# Structured Lighting

Guido Gerig

CS 6320, 3D Computer Vision

Spring 2013
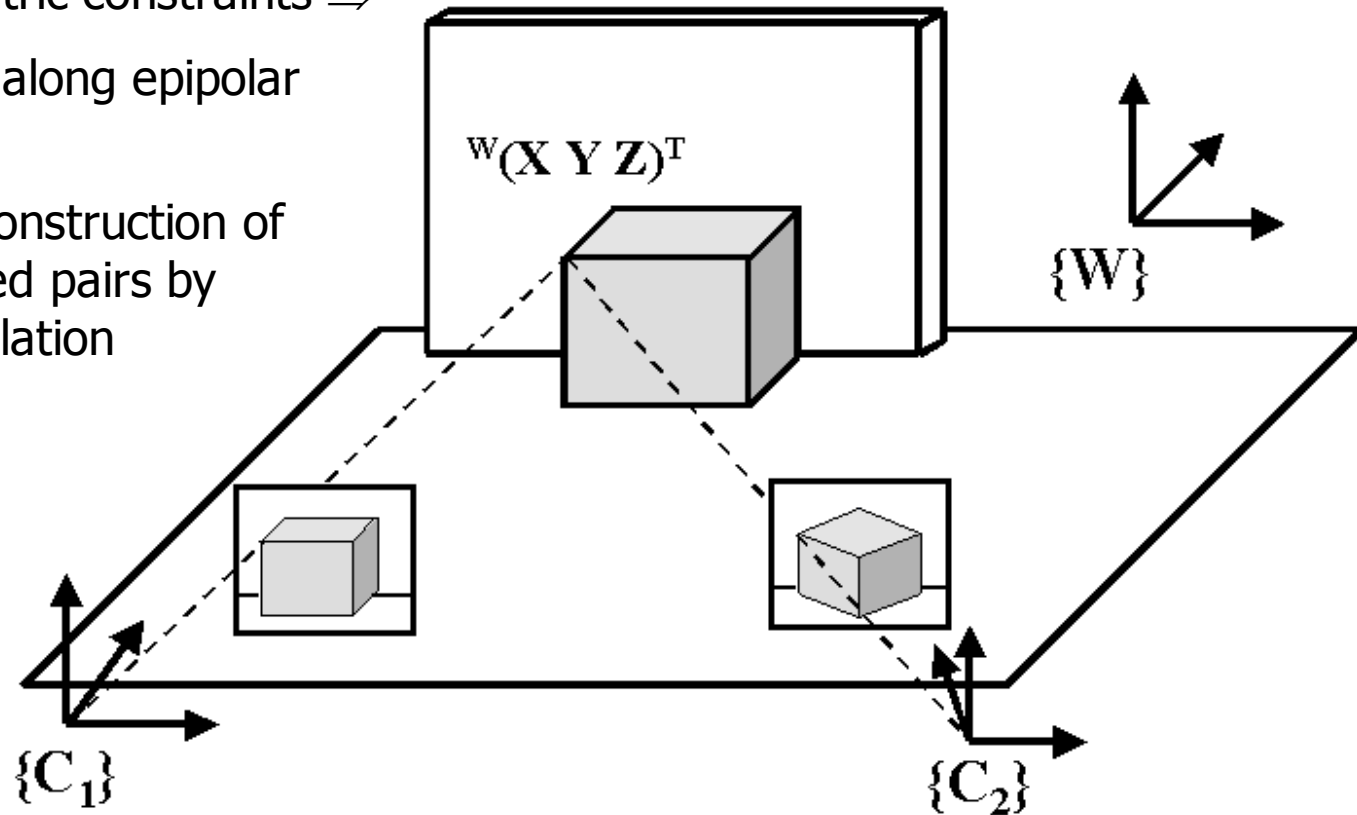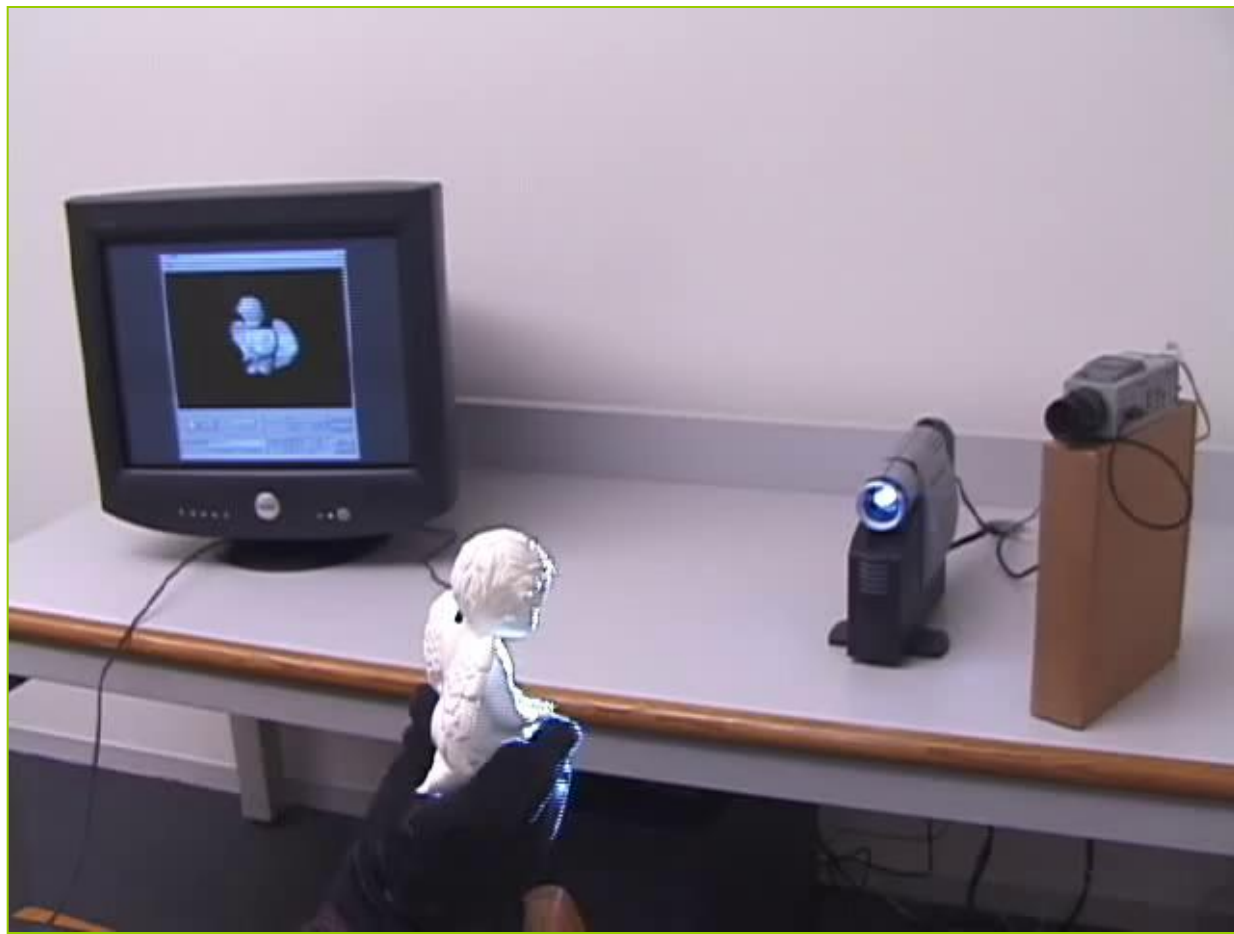
# Passive triangulation: Stereo vision

- Correspondence problem

- Geometric constraints $\Rightarrow$

  search along epipolar lines

- 3D reconstruction of matched pairs by triangulation

$^W(X\ Y\ Z)^T$

$\{W\}$

$\{C_1\}$

$\{C_2\}$

# Real-Time 3D Model Acquisition



Link:

http://graphics.stanford.edu/papers/rt_model/

http://graphics.stanford.edu/papers/rt_model/

The SIGGRAPH Paper:
Full paper as PDF.
One-page abstract and Figure 1 as PDF.
Two-page abstract and Figure 1 as PDF.
A 5-minute video describing the system:
AVI file, 640 x 480 pixels (19MB)
RealVideo stream, 640 x 480 pixels, 1536 kbs
RealVideo stream, 320 x 240, 56 - 904 kbs
SIGGRAPH 2002 talk:
Talk as PPT
Embedded video clip: sig02_begin_m.avi
Embedded video clip: sig02_recap.avi
Embedded video clip: turtle2.avi

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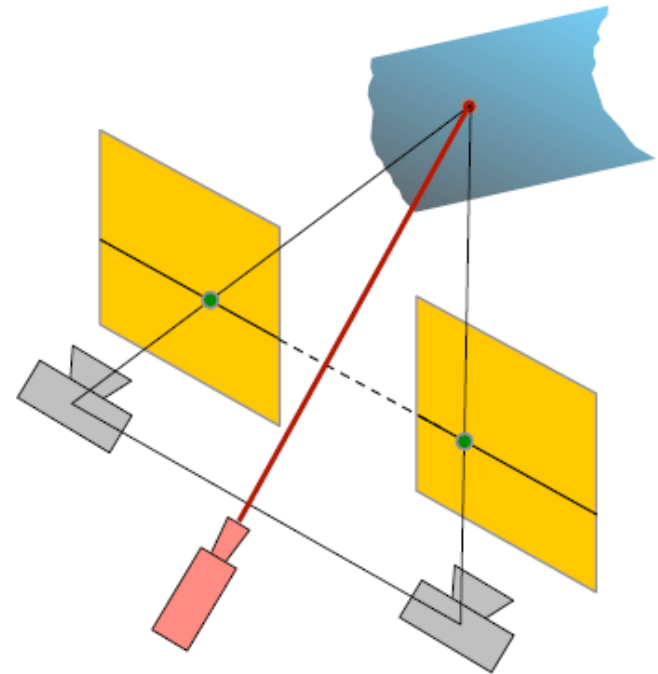
  - **Note**: less sophisticated variants include dusting surfaces with chalk, spraying them with water, etc.

# Special Case: Light Spot Stereo



**Figure 9.5:** General arrangement for a method based on light spot stereo analysis.
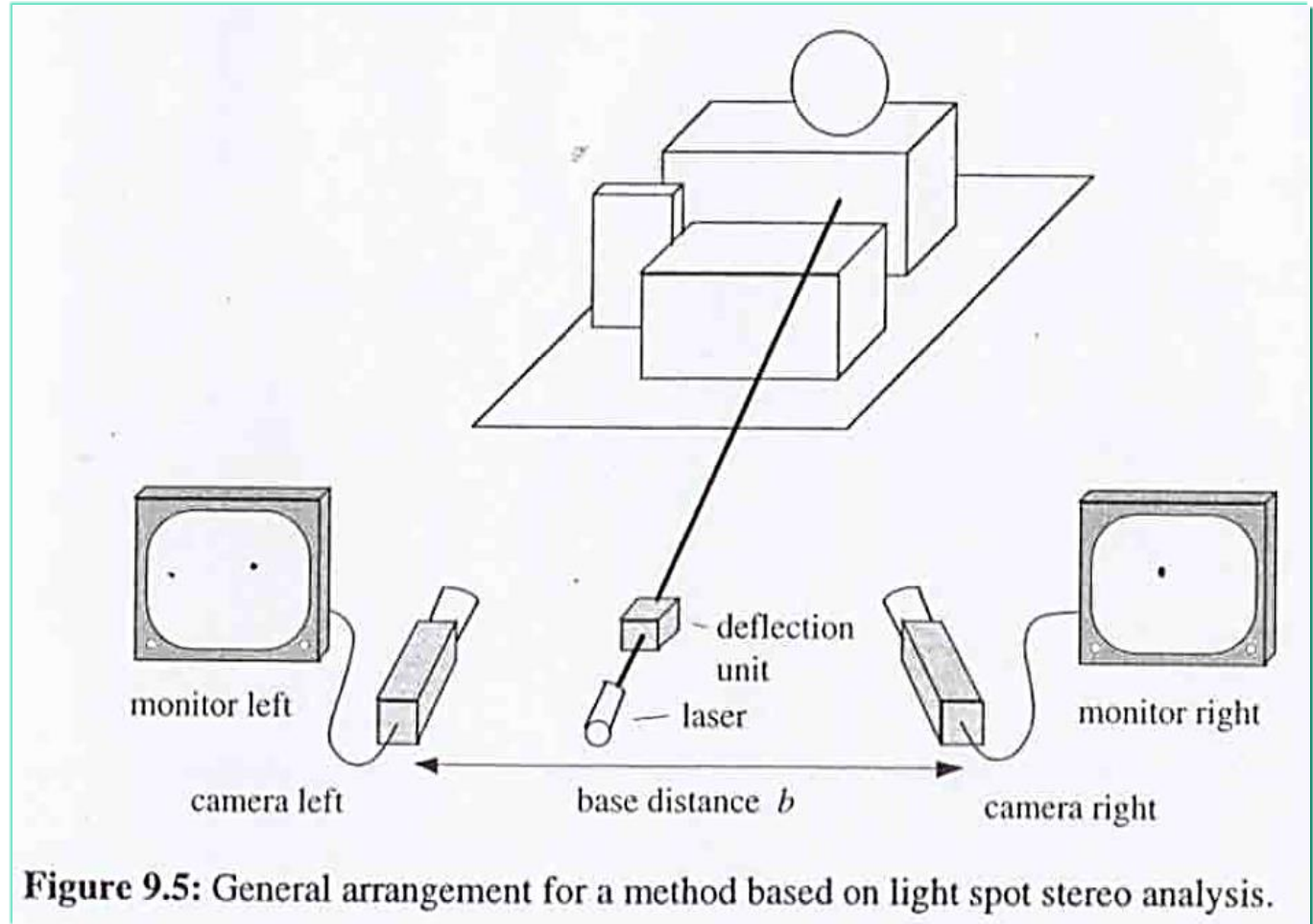
Calibrated Cameras: Detection of spot in left and right cameras fully determines its 3D location. Spot to be scanned across scene.

# 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)
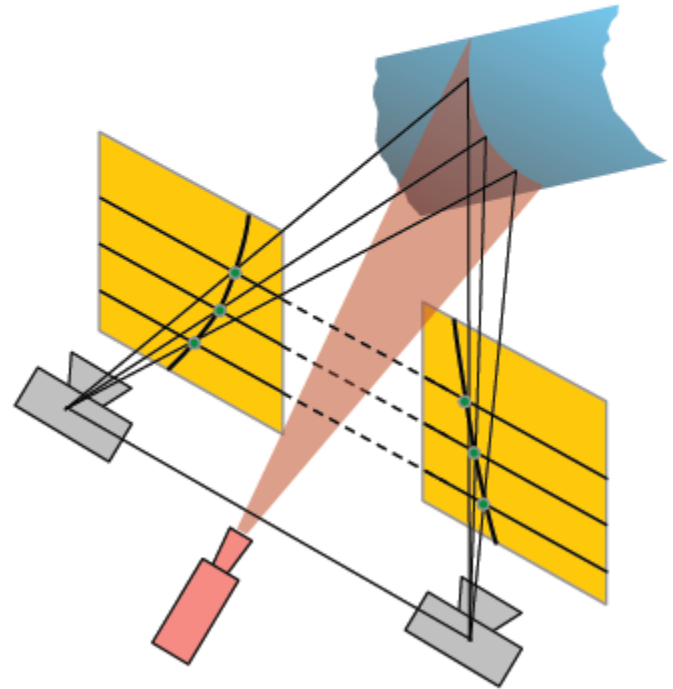  - more on this later
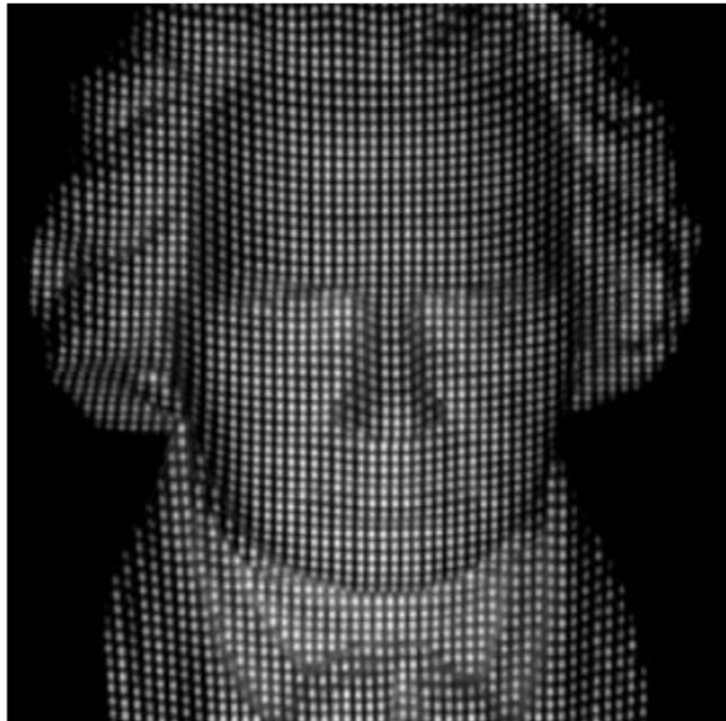
# Line Projection

- **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
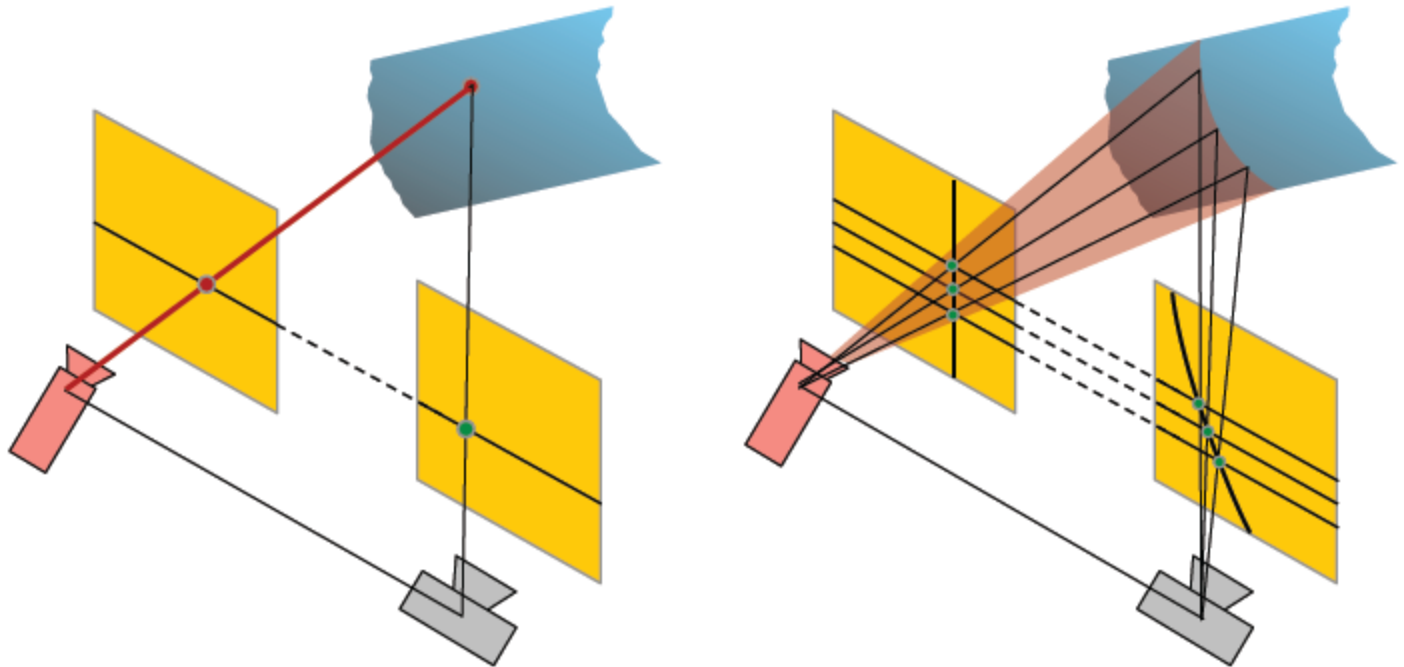    - → matching is still unique

# 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
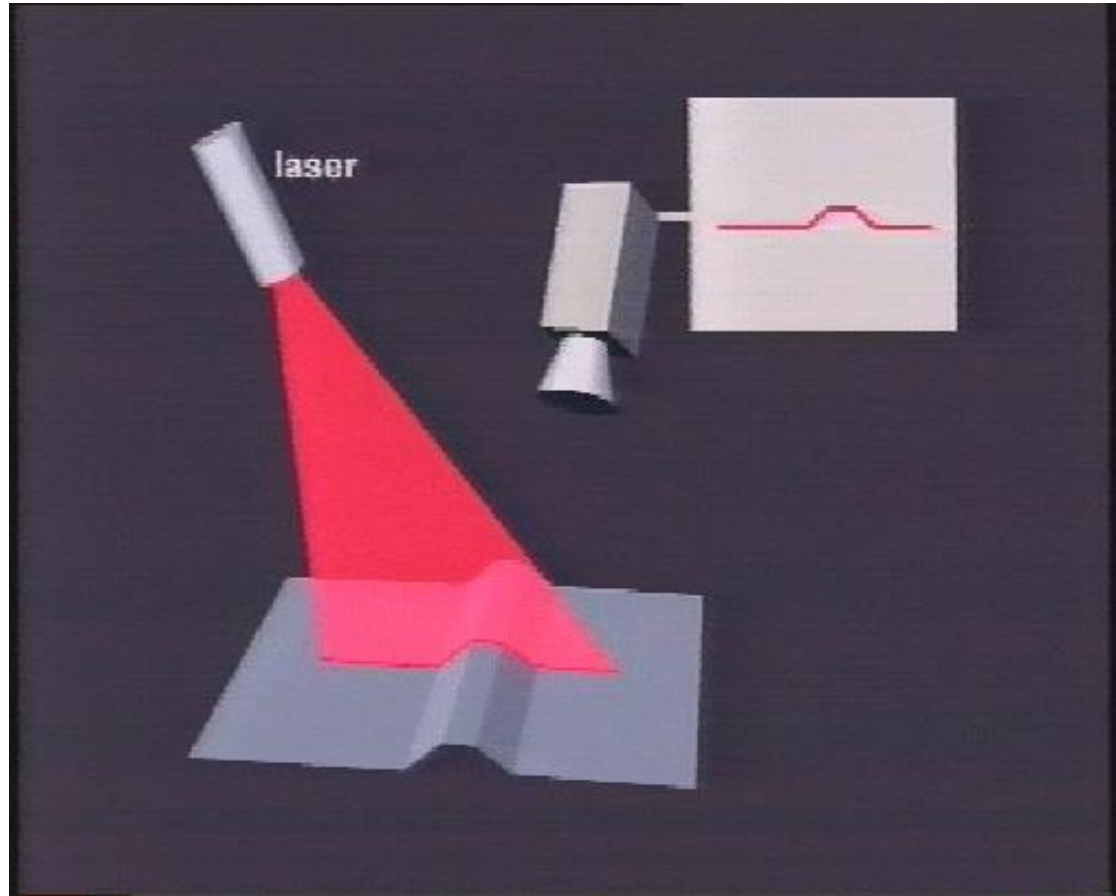
# Calibrated Projection

- 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
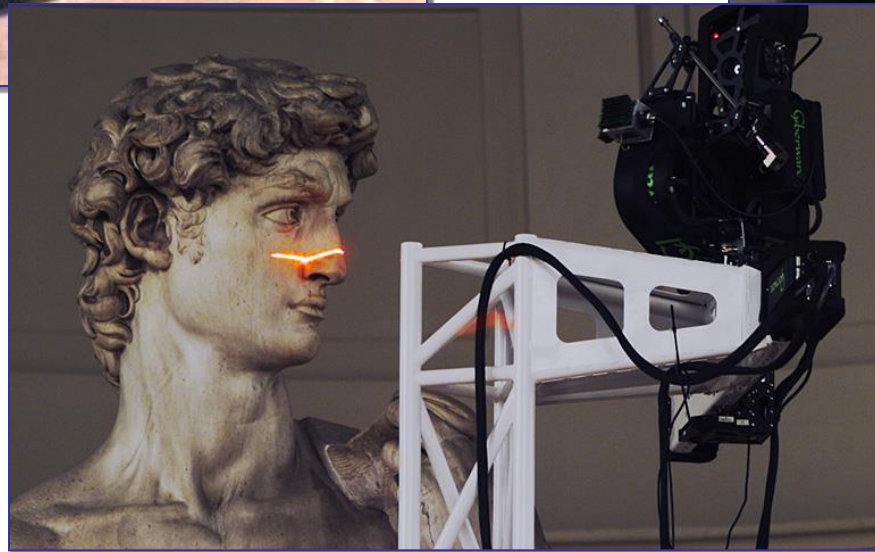    - depth computation reduces to table-lookup
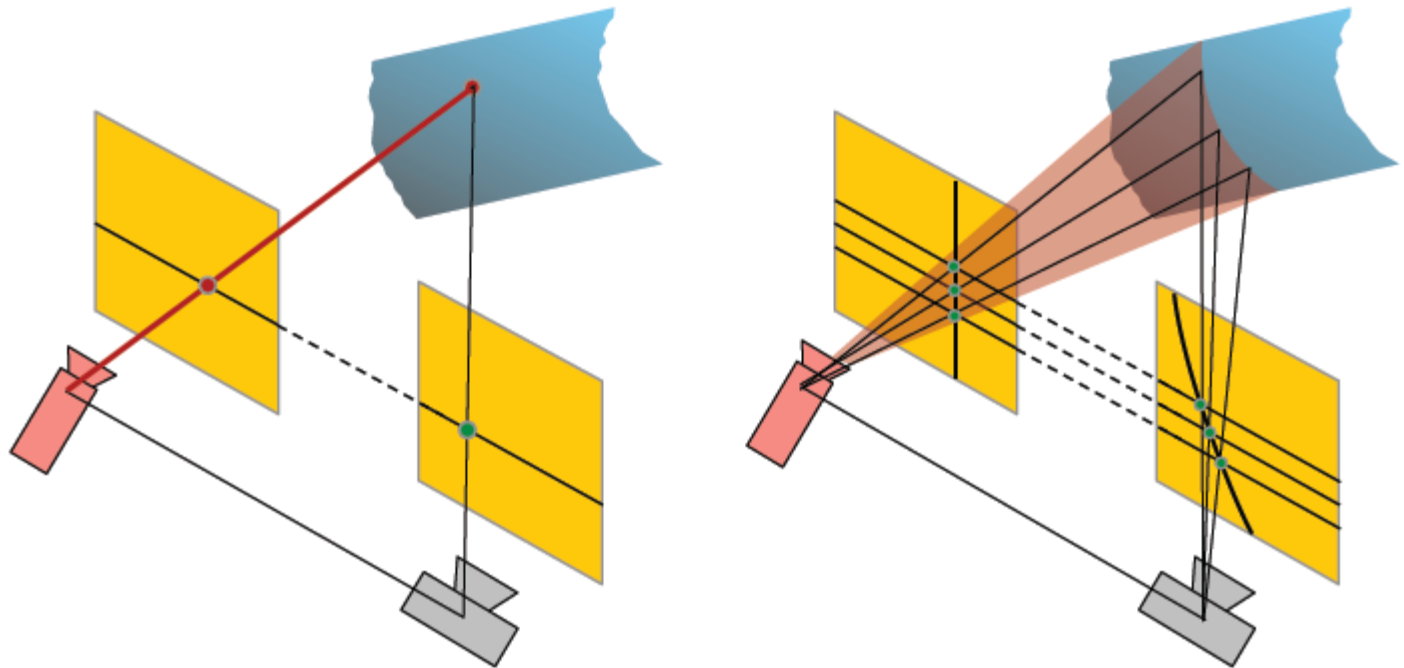
# Concept: Active Vision



Active manipulation of scene: Project light pattern on object. Observe geometry of pattern via camera → 3D geometry

# 3D Scanning

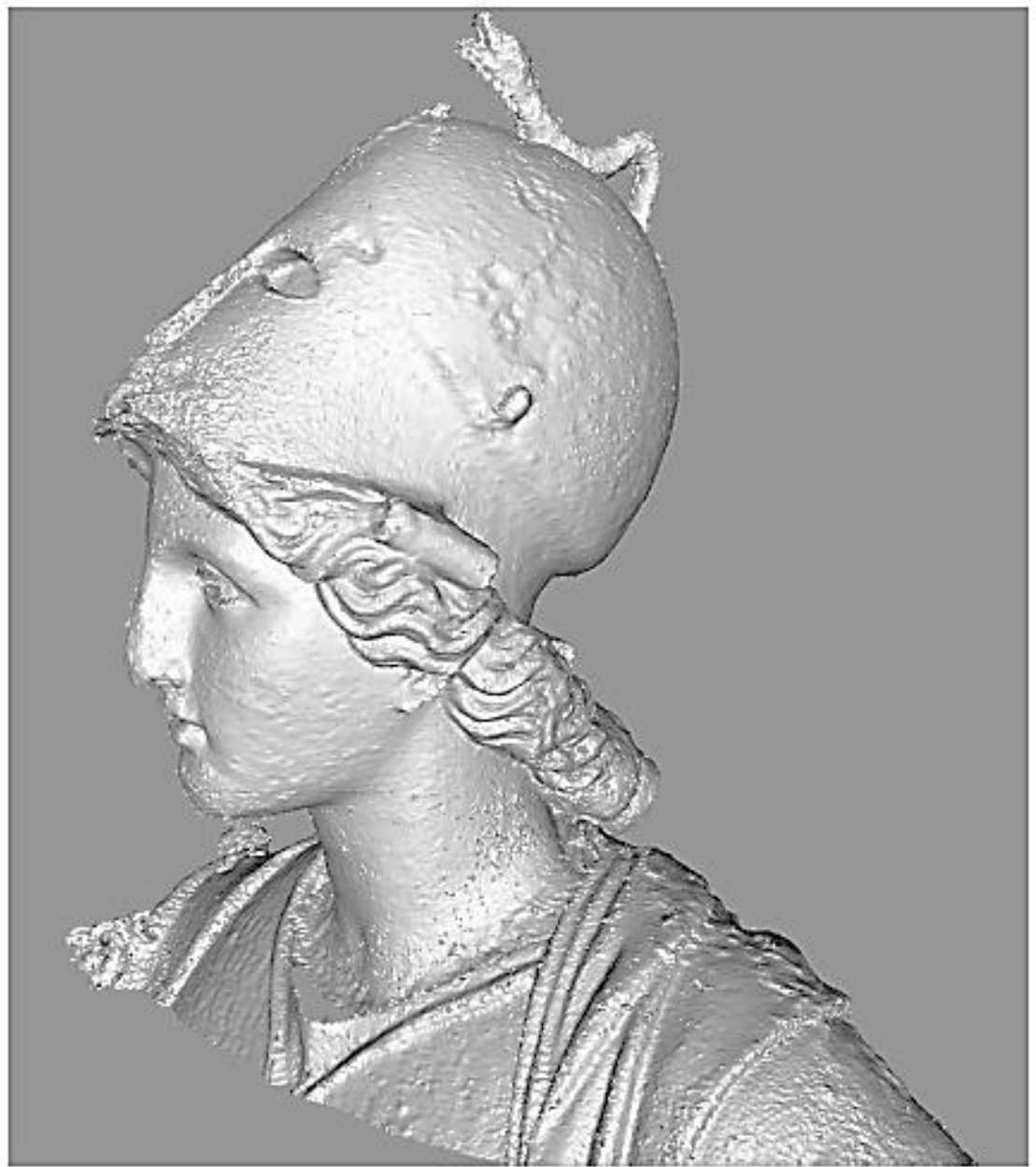Courtesy S. Narasimhan, CMU

# Typical Application



**Figure 10:** *The Minerva statue; note the corrosion of the bronze surface (pre-restoration status).*



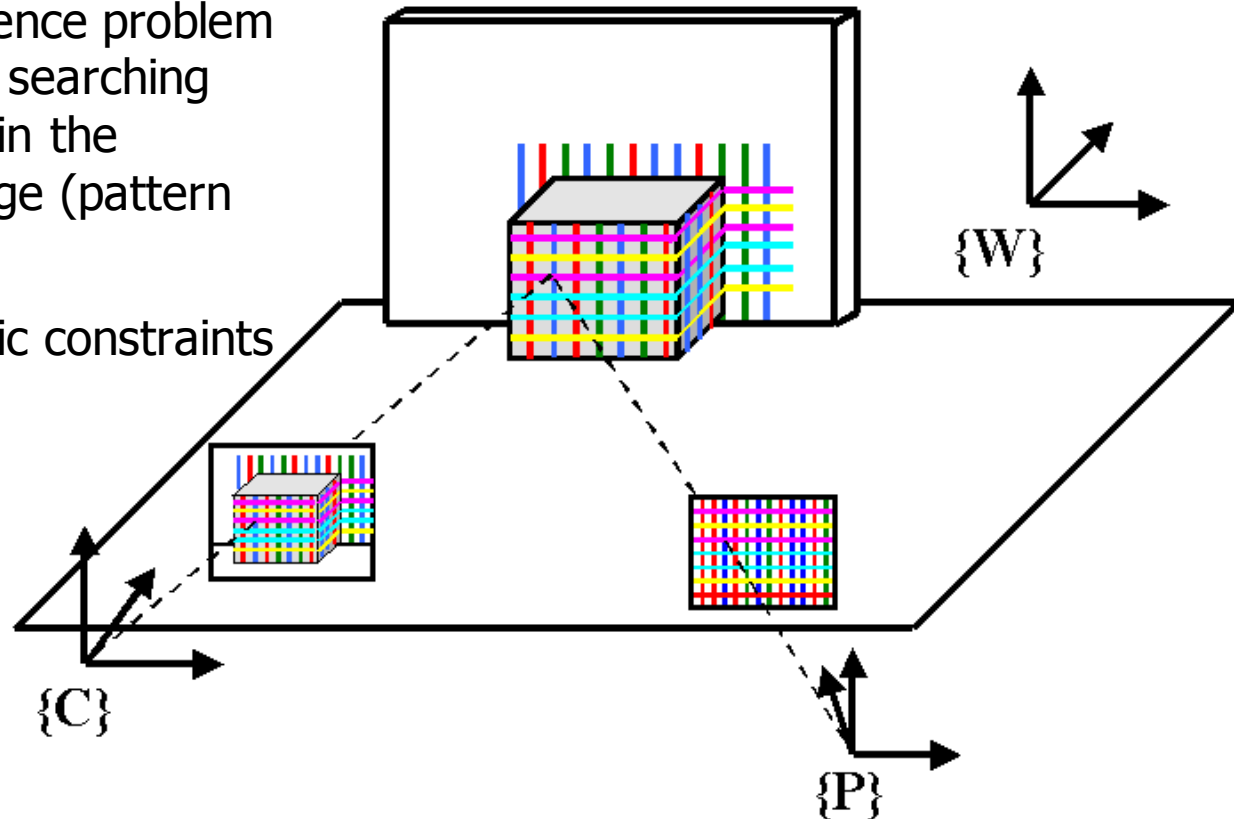**Figure 11:** *A digital model of the Minerva (simplified down to 1,034,029 faces).*

**Figure 12:** *The Minerva head section (simplified down to 1,094,368 faces).*

# 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

# Overview



- Background
- General Setup
- Light Point Projection 2D and 3D
- Light Stripe Projection
- Static Light Pattern Projection
  - Binary Encoded Light Stripes
  - Segmenting Stripes
- 3D Photography on Your Desk

# General Setup

- one camera
- one light source
  - types
    - slide projector
    - laser
  - projection
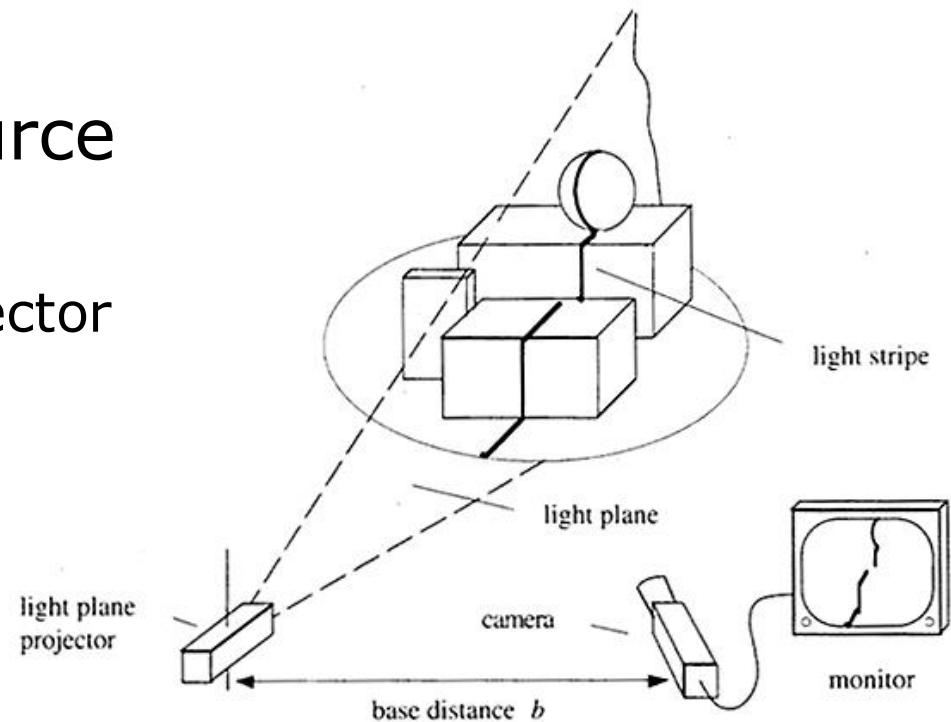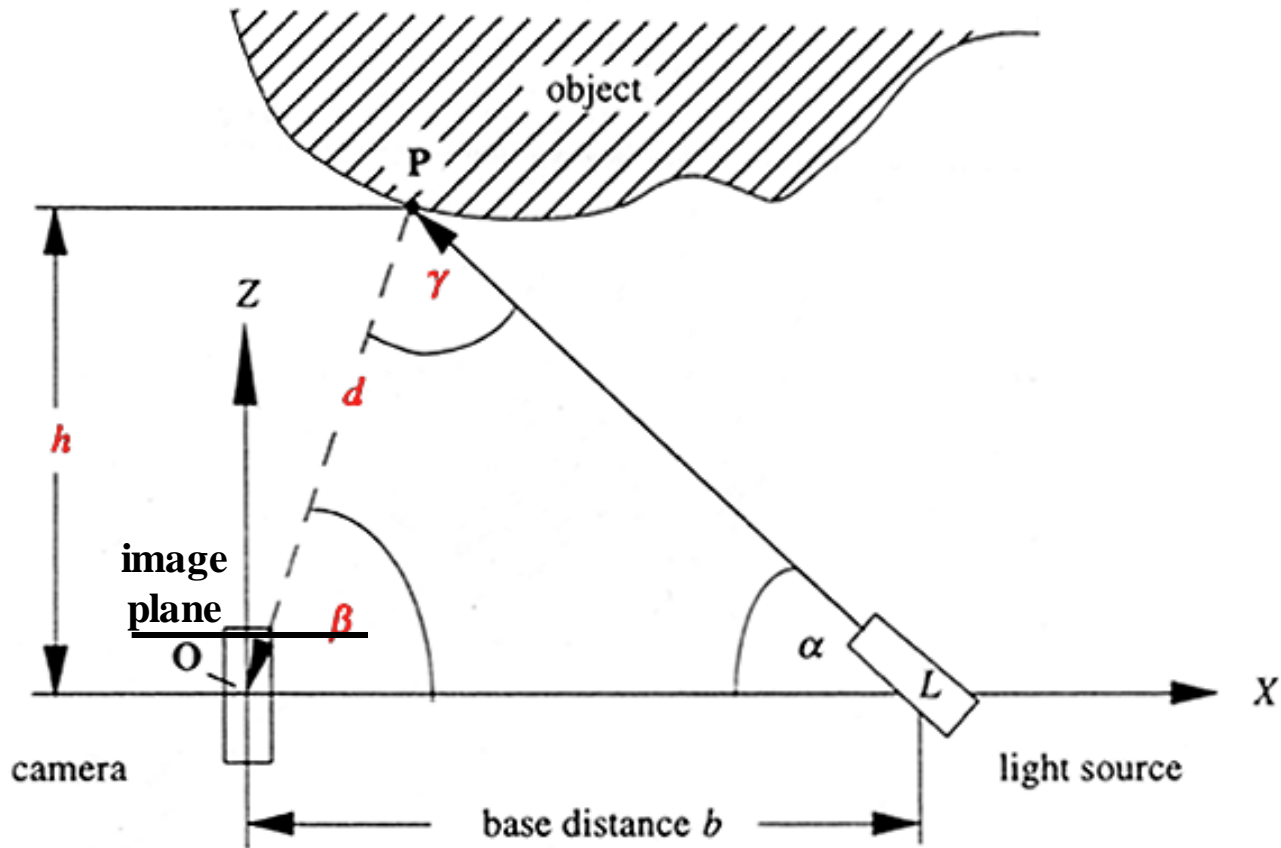    - spot
    - stripe
    - pattern



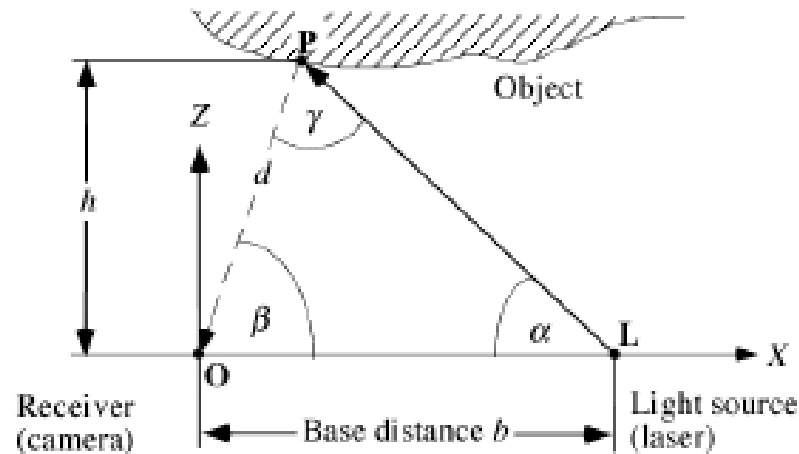Figure 9.6: Image acquisition set-up for the light stripe projection technique.

# Light Spot Projection 2D

Assume point-wise illumination by laser beam, only 2D

# Light Spot Projection 2D



O, L, and P define a triangle, and we determine the position of P by *triangulation*, using basic formulas about triangles such as the law of sines:

$$\frac{d}{sin(\alpha)} = \frac{b}{sin(\gamma)}.$$

From $\gamma = \pi - (\alpha + \beta)$ and $sin(\pi - \gamma) = sin(\gamma)$ it follows that

$$\frac{d}{sin(\alpha)} = \frac{b}{sin(\pi - \gamma)} = \frac{b}{sin(\alpha + \beta)}.$$

Thus, the distance $d$ is given as
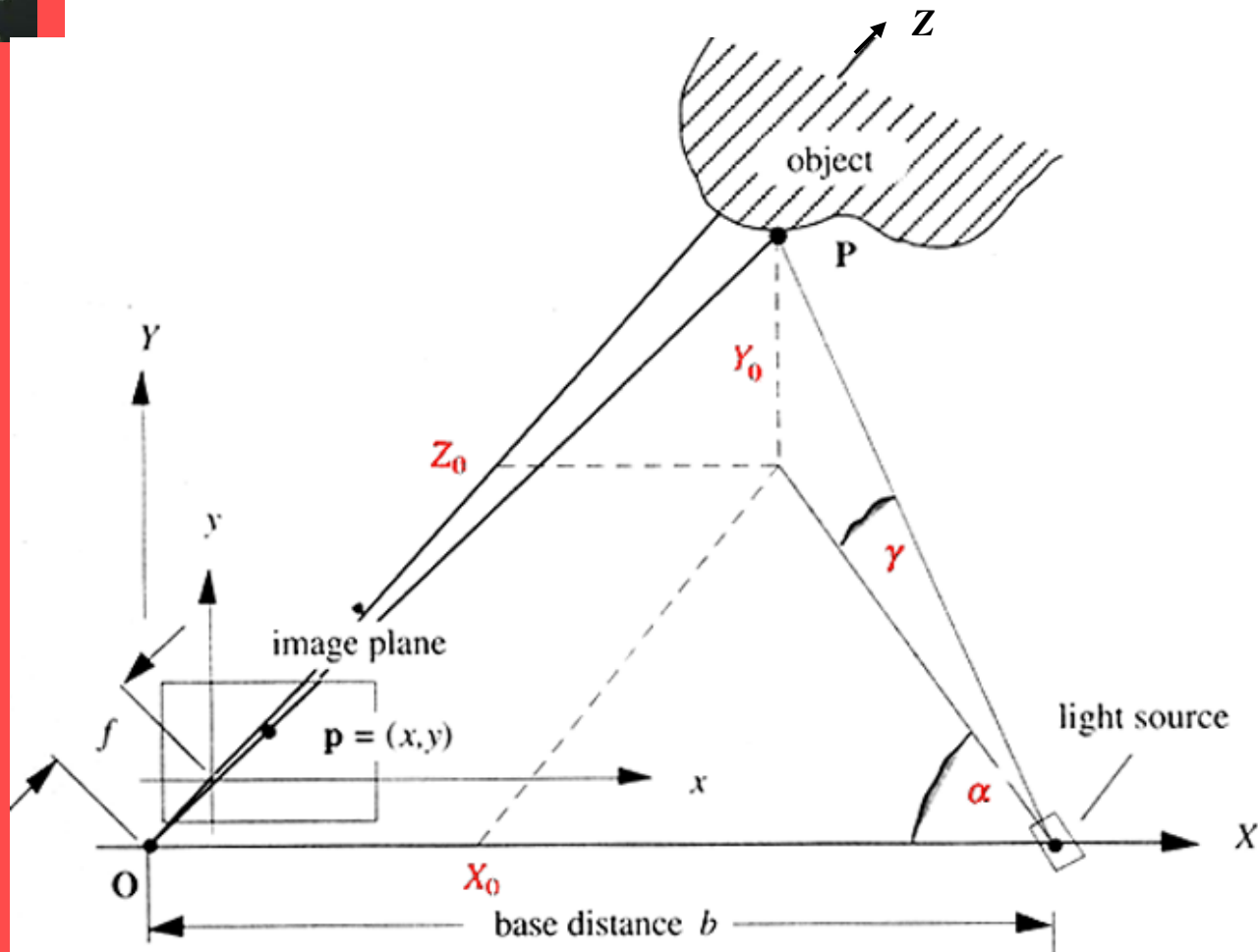
$$d = \frac{b \cdot sin(\alpha)}{sin(\alpha + \beta)}.$$

Reinhard Klette, Computer Vision

# Light Spot Projection 2D

- Coordinates found by triangulation:
  - $\beta$ can be found by projection geometry
  - $d = b*\sin(\alpha)/\sin(\alpha + \beta)$
  - $P = (X_0, Z_0)$
  - $X_0 = d*\cos(\beta)$
  - $Z_0 = h = d*\sin(\beta)$

- Calculating Location of P:
  - known b and $\alpha$
  - $\beta$ defined by projection geometry/calibrat.
  - Given image coordinate u and focal length f -> calculate $\beta$
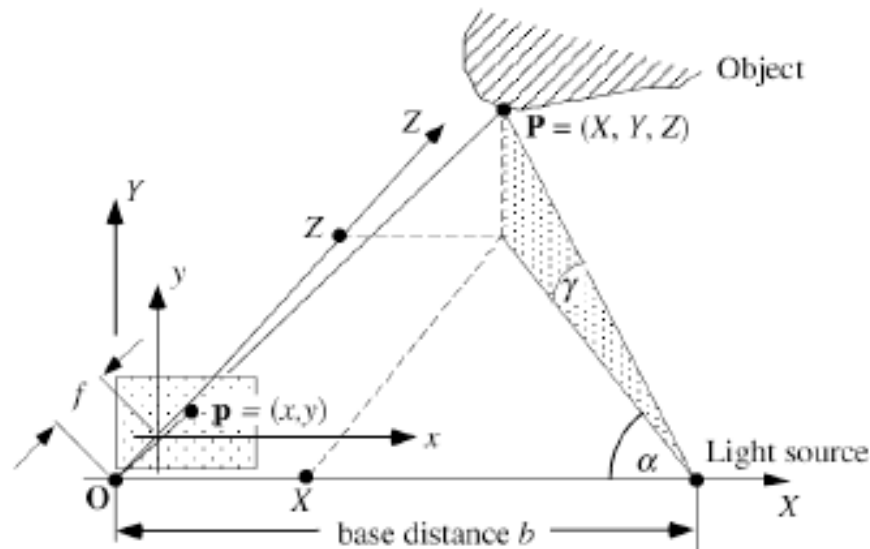  - Given b, $\alpha$, $\beta$ -> <u>calculate d</u>

# Light Spot Projection 3D

# Light Spot Projection 3D

Now we consider the 3D case. Assume that $\alpha$ and $b$ are given.



The ray theorem (of central projection) tells us that $\frac{X}{x} = \frac{Z}{f} = \frac{Y}{y}$, and from the trigonometry of right triangles we know that $\tan\alpha = \frac{Z}{b-X}$. It follows that

$$Z = \frac{X}{x} \cdot f = \tan\alpha \cdot (b - X) \quad \text{and} \quad X \cdot \left(\frac{f}{x} + \tan\alpha\right) = \tan\alpha \cdot b$$

The solution is

$$X = \frac{\tan\alpha \cdot b \cdot x}{f + x \cdot \tan\alpha}, \quad Y = \frac{\tan\alpha \cdot b \cdot y}{f + x \cdot \tan\alpha}, \quad Z = \frac{\tan\alpha \cdot b \cdot f}{f + x \cdot \tan\alpha}$$

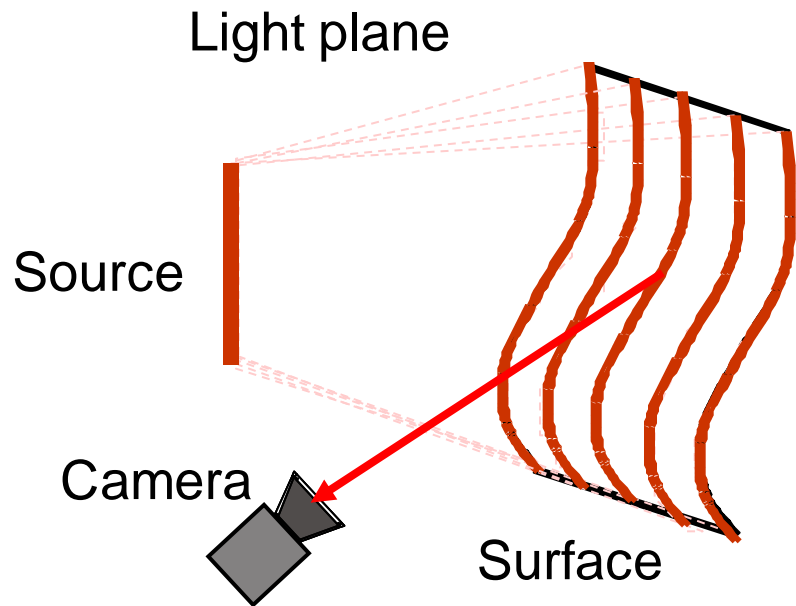Why does $\gamma$ not appear in these equations?

# Light Spot Projection 3D



- $X_0 = (\tan(\alpha)*b*x)/(f + x*\tan(\alpha))$
- $Y_0 = (\tan(\alpha)*b*y)/(f+x*\tan(\alpha))$
- $Z_0 = (\tan(\alpha)*b*f)/(f+x*\tan(\alpha))$

OBSERVATION????

Angle gamma γ not used !!!!
(Exercise)

# Light Stripe Scanning – Single Stripe
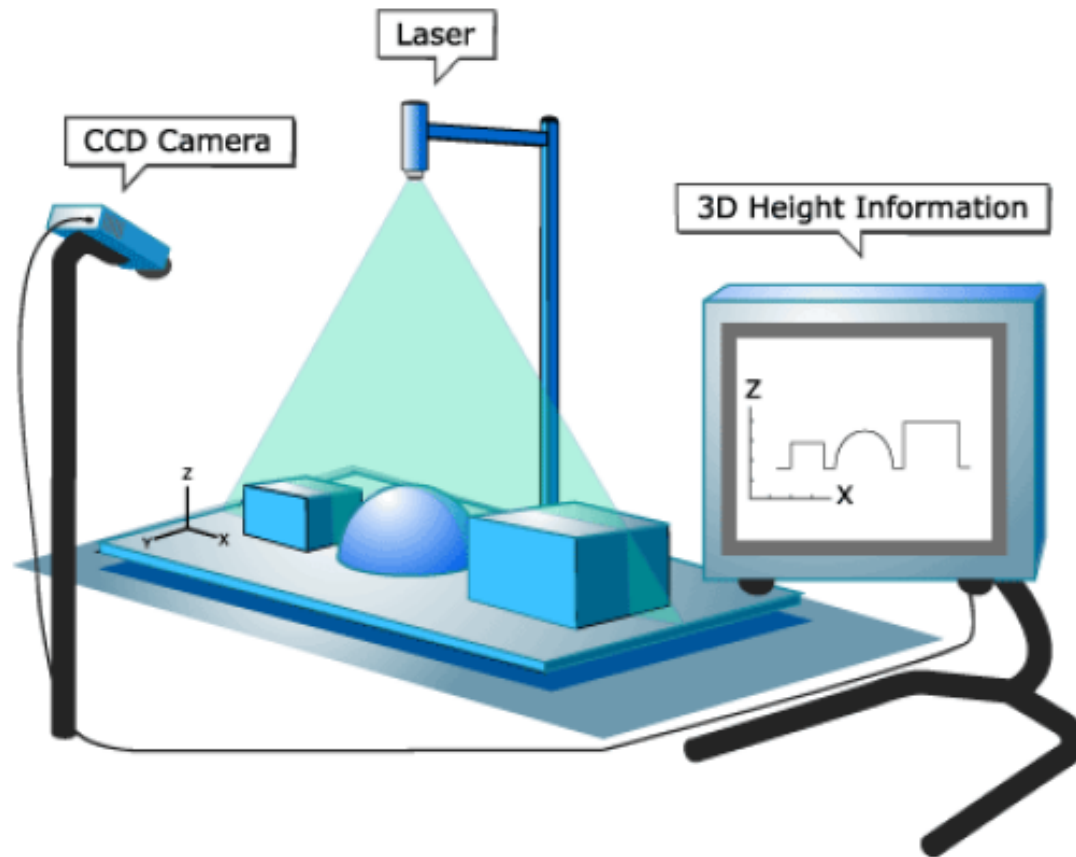
Light plane

Source

Camera

Surface

- Optical triangulation
  - Project a single stripe of laser light
  - Scan it across the surface of the object
  - This is a very precise version of structured light scanning
  - Good for high resolution 3D, but needs many images and takes time

# Light Stripe Projection

Structured light is the projection of a light pattern (ray, plane, grid, encoded light, and so forth) under calibrated geometric conditions onto an object whose shape needs to be recovered.

# Triangulation

Light Plane
$$Ax + By + Cz + D = 0$$

Object
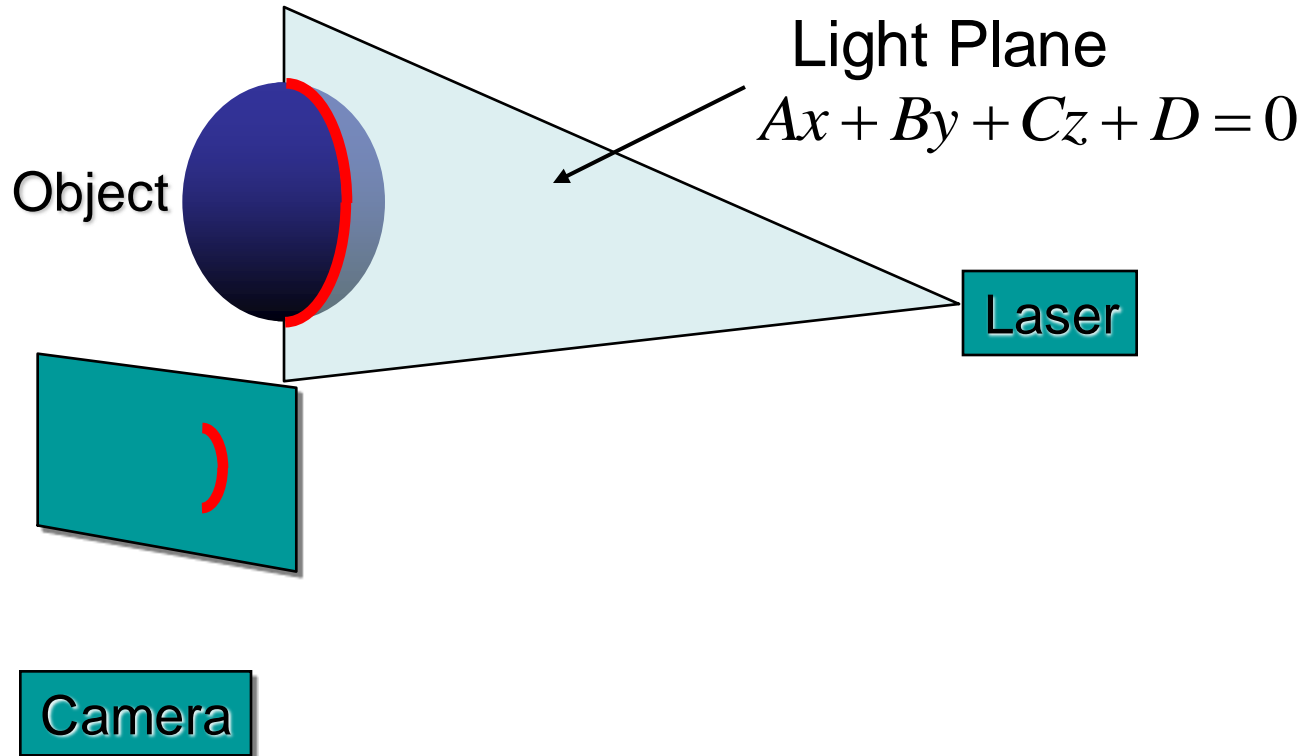
Laser

Camera

- Project laser stripe onto object

# Triangulation



Light Plane
$$AX + BY + CZ + D = 0$$
$$D = -d \ \text{(distance)}$$

Object

Laser

Image Point
$(x', y')$

$f'$

Camera

Plug X, Y into plane equation to get Z
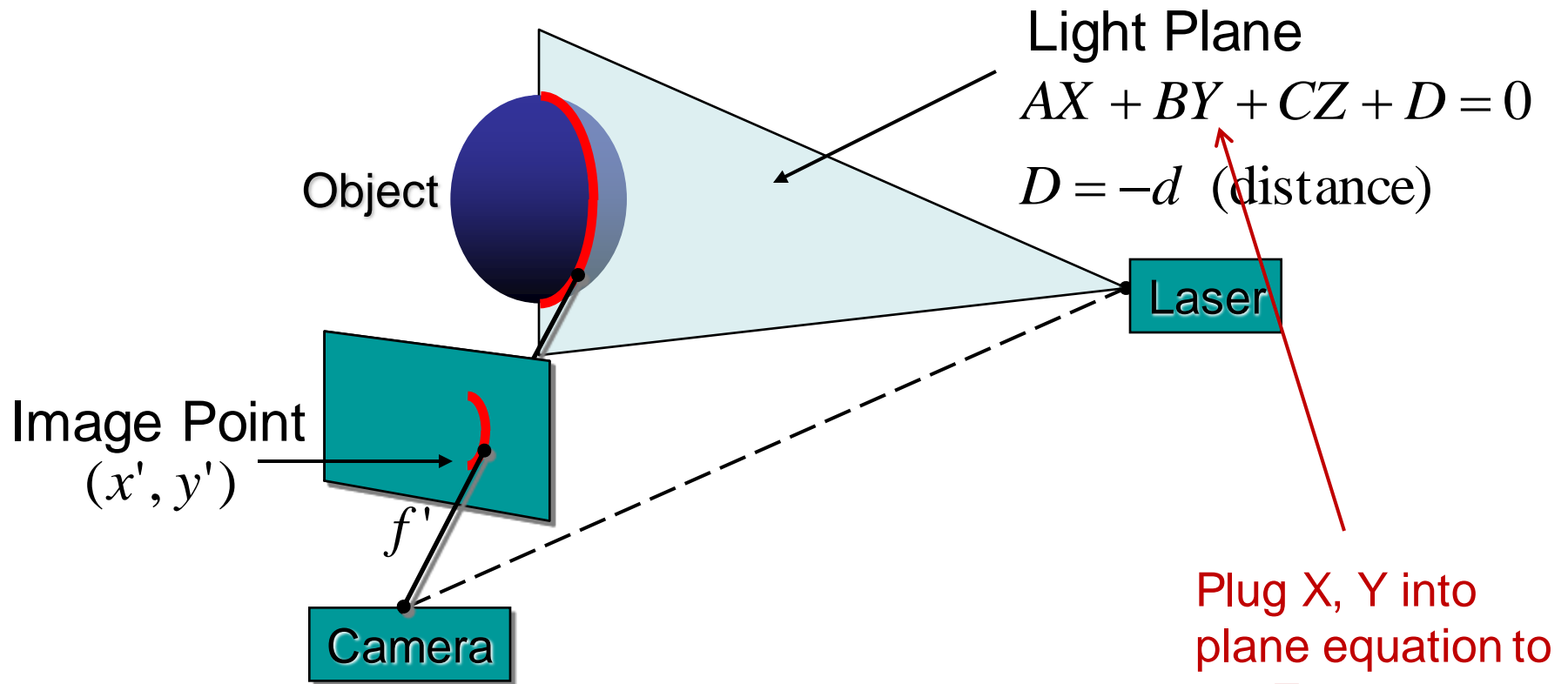
- Depth from ray-plane triangulation:
  - Intersect camera ray with light plane

$$X = x'Z / f'$$
$$Y = y'Z / f'$$
$$Z = \frac{-Df'}{Ax' + By' + Cf'}$$

Courtesy S. Narasimhan, CMU

# Light Stripe Projection: Calibration

- Put calibration object into scene
- Shift object along light plane
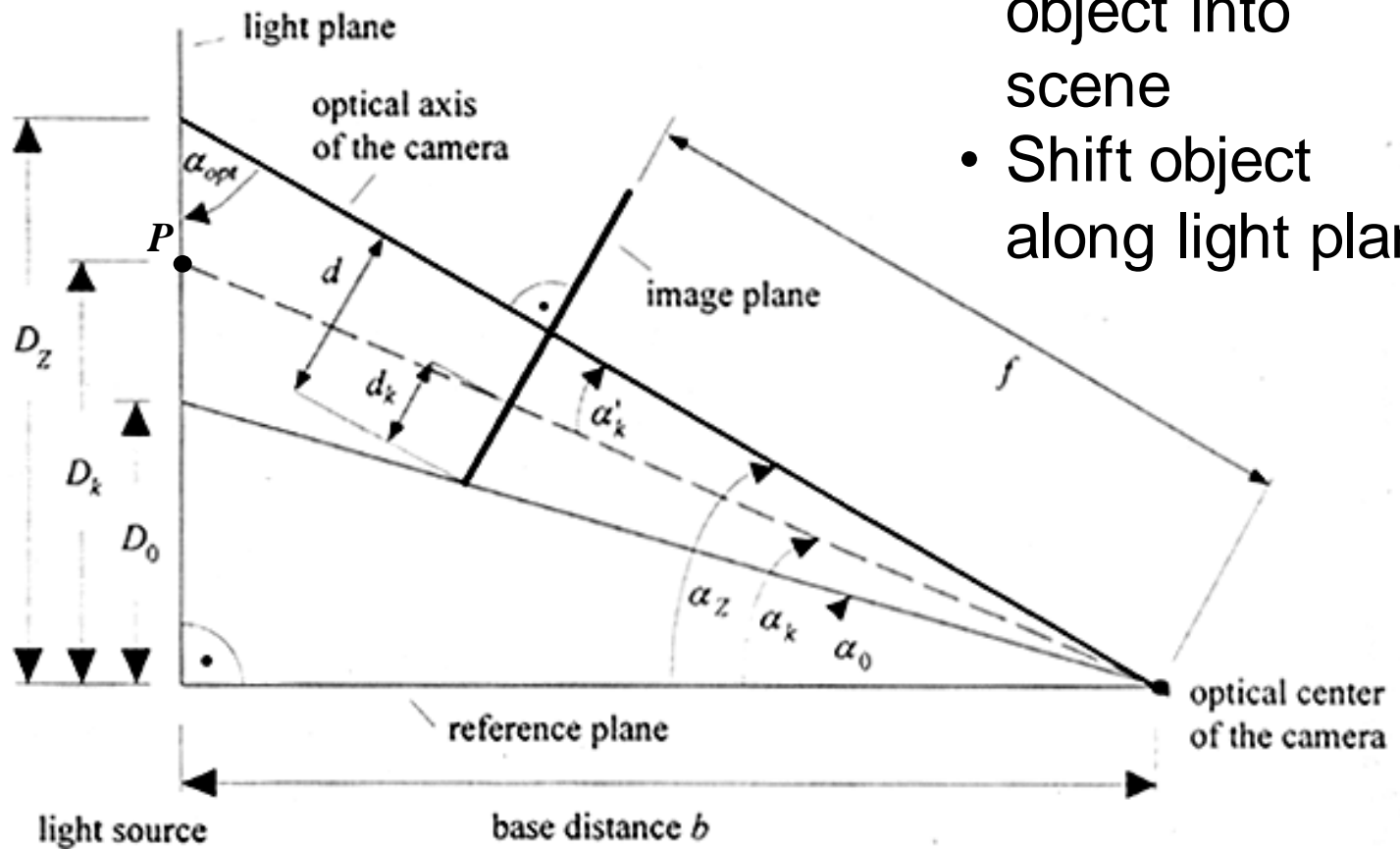
# Light Stripe Projection: Calibration

## Distance Calibration

A simple method for calibrating distance for a system with a fixed light-plane is as follows: objects are assumed on a turntable, which has its rotation center at the origin of the $X_{light}Y_{light}$ plane.
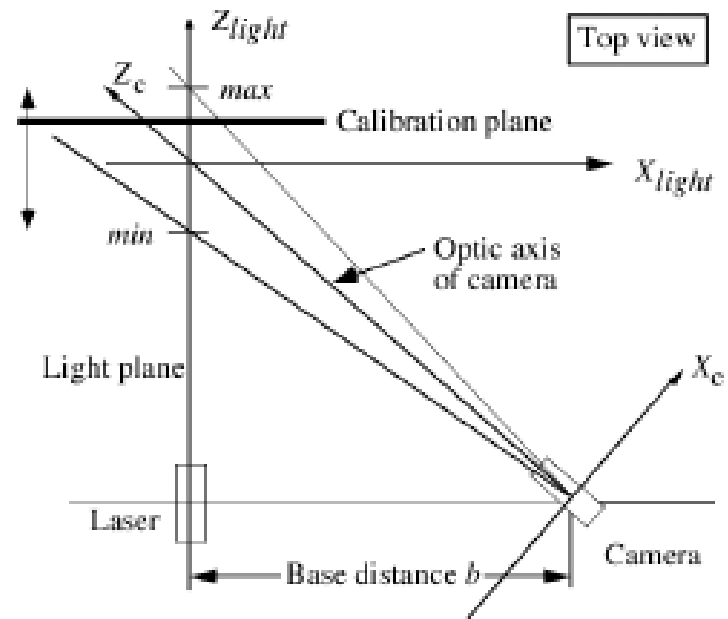


The calibration plane is now moving between two positions max and min, parallel to the $X_{light}, Y_{light}$ plane. At max, the rightmost column in the image (of the camera) is illuminated, at min the leftmost column. For each column $y$ we measure the $Z_{light}$ coordinate of the calibration plane such that column $y$ is illuminated at this position.

# Straightforward: Single light stripe and rotating Object



Figure 9.10: Left: Rear view of the recovered 3D profiles of the Beethoven statue shown on the left of Fig. 9.9. Right: Recovered triangular mesh around nose and mouth of the statue.
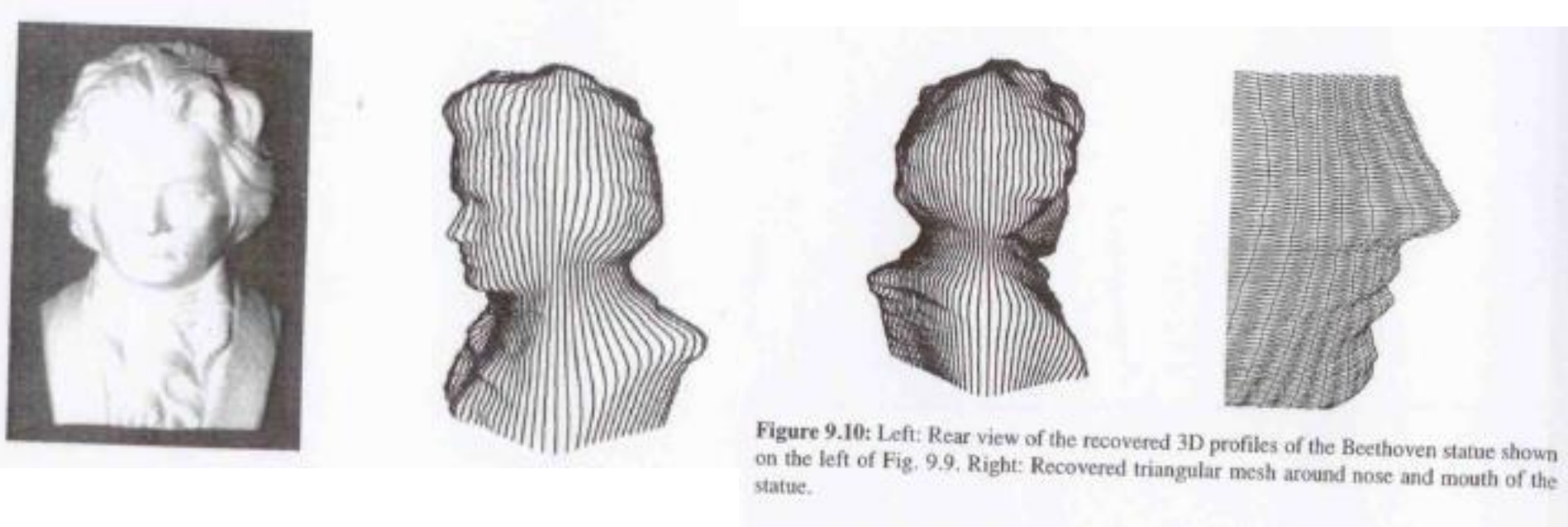
Object on turntable:
- Create P(X,Y,Z) profile for each rotation and fixed light slit
- Rotate object in discrete intervals and repeat
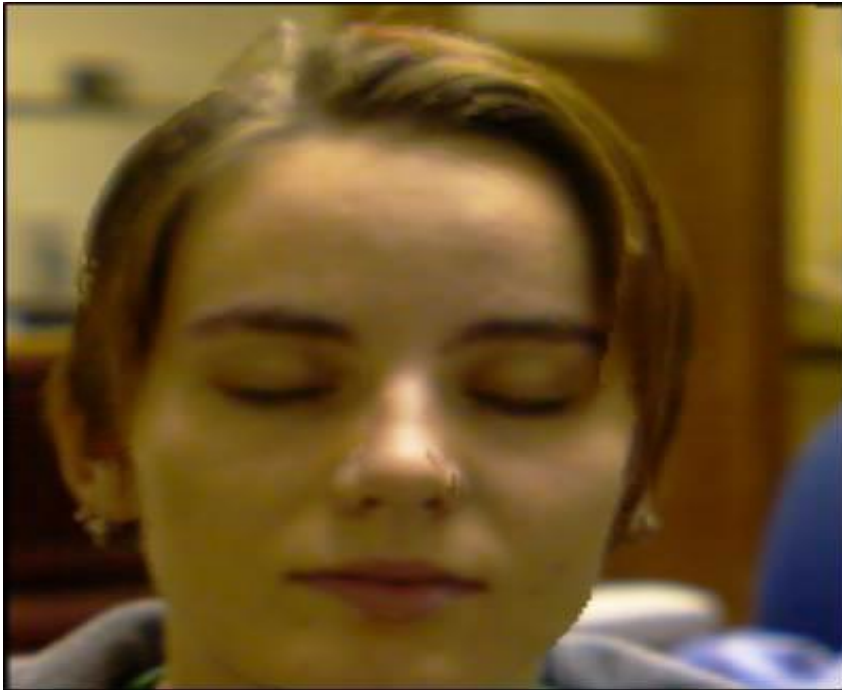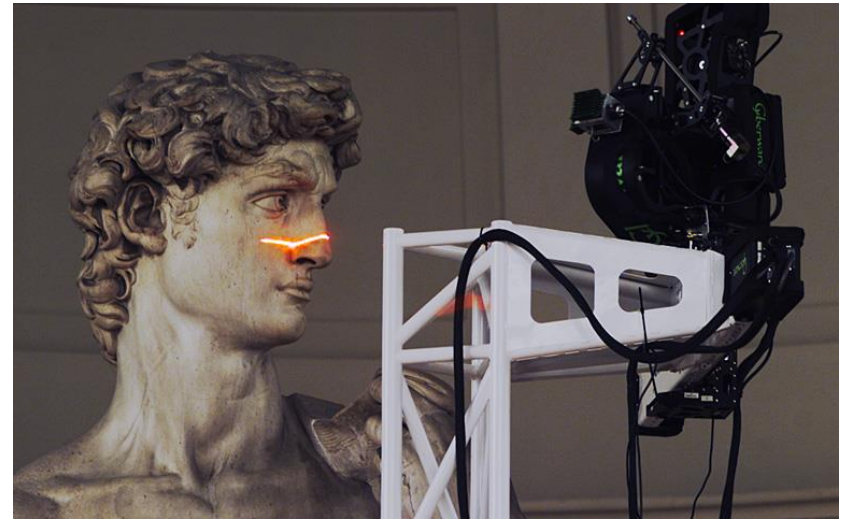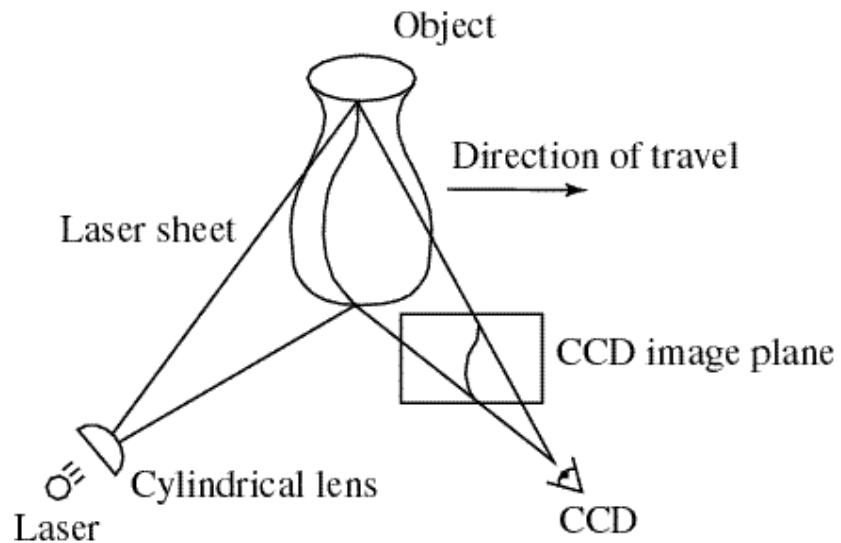- Reconstruct 3D object by cylindric assembly of profiles → 3D mesh

# Example: Laser scanner
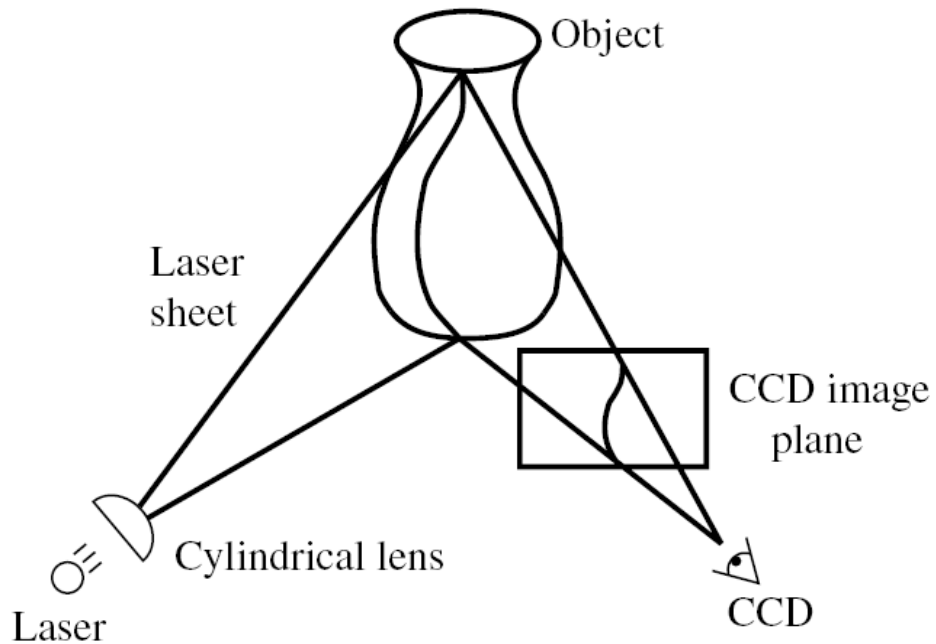




Cyberware® face and head scanner

**+**  very accurate < 0.01 mm
**−**  more than 10sec per scan

# Portable 3D laser scanner (this one by Minolta)

# Example: Laser scanner



Object

Direction of travel

Laser sheet

CCD image plane

Cylindrical lens

Laser

CCD
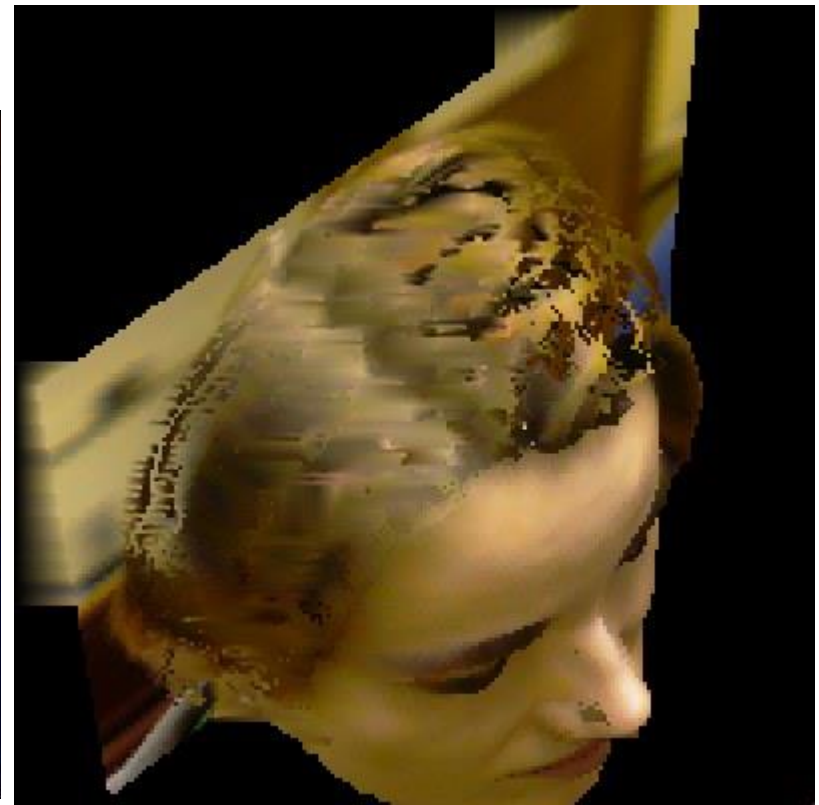
Digital Michelangelo Project

# Can we do it without expensive equipment?

# 3D Acquisition from Shadows

## 3D photography on your desk

Jean-Yves Bouguet[†] and Pietro Perona[†‡]

† California Institute of Technology, 136-93, Pasadena, CA 91125, USA

‡ Università di Padova, Italy

{bouguetj,perona}@vision.caltech.edu

### Abstract

A simple and inexpensive approach for extracting the three-dimensional shape of objects is presented. It is based on 'weak structured lighting'; it differs from other conventional structured lighting approaches in that it requires very little hardware besides the camera: a desk-lamp, a pencil and a checker-board. The camera faces the object, which is illuminated by the desk-lamp. The user moves a pencil in front of the light source casting a moving shadow on the object. The 3D shape of the object is extracted from the spatial and temporal location of the observed shadow. Experimental results are presented on three different scenes demonstrating that the error in reconstructing the surface is less than 1%.
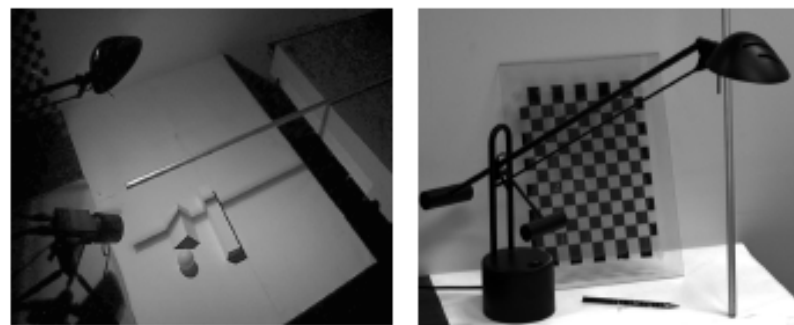
Figure 1: **The general setup of the proposed method:** The camera is facing the scene illuminated by a halogen desk
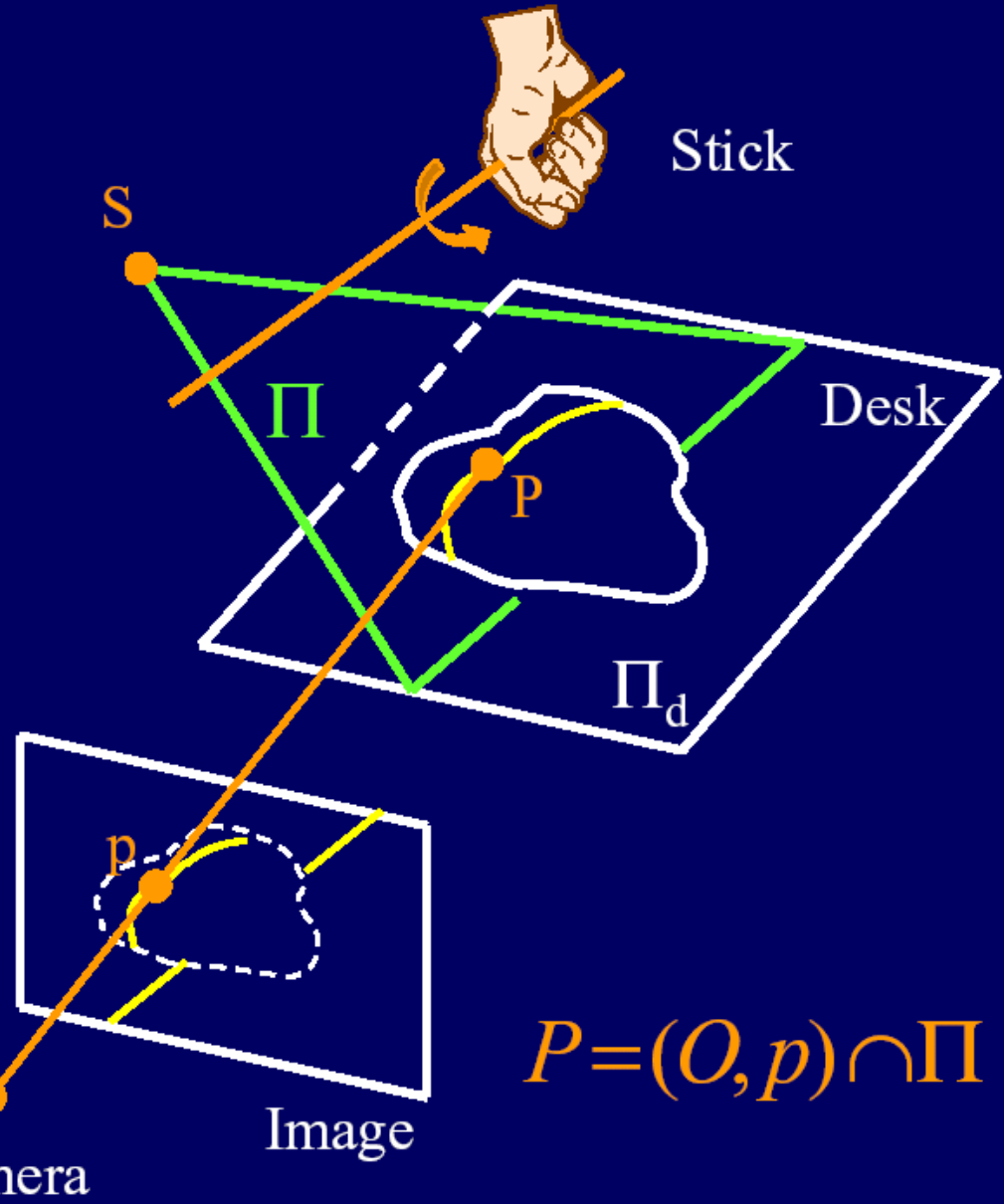
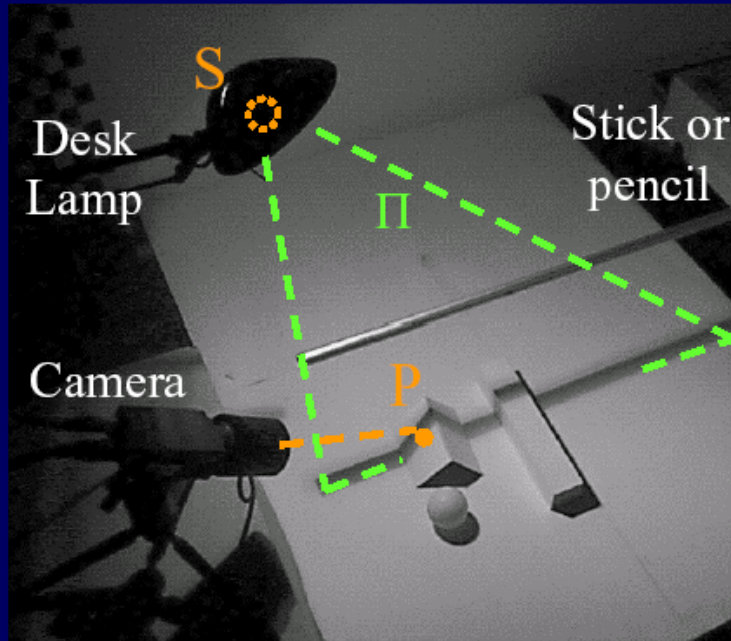Bouguet-Perona, ICCV 98

# 3D Photography on Your Desk

- "Cheap" method that uses very common tools to do 3D photography

- Requirements: PC, camera, stick, lamp, and a checker board

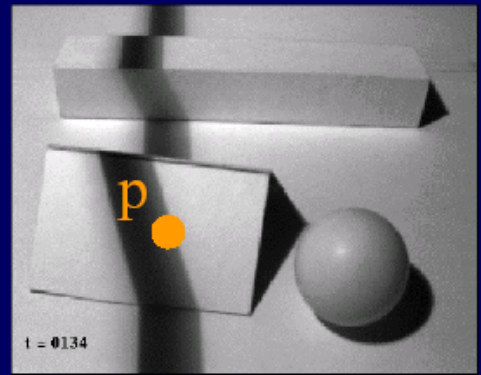- Uses "weak structured light" approach

The idea

Desk Lamp

Stick or pencil

Camera

Desk

Time t

# The geometry



Desk Lamp

S

Π

Camera

Stick or pencil

P

Stick

S

Π

Desk

P

Π_d

p

O

Image

Camera

$P = (O, p) \cap \Pi$

t = 0134
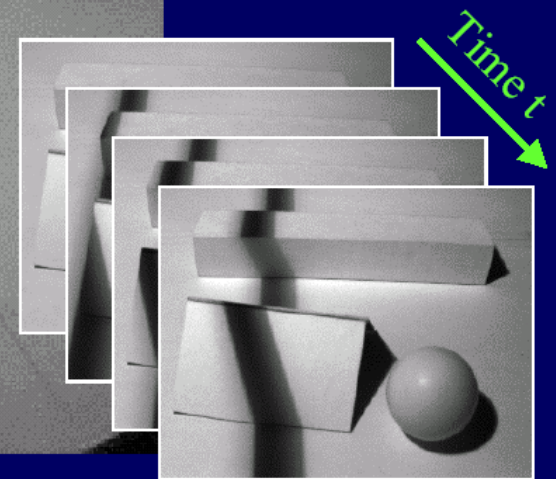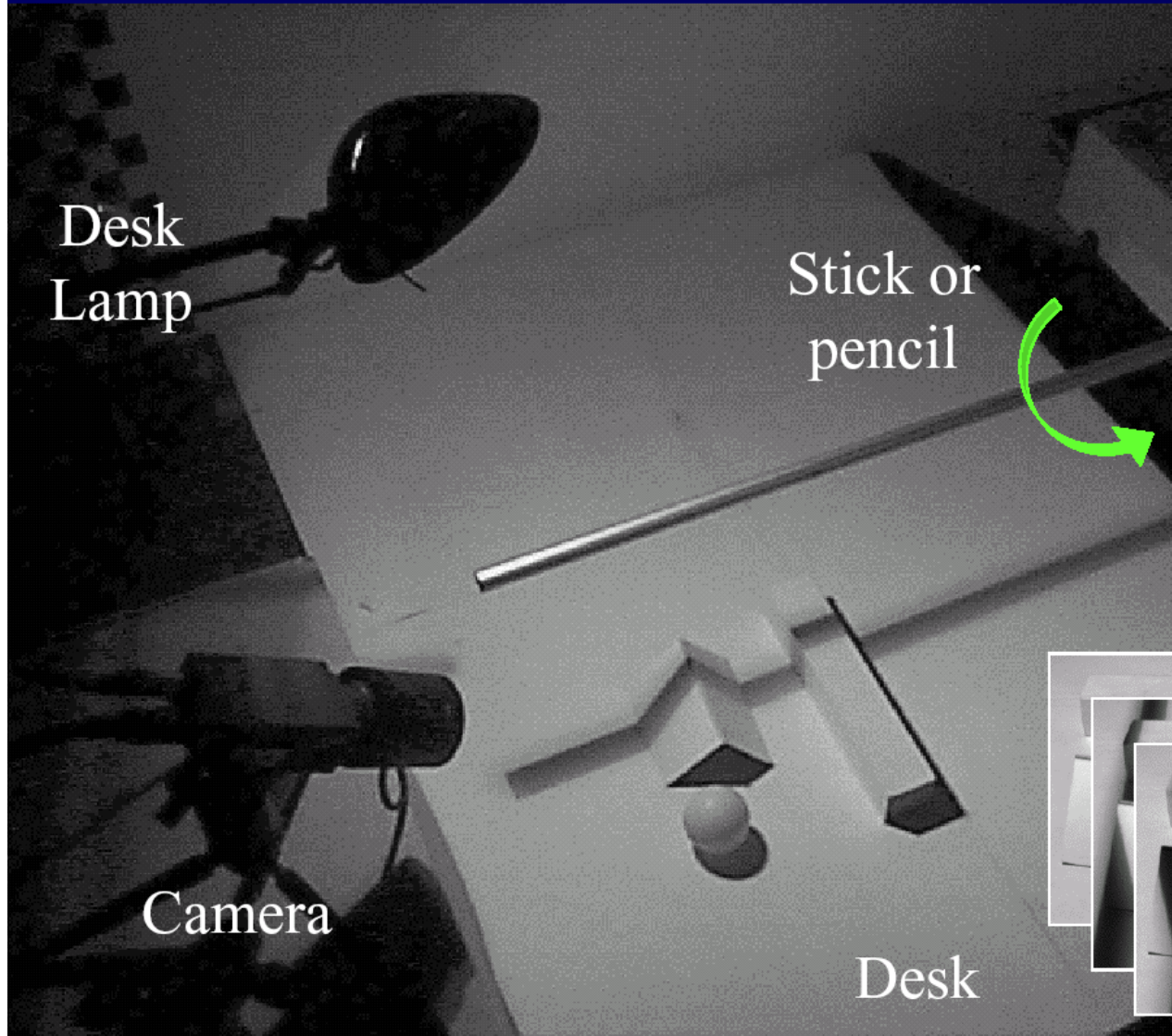
p
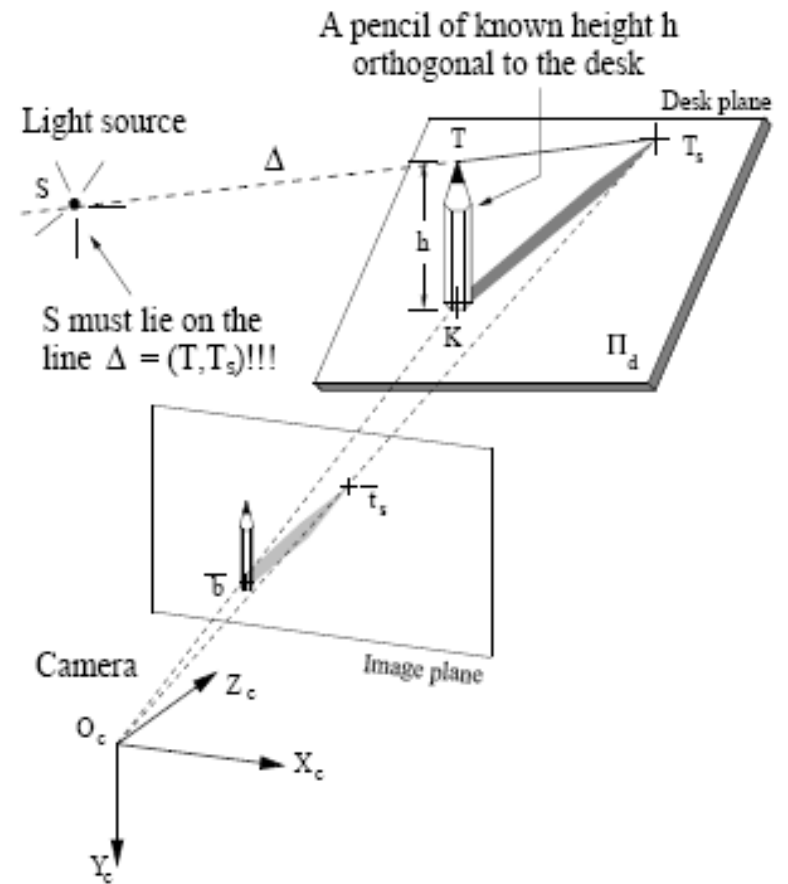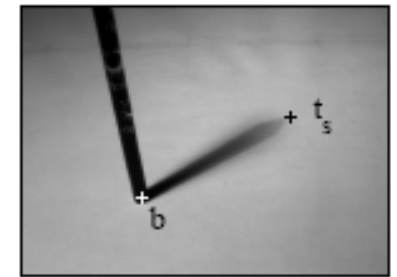
# Lamp Calibration



Figure 3: **Lamp calibration:** The operator places a pencil on the desk plane $\Pi_d$, orthogonal to it (top-left). The camera observes the shadow of the pencil projected on the tabletop.
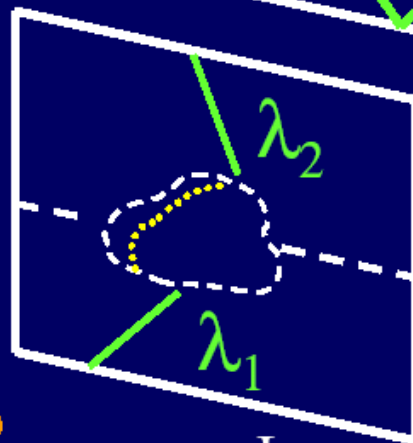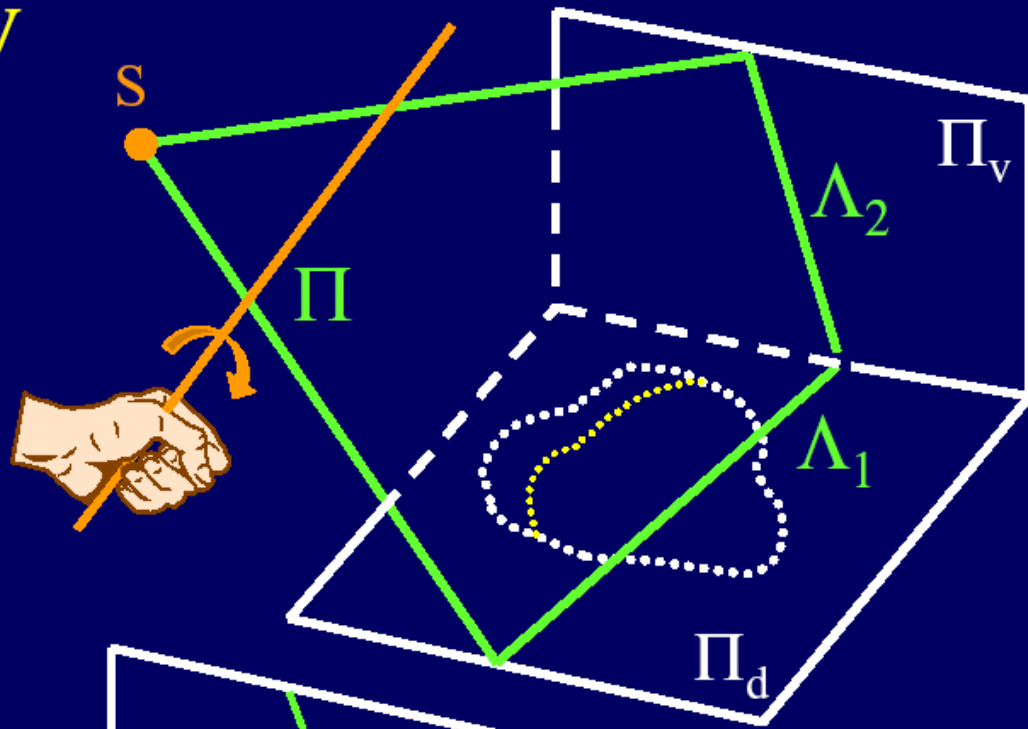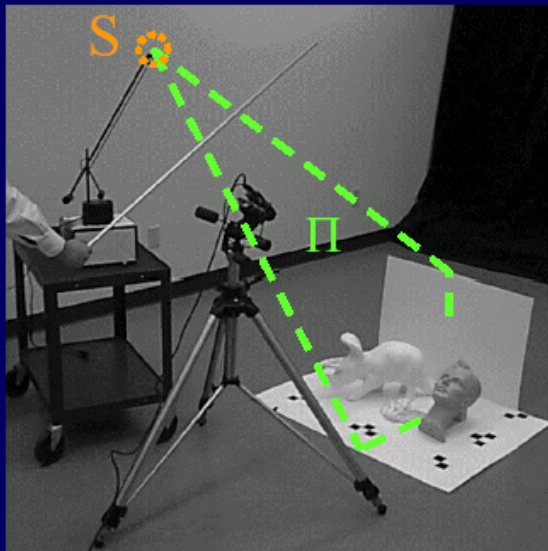
# The geometry



Desk Lamp

S

Stick or pencil

$\Pi$

Camera

$\lambda$

$t = 0134$

Stick

S

$\Pi$

$\Lambda$

Desk

$\Pi_d$

$\lambda$

Image

O
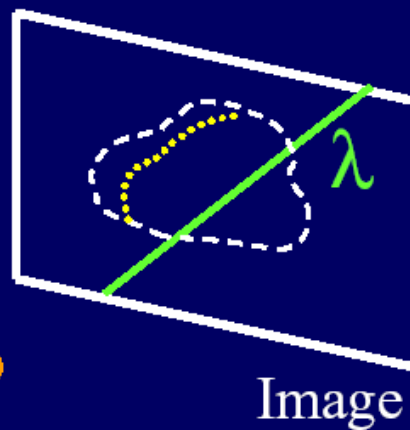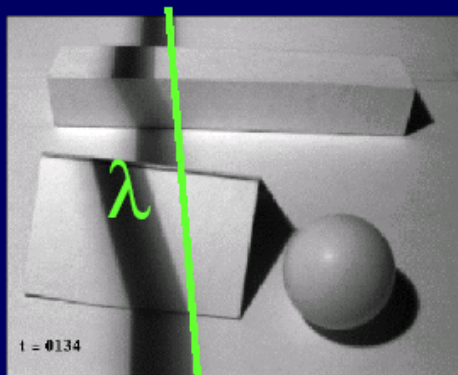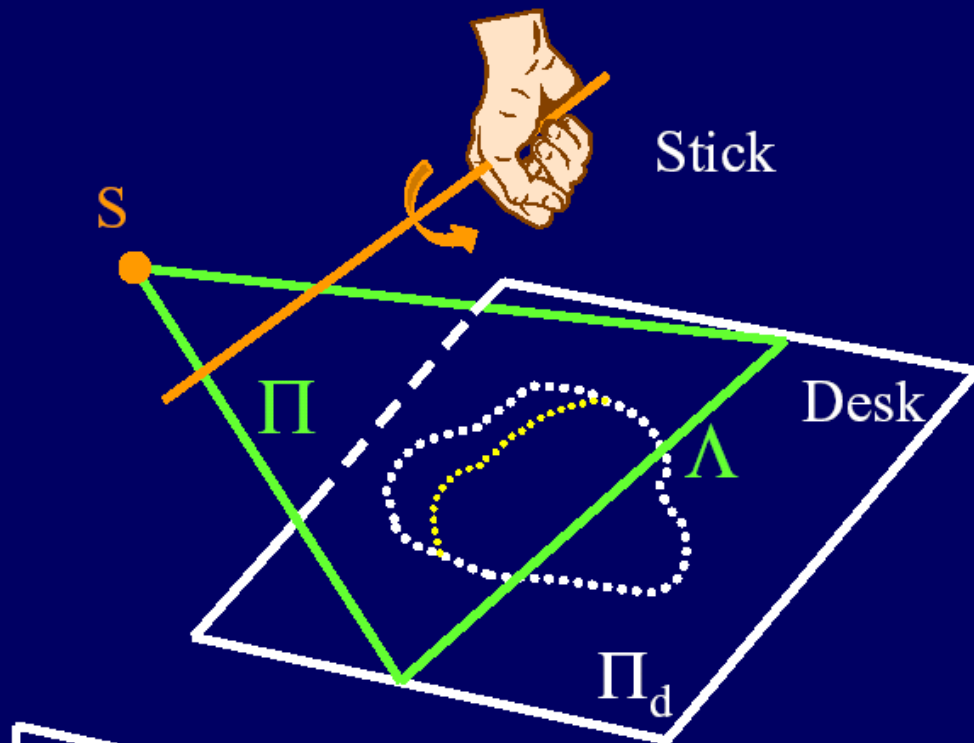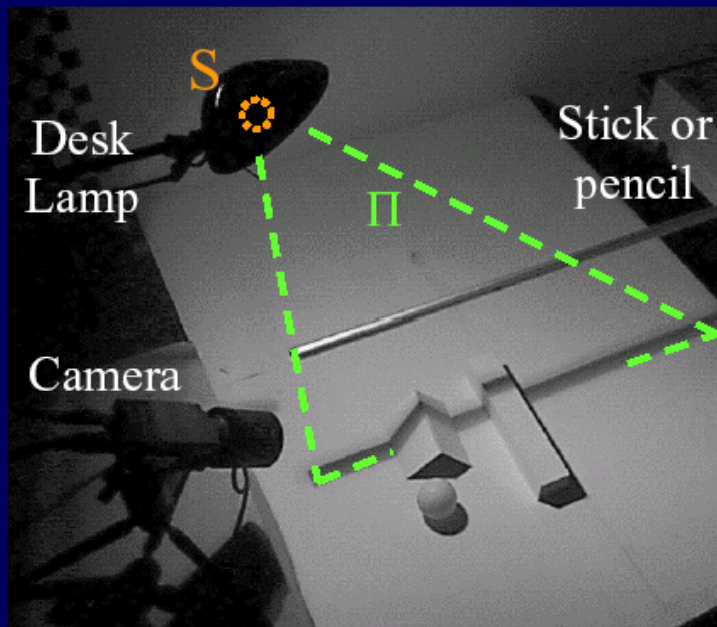
Camera

$\Lambda = (O, \lambda) \cap \Pi_d$

$\Pi = (S, \Lambda)$

# The geometry



$\Pi_v$

$\Lambda_2$

$\Pi$

$\Lambda_1$

$\Pi_d$

$\lambda_2$

$\lambda_1$

O ●

Camera

Image

$\Lambda_1 = (O, \lambda_1) \cap \Pi_d$

$\Lambda_2 = (O, \lambda_2) \cap \Pi_v$

$\Pi = (\Lambda_1, \Lambda_2)$
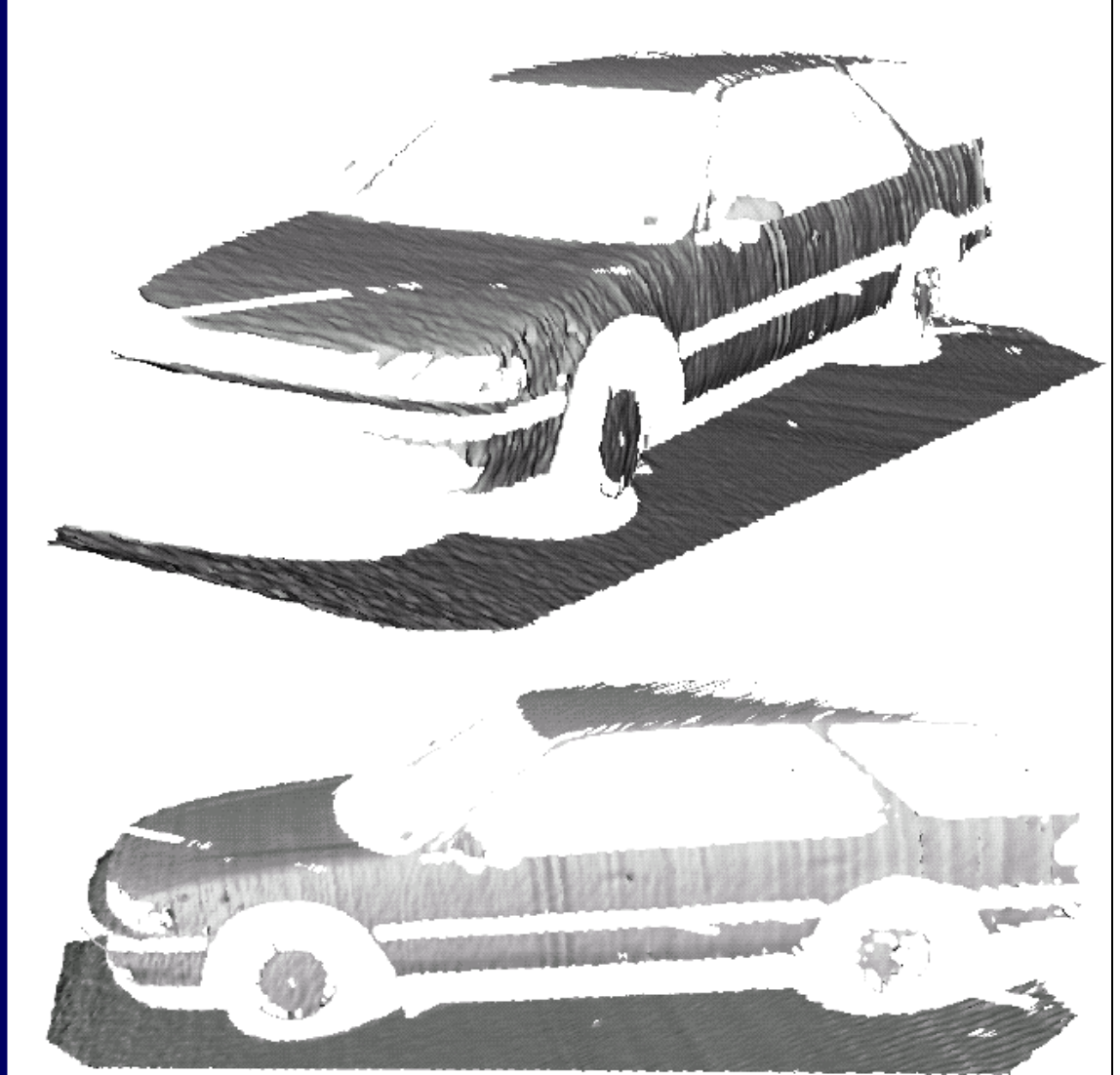
# Angel experiment



Accuracy: 0.1mm over 10cm ➡ ~ 0.1% error

# Scanning with the sun



Accuracy: 1cm over 2m

➡ ~ 0.5% error

# Low-Cost 3D Scanner for Everyone

http://www.david-laserscanner.com/



What do I need to build a 3D scanner?

- A camera (e.g. web cam)
- A hand-held line laser (starting at €19.90)
- Two plain boards in the background
- A Windows PC
- Our free software DAVID-LASERSCANNER

Or use the brand-new DAVID Starter-Kit!

If you don't want to start searching and tinkering, the DAVID Starter-Kit contains all necessary hardware and software to set up your own 3d scanner!

3D Laser Scanner for only € 399,- Order now!
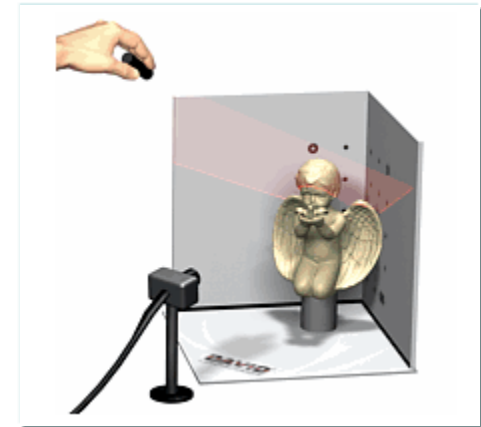


Roter Linienlaser, 5mW, Batteriebetrieben, 90°

19,90 EUR incl. 19 % UST exkl. Versandkosten
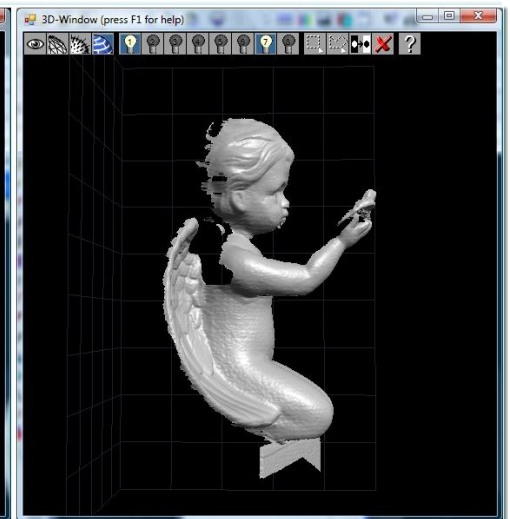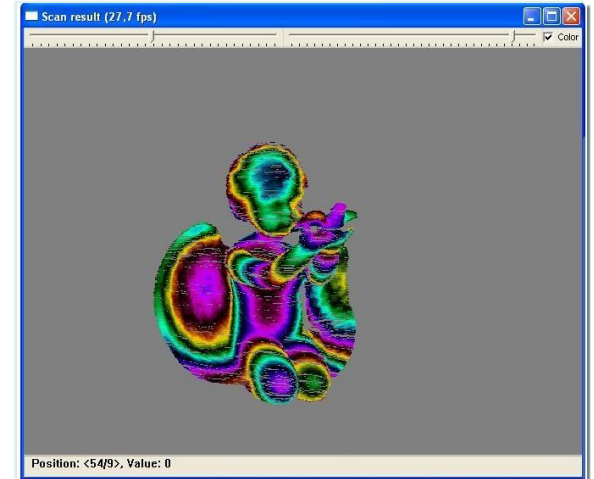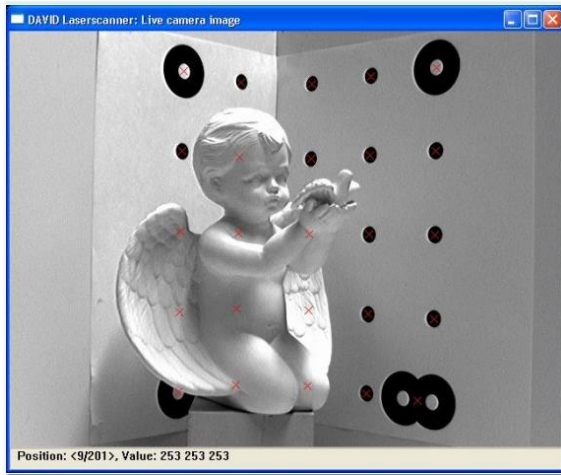


CLOSE X

Strait-Line
Laser Level

★★★★☆ 4/5   8 Reviews

$15.97

Ships FREE with $45.00 Order
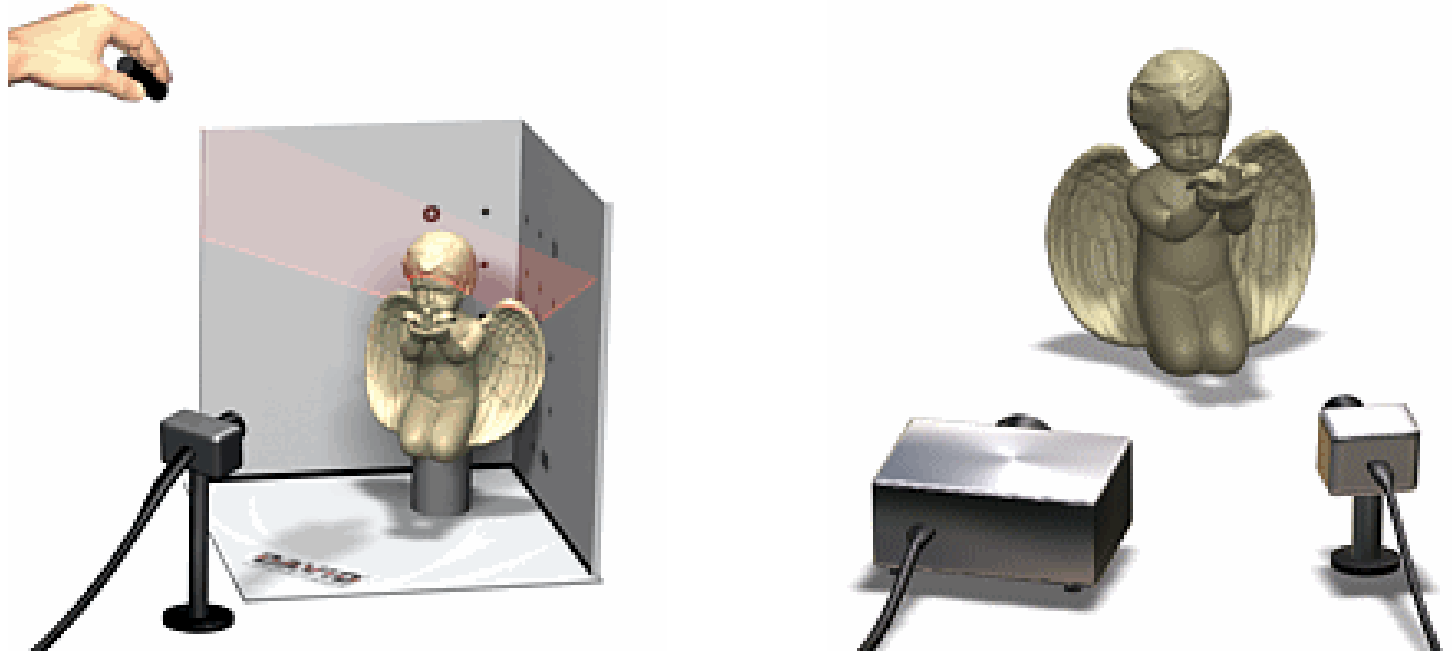
Description:
The Strait-Line Laser Level features dual-bubble vials for accurate, easy-to-read horizontal and vertical readings. The laser level projects up to a 15 ft. laser line to help provide accurate readings at a distance. The 360-degree rotation and pivot creates 30 ft. of work space. The level is accurate within

# Low-Cost 3D Scanner for Everyone

http://www.david-laserscanner.com/wiki/user_manual/3d_laser_scanning

# Cheap Scanner



- http://www.igp.ethz.ch/photogrammetry/education/lehrveranstaltungen/MachineVisionFS2011/coursematerial/MV-SS2011-structured.pdf
- Cheap Scanner: http://www.david-laserscanner.com/

# Build your own 3D scanner



- Course notes: http://mesh.brown.edu/byo3d/notes/byo3D.pdf
- Slides: http://mesh.brown.edu/byo3d/slides.html
- Source code: http://mesh.brown.edu/byo3d/source.html

# Next Lecture: Encoded Patterns
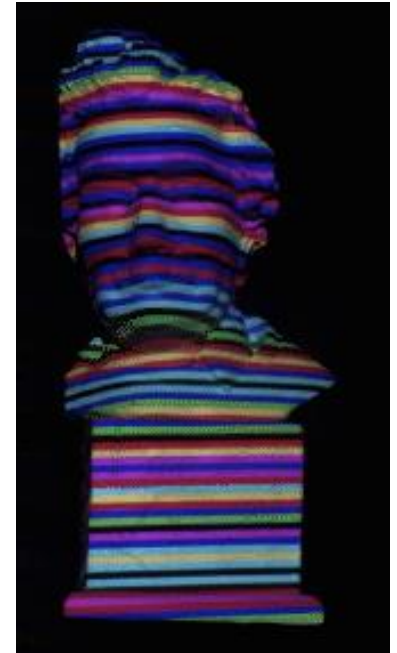


- Any spatio-temporal pattern of light projected on a surface (or volume).
- Cleverly illuminate the scene to extract scene properties (eg., 3D).
- Avoids problems of 3D estimation in scenes with complex texture/BRDFs.
- Very popular in vision and successful in industrial applications (parts assembly, inspection, etc).