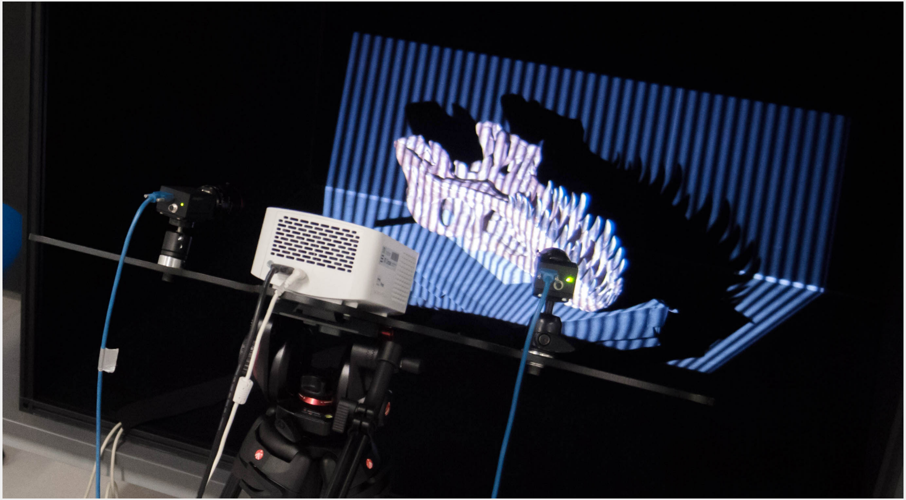
- Use a stereo camera set up and a laser/projector.
- The laser/projector encodes the object surface, but is not calibrated.
- Instead of laser/projector plane triangulation, we use epipolar lines in the cameras.
- Only requires that the projected planes are not parallel with the epipolar planes.

Exercise: structured light

Structured light exercise

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

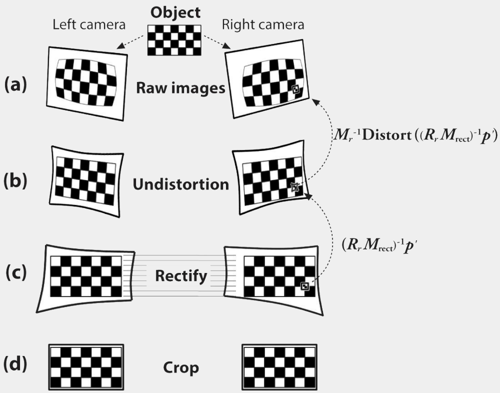
Casper the baby T-Rex



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]

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

Exercise time!