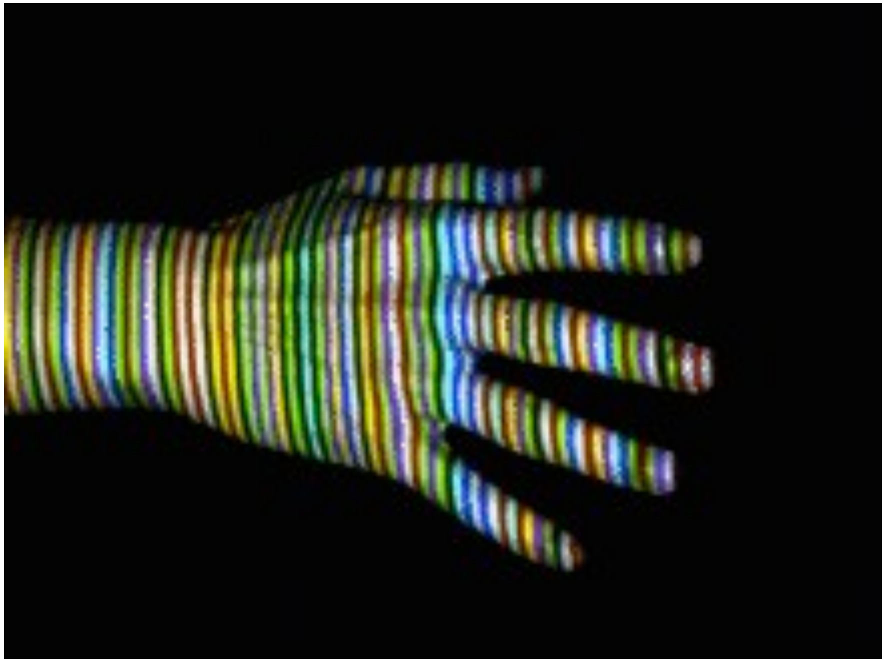
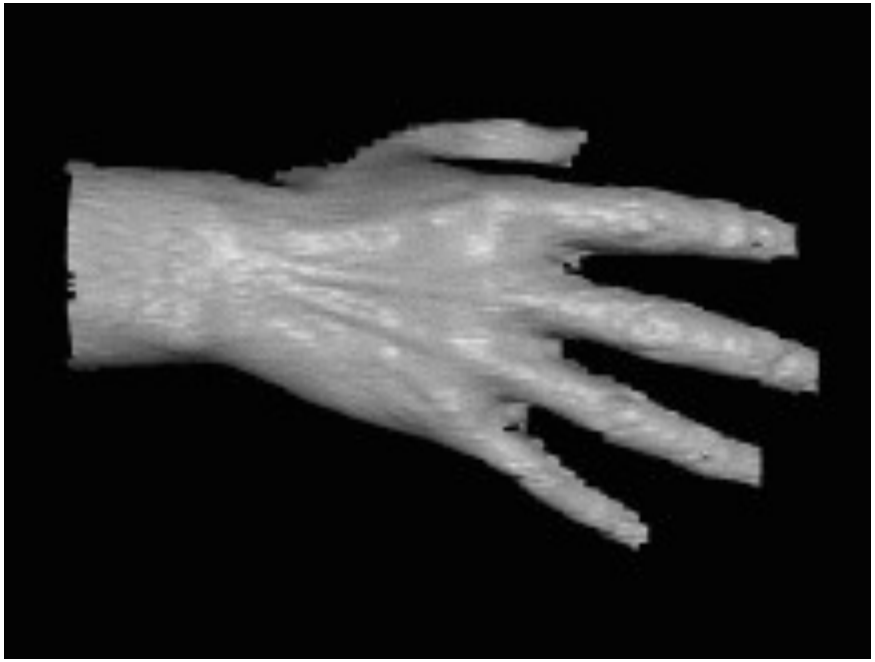
Structured Light



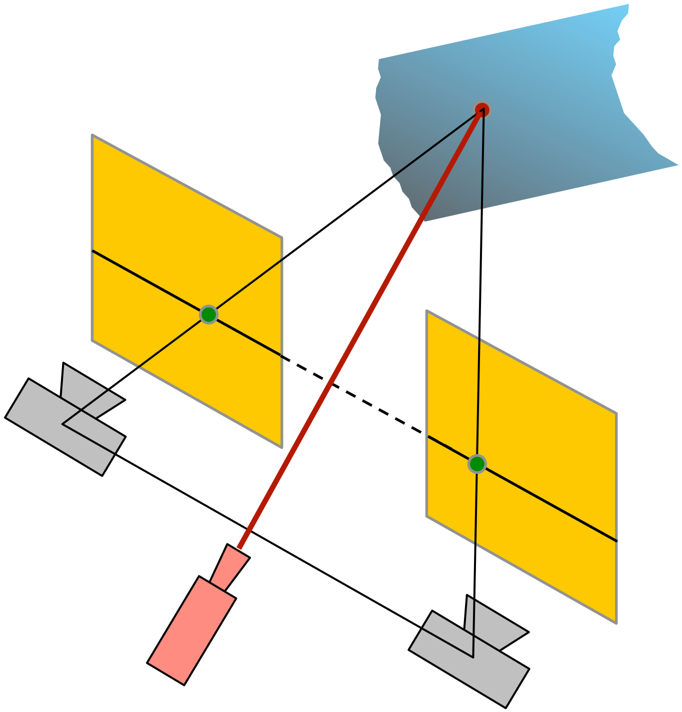


Structured Light

- The main problem of photogrammetry
  - to recover shape from multiple views of a scene, we need to find correspondences between the images
  - the matching/correspondence problem is hard
  - the 3D object geometry cannot be reconstructed in image regions without well-defined image points
- Structured light
  - **idea**: find ways to simplify matching and guarantee dense coverage with homologous points
  - **general strategy**: use illumination to create your own correspondences
  - probably the most robust method in practice
  - widely used (industrial metrology, entertainment, ...)
  - also known as “active stereo” or “white light scanning”

Basic Principle

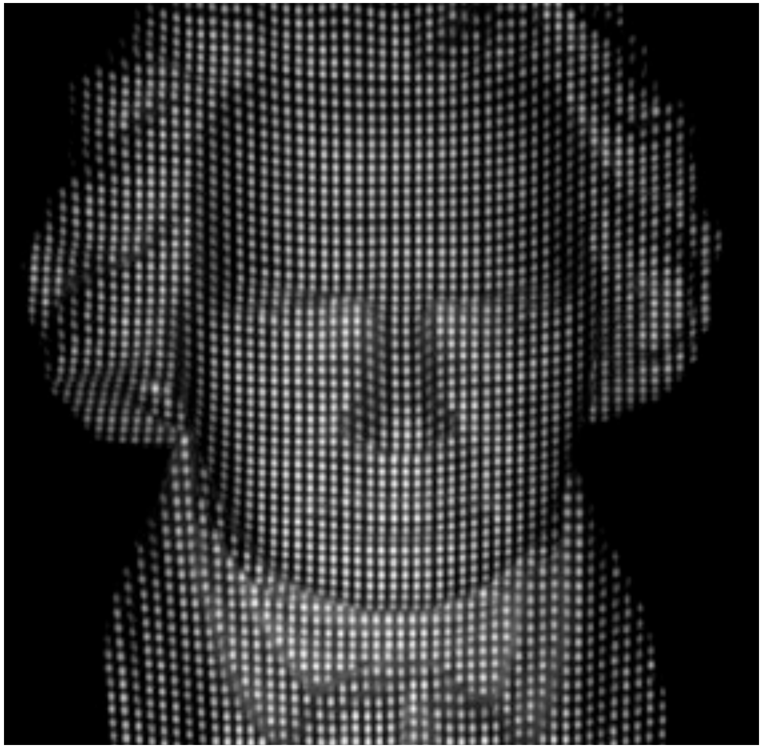
- Light projection
  - use a projector to create unambiguous correspondences
  - with these correspondences, apply conventional stereo
  - if we project a single point, matching is unique
  - ... but many images needed to cover the object



  - ***Note***: less sophisticated variants include dusting surfaces with chalk, spraying them with water, etc.

Variant

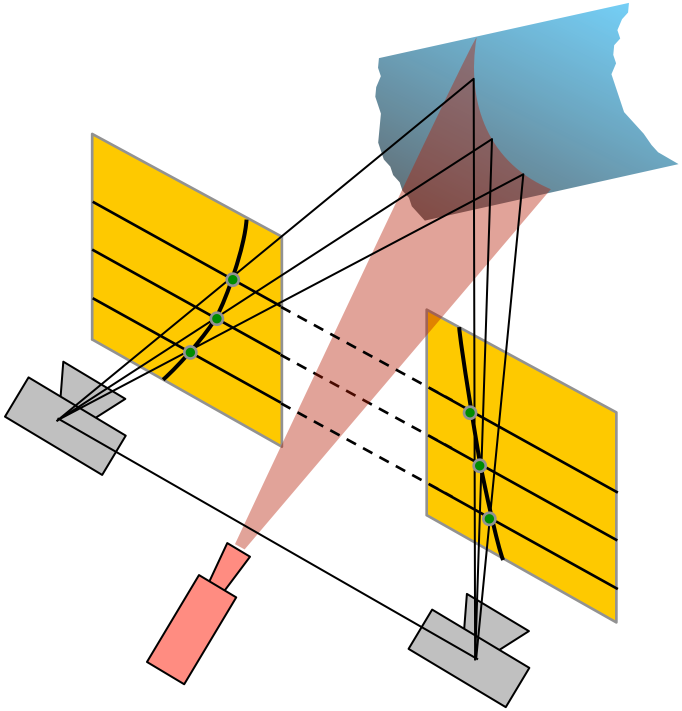
- Pattern projection
  - project a pattern instead of a single point
  - needs only a single image, one-shot recording
  - ...**but** matching is no longer unique (although still easier)
  - more on this later



Line projection

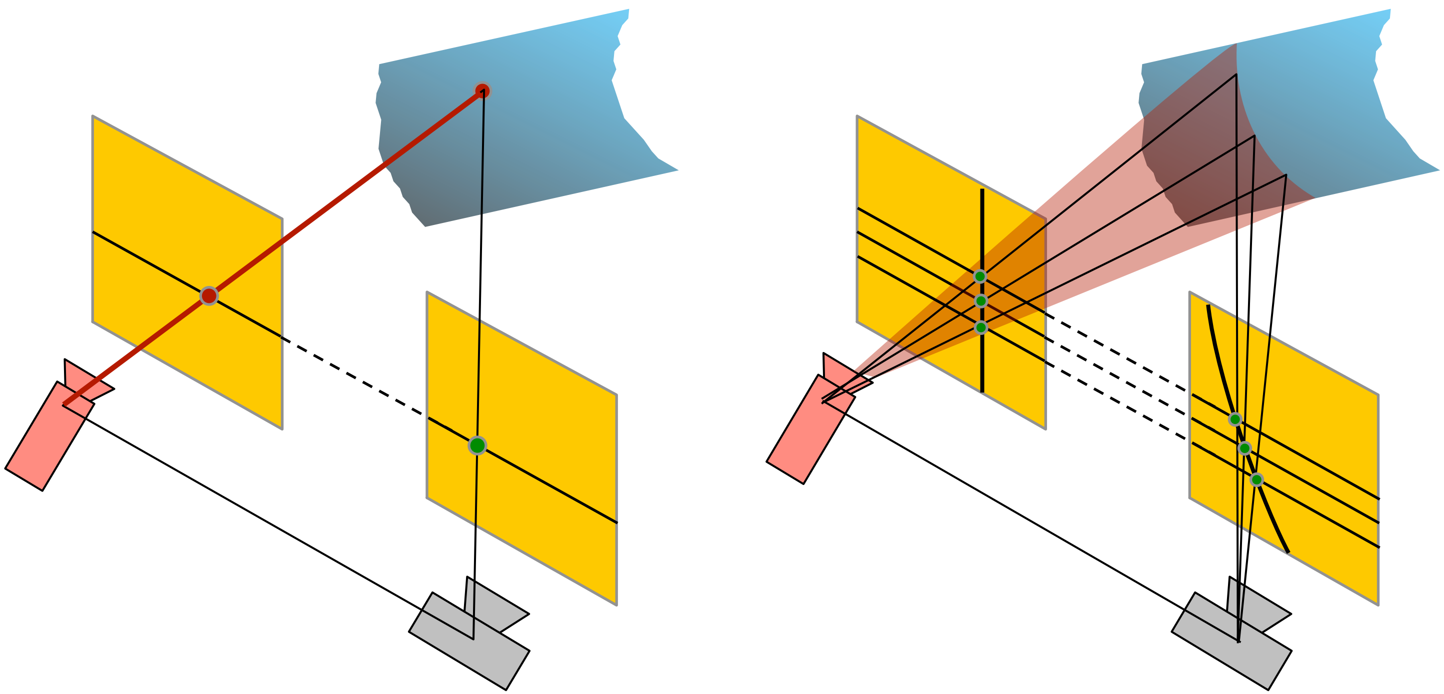
- Extension
  - for a calibrated camera rig, the epipolar geometry is known
  - can project a line instead of a single point
  - a lot fewer images needed (one for all points on a line)
  - the line intersects each epipolar line in one point

    → matching is still unique



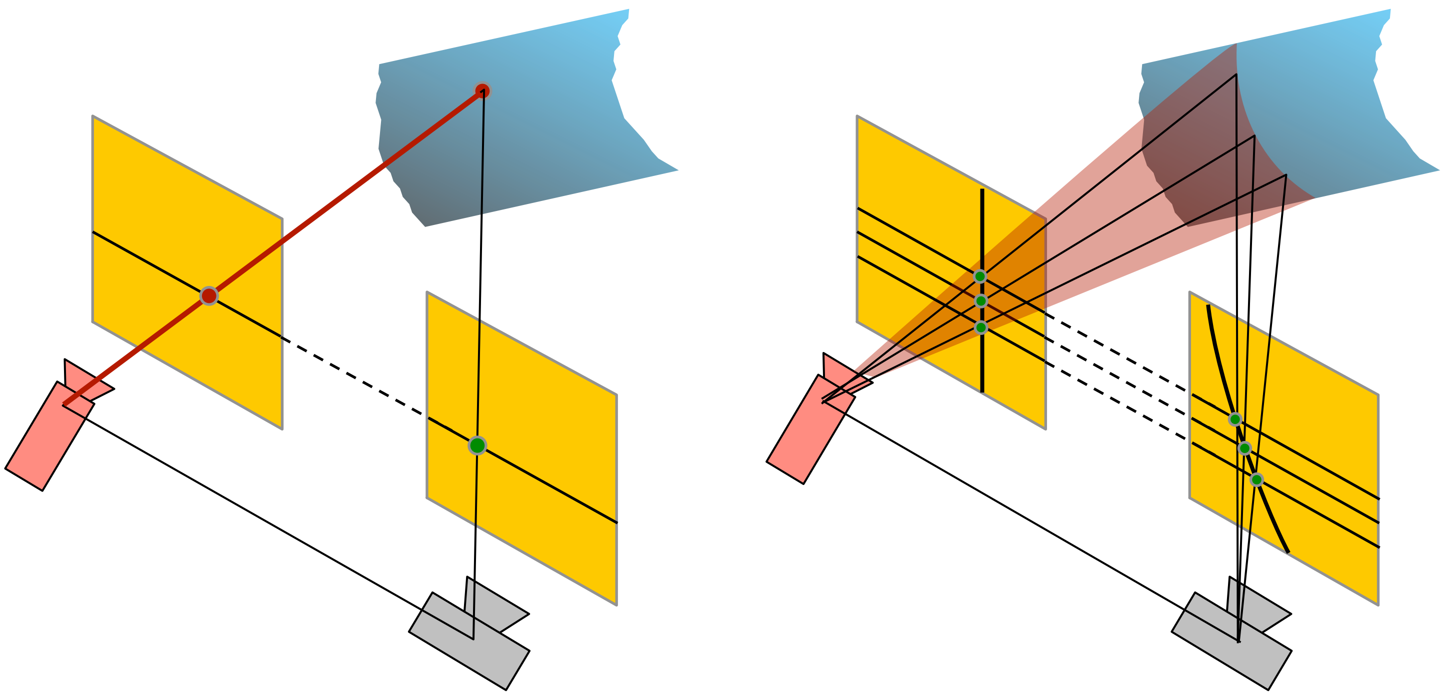
But we can do better

- Observation
  - a projector is just an inverse camera, ray direction is reversed
  - the projector is described by the same geometric model
  - projected pattern and image define two rays in space → projector and **one** camera are sufficient for triangulation



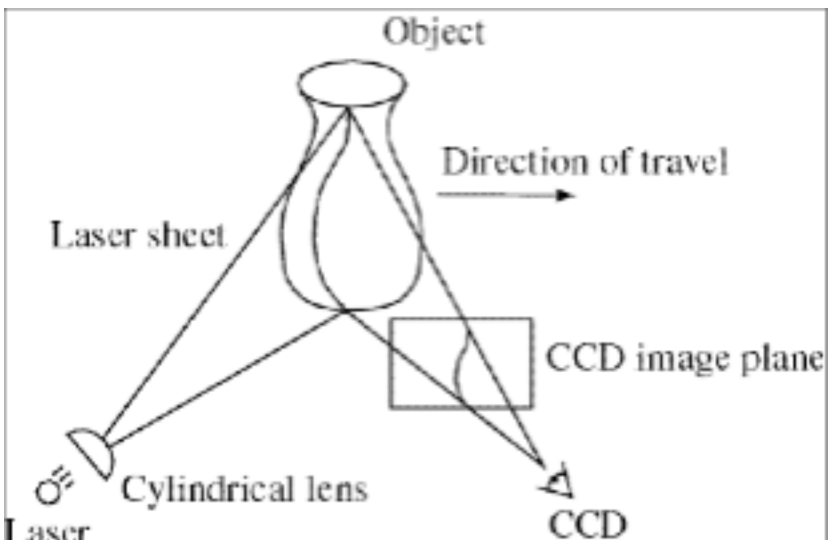
Calibrated projection

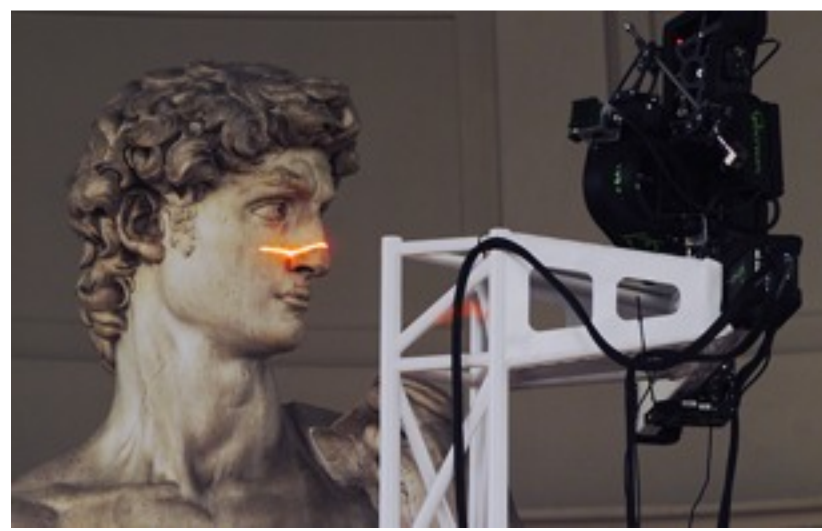
- Projector-camera system must be calibrated
  - (otherwise would not be able to triangulate)
  - the projected pattern is known
  - thus the depth depends only on the image point location
  - depth computation reduces to table-lookup



Laser stripe

- Line projection
  - shine a laser through a cylindrical lens
  - results in a planar sheet of light
- Example: the Digital Michelangelo Project
  - laser line rigidly mounted to camera
  - complete system is scanned across the object

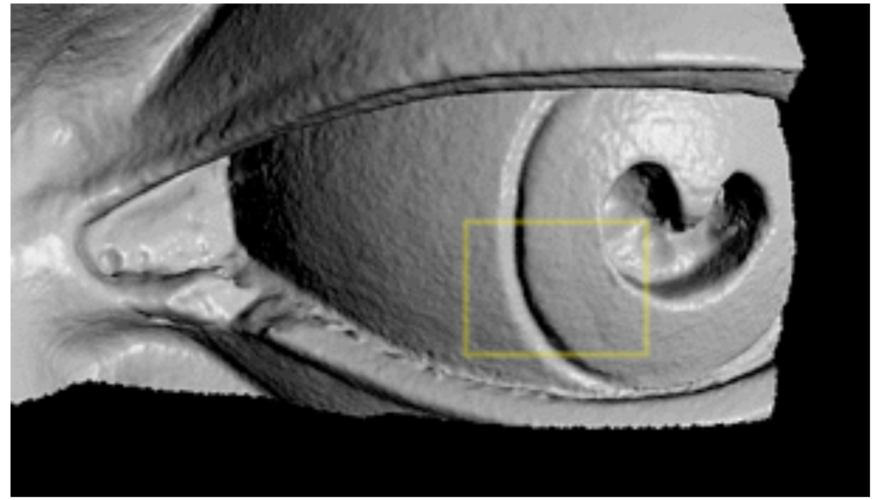


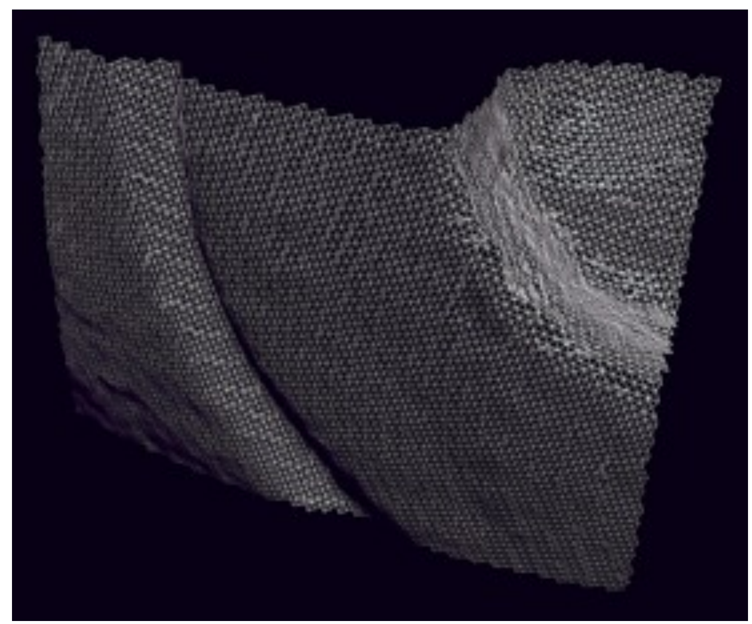


Digital Michelangelo Project

- http://graphics.stanford.edu/projects/mich

Digital Michelangelo Project



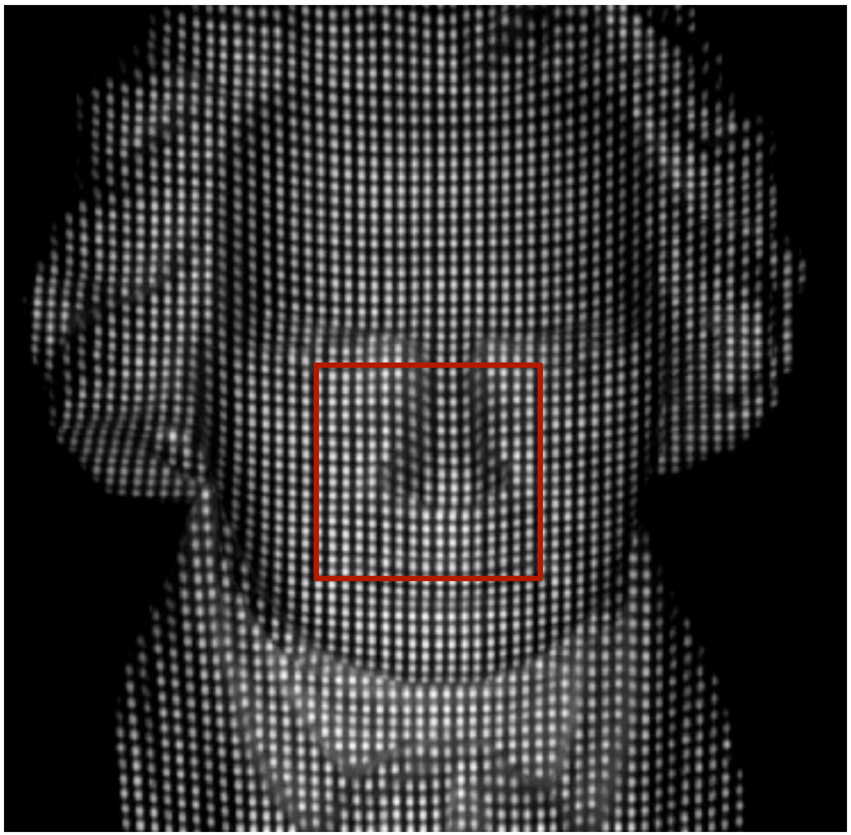


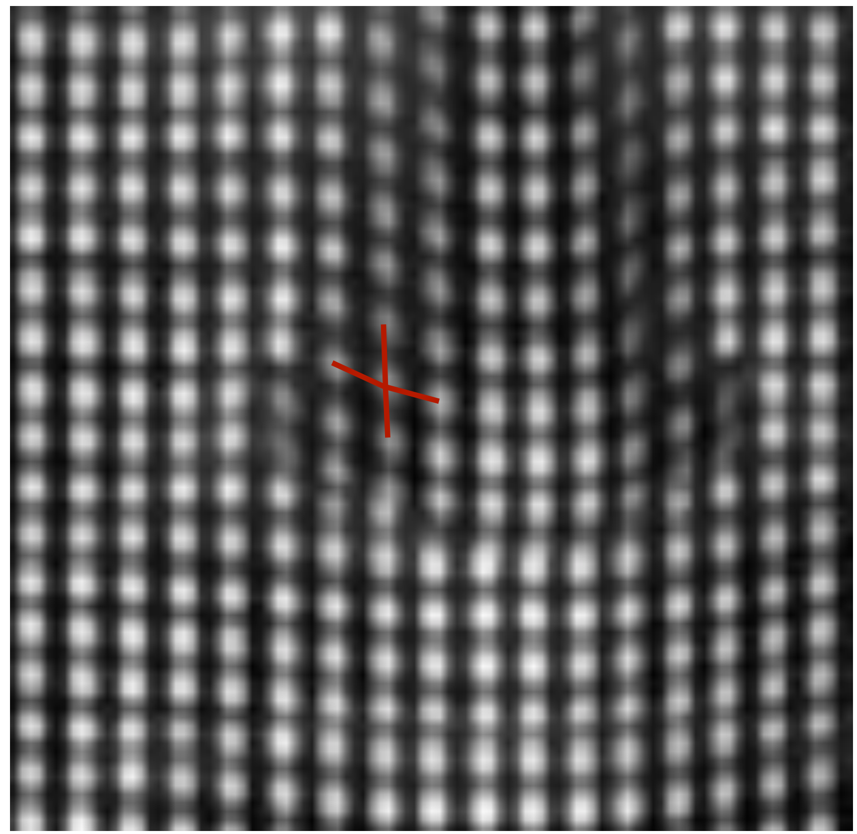
Pattern projectors

- Project multiple stripes or a grid
  - avoids scanning, respectively taking multiple images
  - only a single image is required to cover the scene
  - ... but stripes/grid points are no longer unique
  - **Which stripe matches which?** ... the correspondence problem again

Pattern projectors

- Answer 1: assume surface continuity
  - ... the ordering constraint, as in conventional stereo





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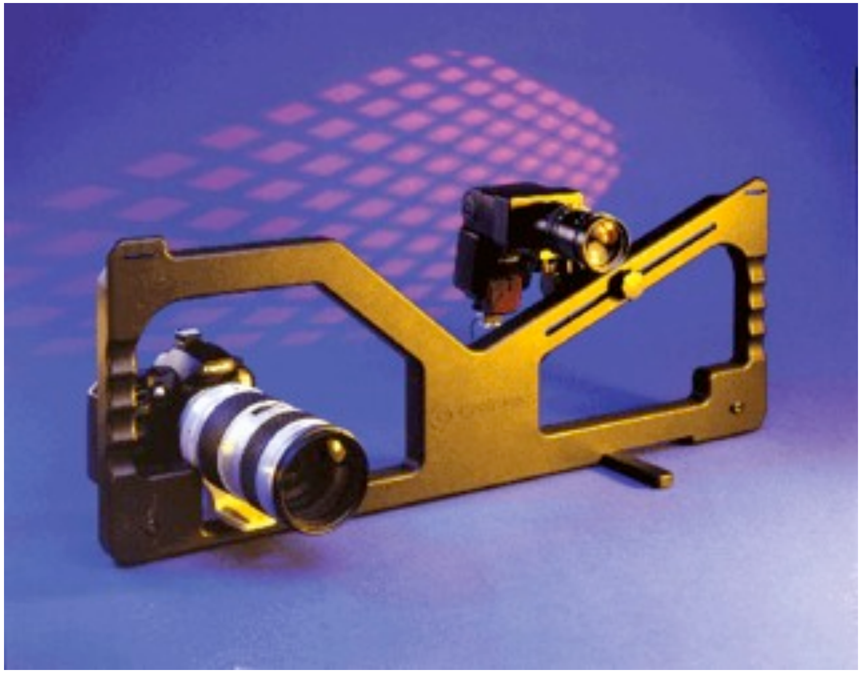
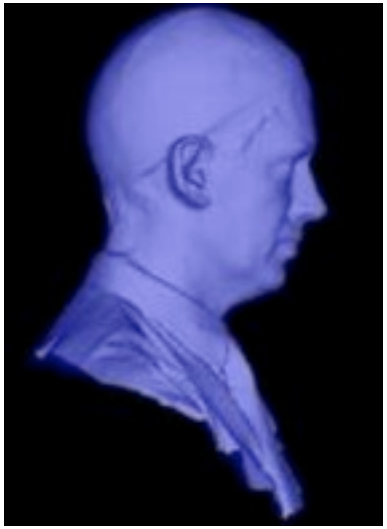
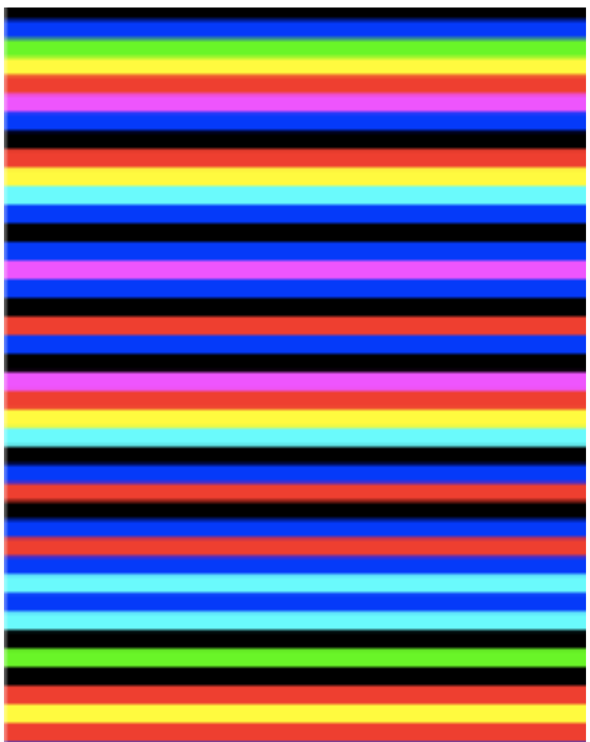
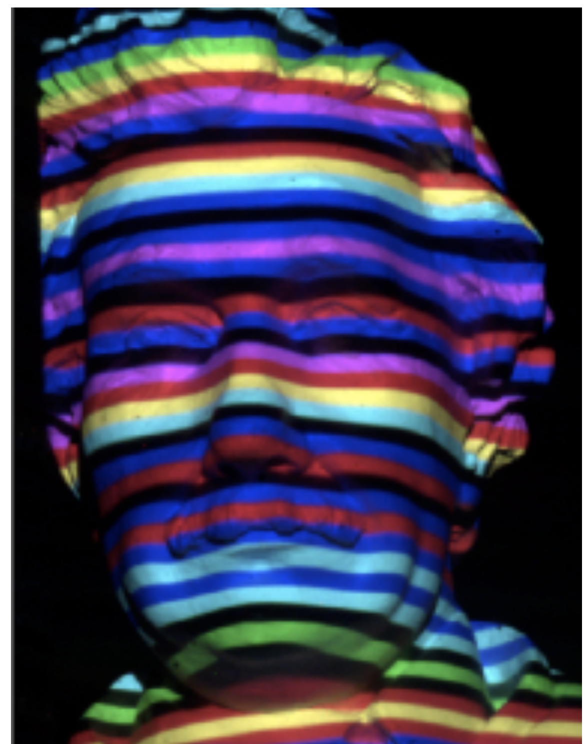




Pattern projectors

- Answer 2: coloured stripes or dots
  - can be designed such that local patterns are unambiguous (c.f. bar-codes)
  - difficult to use for coloured surfaces





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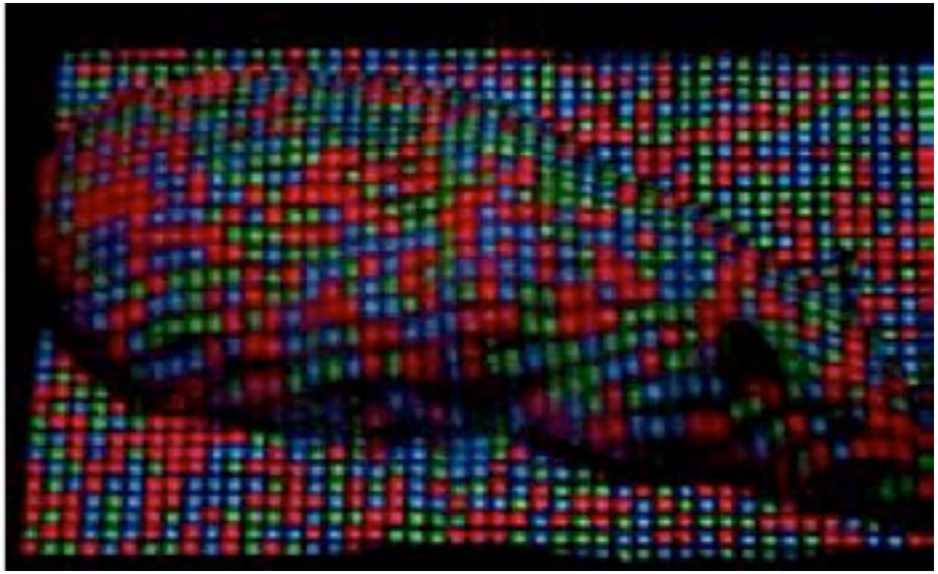
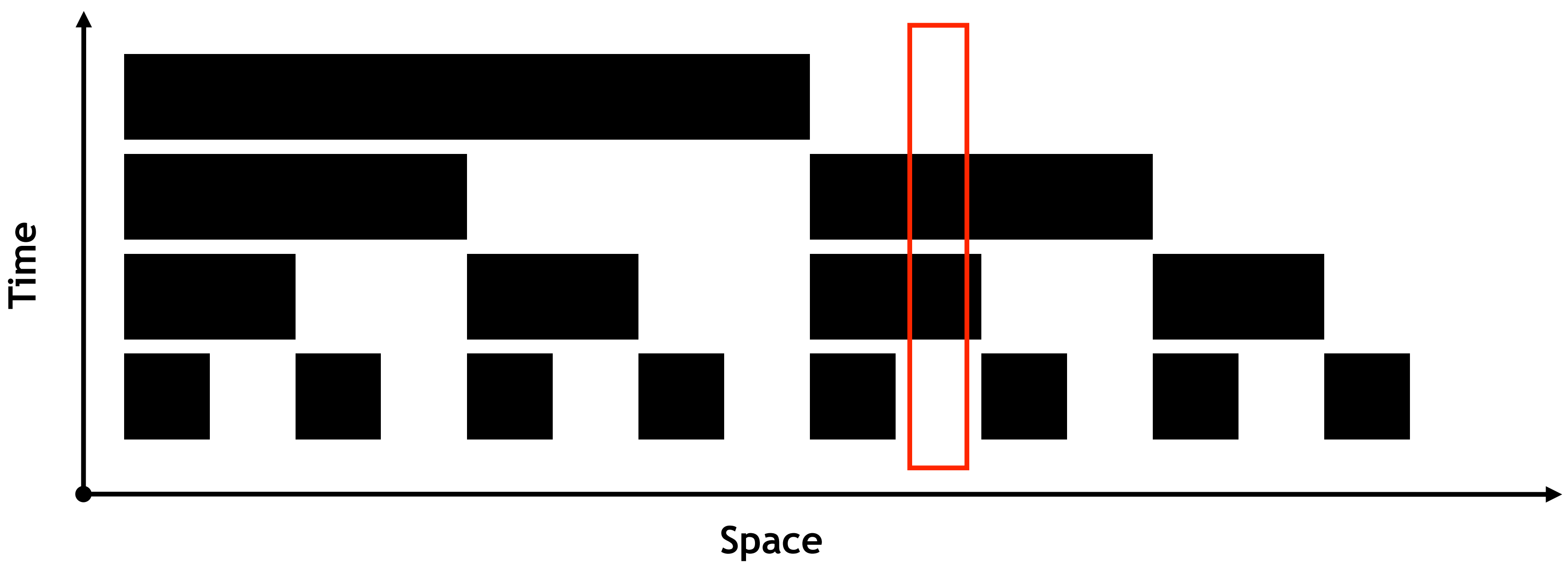


Multi-stripe Projectors

- Answer 3: time-coded light patterns
  - “best compromise” between single stripes and stripe pattern
  - Use a sequence of binary patterns $\rightarrow (\log N)$ images
  - Each stripe has a unique binary illumination code



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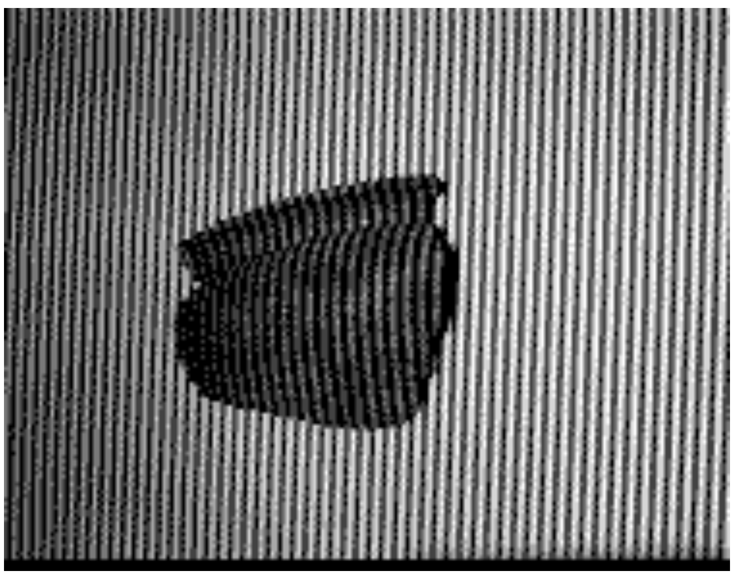
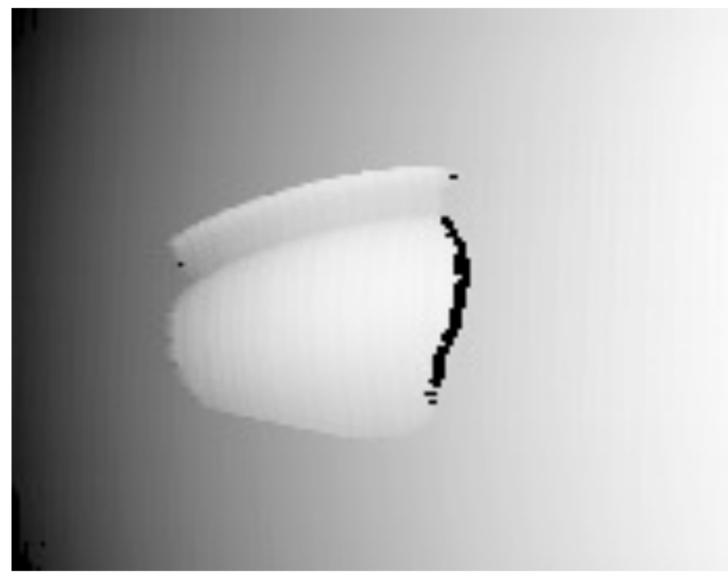
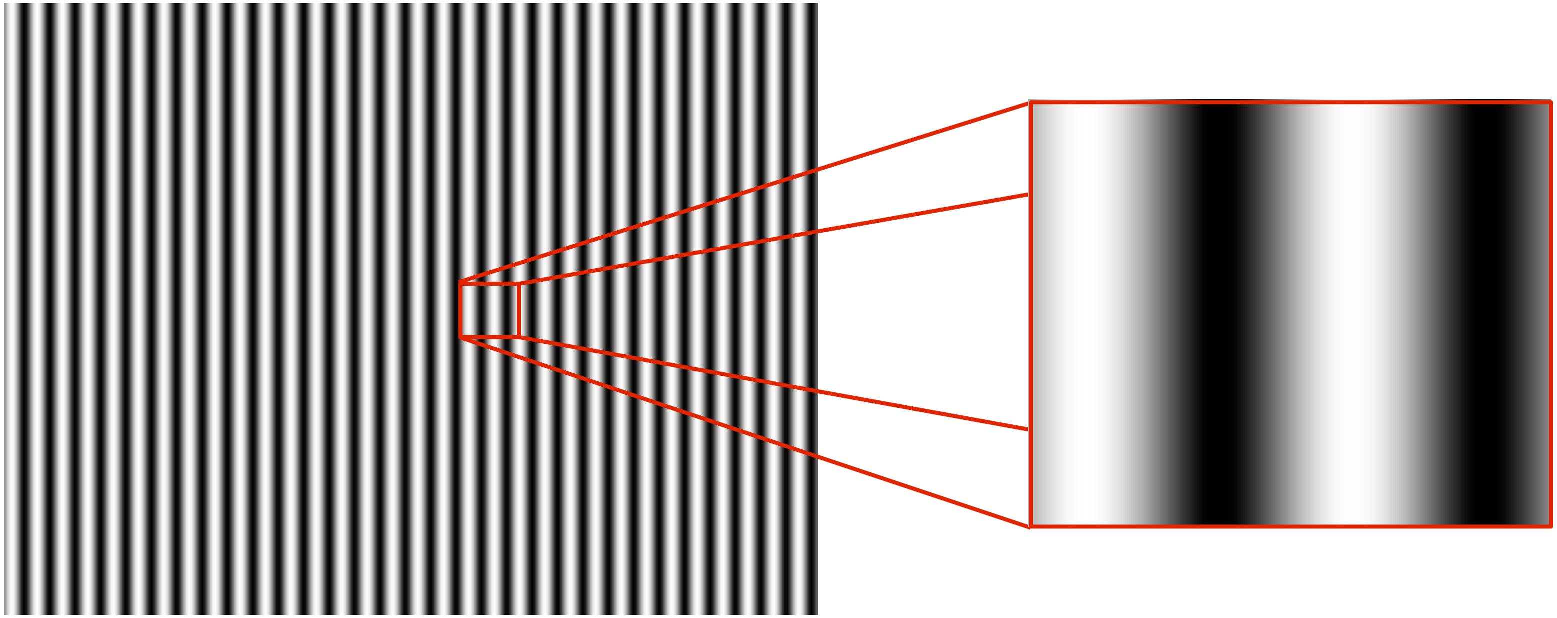




Phase-shift projection

- 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-shift projection

- 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

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

$$I_0 = I_{base} + I_{var} \cos(\phi)$$

$$I_+ = I_{base} + I_{var} \cos(\phi + \theta)$$

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➡ removed dependence on I_{base}

➡ removed dependence on I_{var}

$$\frac{I_- - I_+}{2I_0 - I_- - I_+} = \frac{I_{base} + I_{var}\cos(\phi - \theta) - I_{base} - I_{var}\cos(\phi + \theta)}{2I_{base} + 2I_{var}\cos\phi - I_{base} - I_{var}\cos(\phi - \theta) - I_{base} - I_{var}\cos(\phi + \theta)}$$

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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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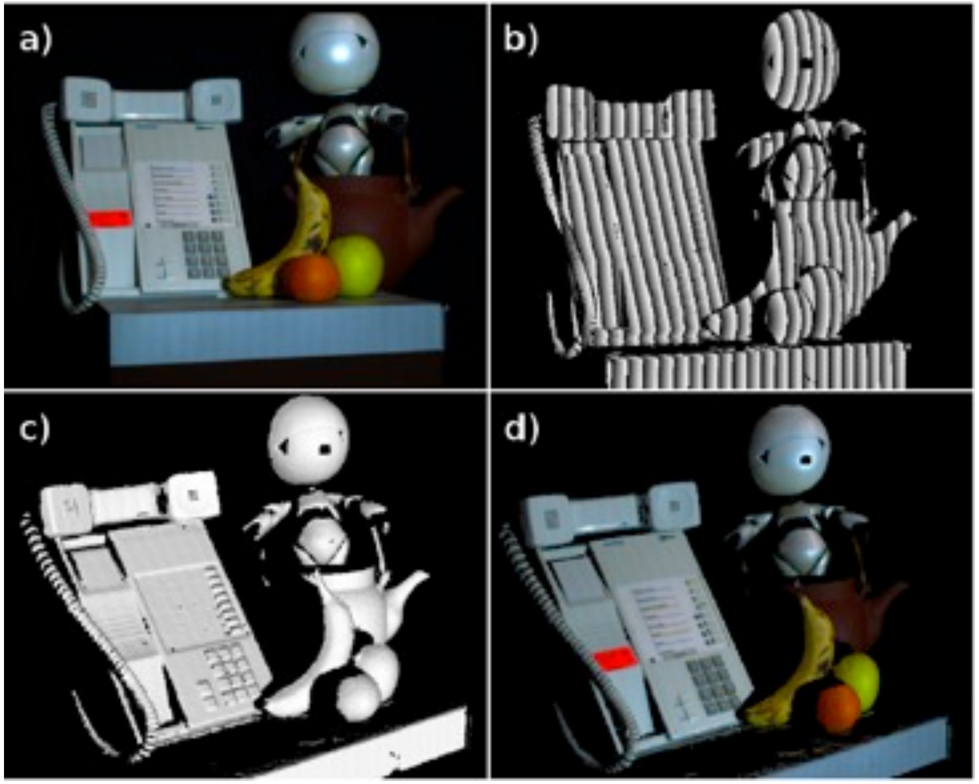
phase angle

$$\frac{I_- - I_+}{2I_0 - I_- - I_+} = \frac{\tan(\phi)}{\tan(\theta/2)}$$

$$\phi'(0, 2\pi) = \arctan\left(\tan\left(\frac{\theta}{2}\right)\frac{I_- - I_+}{2I_0 - I_- - I_+}\right)$$

Phase-shift projection

- 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



Phase-shift projection

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

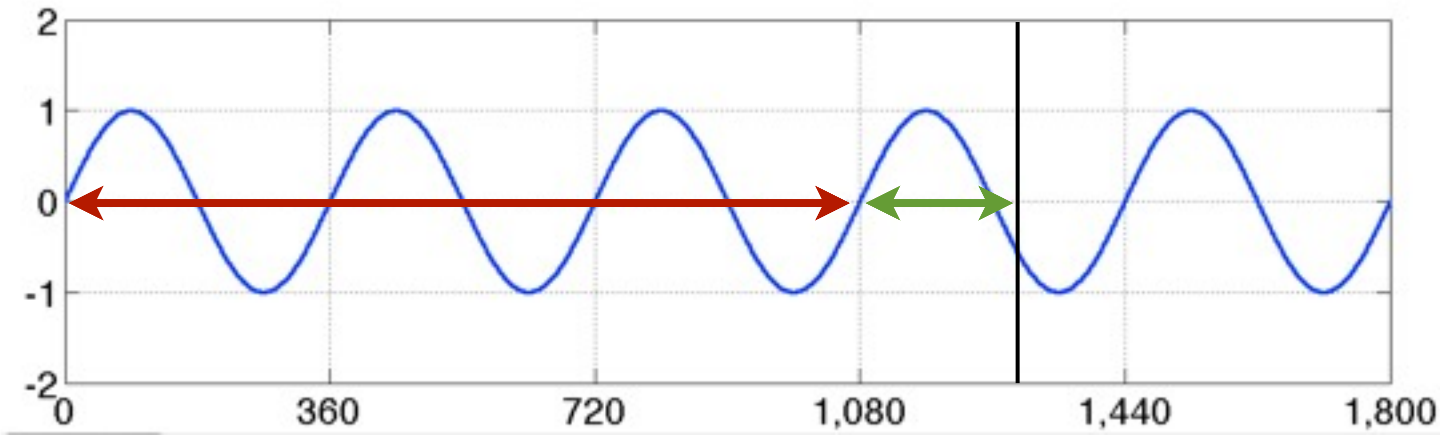
absolute phase

$$\phi(x,y) = 2\pi\, k(x,y) + \phi'(x,y) \qquad k \in [0 \ldots N - 1]$$

from stereo — $k(x,y)$

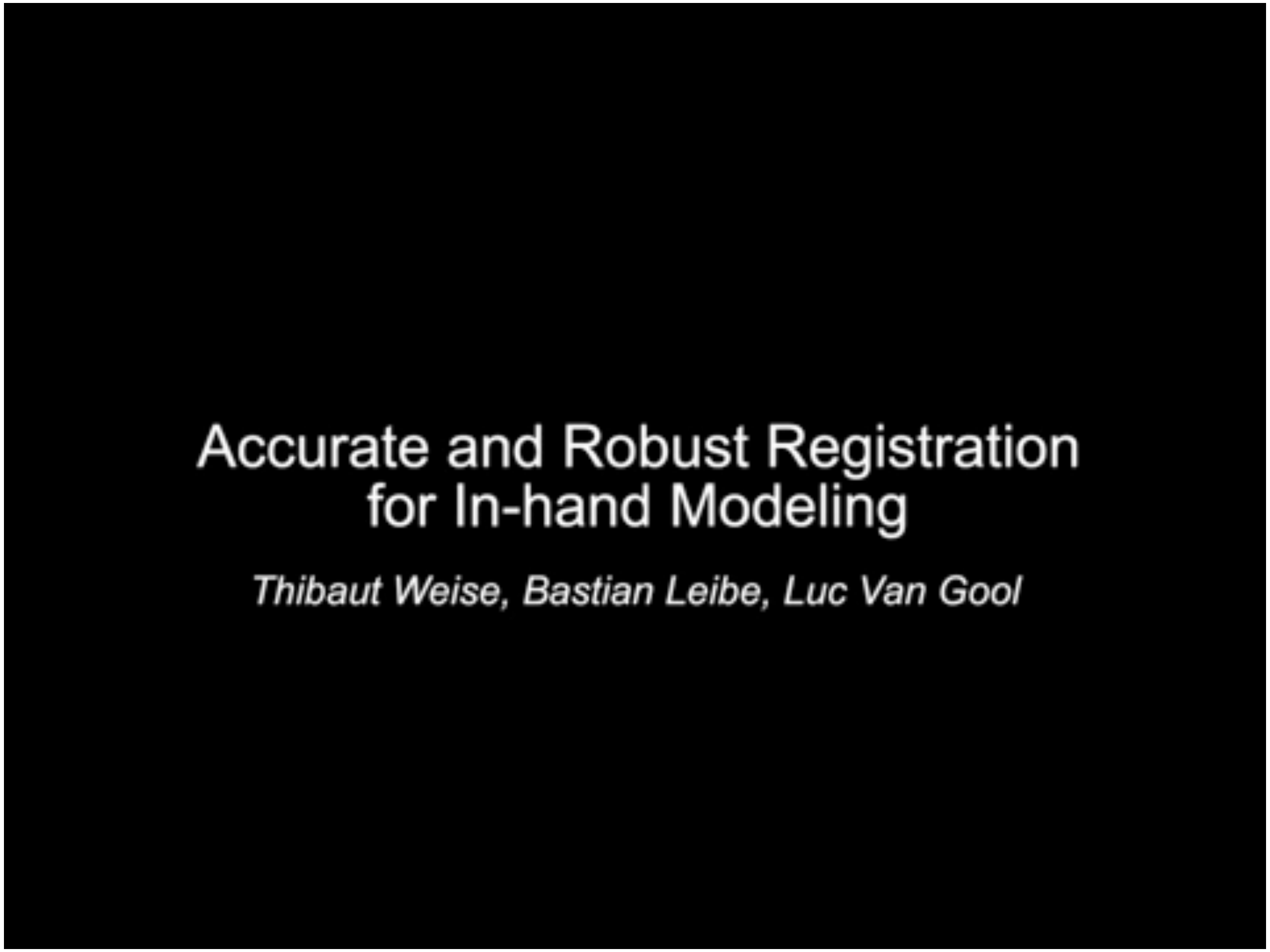
from phase-shift — $\phi'(x,y)$

number of periods (stripes) — N



Phase-shift Projection

- Realtime in-hand scanning



Simple stripe projector

- Quite accurate systems surprisingly cheap
  - **`http://www.david-laserscanner.com`**
  - cost <100 CHF:
    webcam, handheld line-laser, calibration board
  - software freely available from TU Braunschweig

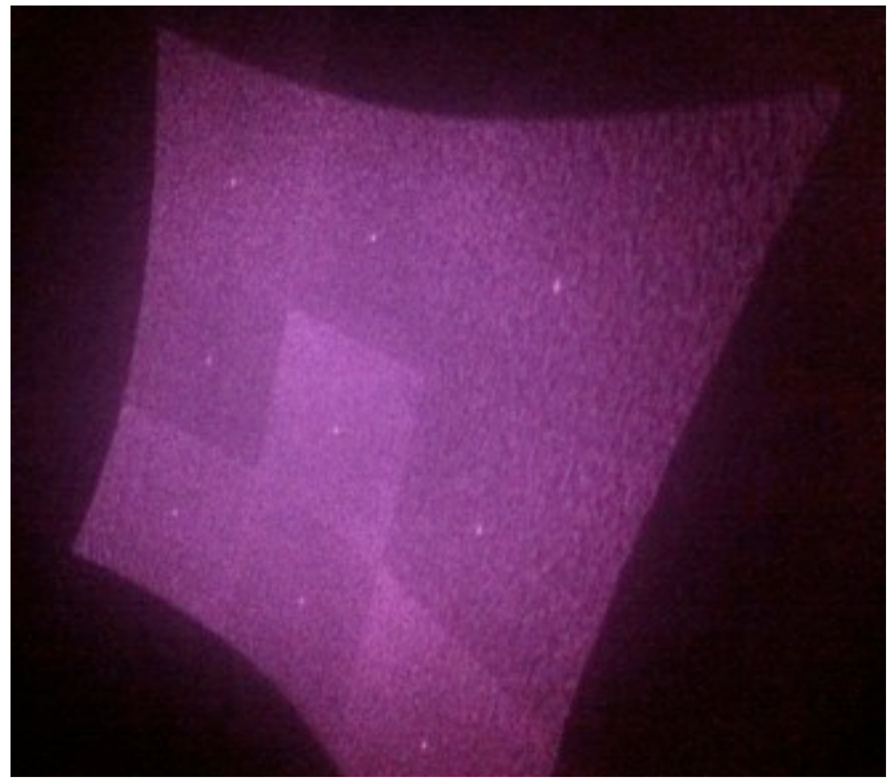
Industrial systems

- Many vendors
  - big business - maybe **the** success story of image-based metrology



Consumer application

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



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
  - ...