

# Image Sensors

## Lecture I

p. 1

- Introduction with stereo and triangulation
- We will focus on several **active** range cameras (stereo is a passive technique)
- One active range camera is studied in more detail during the laboratory assignment.
- Some applications from SICK, Mjärdevi, Linköping
- MICROSOFT KINECT 1 and 2
- Literature
  - Short about some active range cameras: Maria Magnusson (Figure)
  - Active Range Imaging 2: From a PhD-thesis by Mattias Johannesson (Fig., Table)
  - Mesa Data sheet on SR3000 (Not for sale anymore, but an example of a range camera principle, found in e.g. Kinect2.)
  - Some slides are from Per-Erik Forssén.

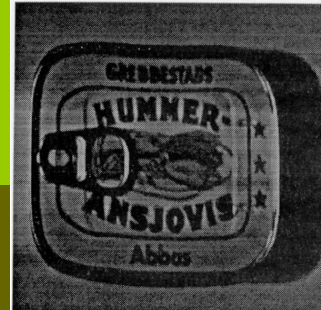
Maria Magnusson, CVL, Dept. of Electrical Engineering, Linköping University



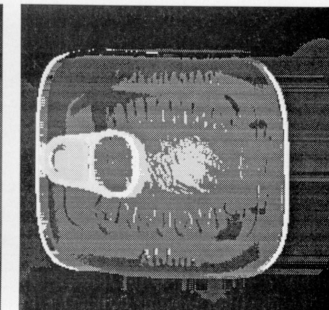
## What is a range image?

p. 2

Normal intensity image



Range image



Compare with depth coding in 3D visualization

Fig. 1.1



## Different range camera principles

p. 3

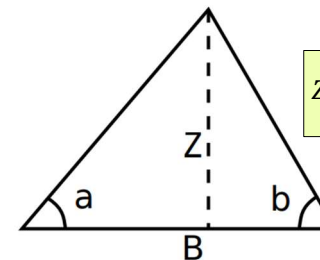
- I) Triangulation and passive stereo
- II) Active light and triangulation
  - a) "Single spot" with triangulation
  - b) "Sheet-of-light" with triangulation
  - c) "Structured light" with triangulation
  - d) "Gray-coded patterns" with triangulation
- III) Time-of-flight
  - a) Light pulse and time measurement
  - b) Amplitude modulated light and phase shift measurement
- i) Stationary scene or moving scene
- ii) Scanning or stationary light



## I) Triangulation

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- The principle that surveyors (Swedish: lantmätare) use when making maps: Measure **angles** to a target from two sources with known **baseline**.



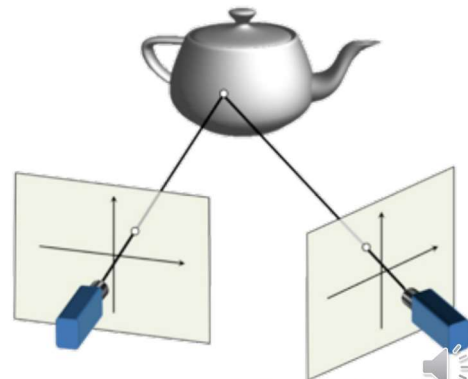
$$Z = B \cdot \frac{1}{1 / \tan(a) + 1 / \tan(b)}$$



## I) Triangulation and passive stereo

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- Measure angles to a target from two sources with known baseline.
- In the stereo camera case, the angles are obtained from positions in two images.

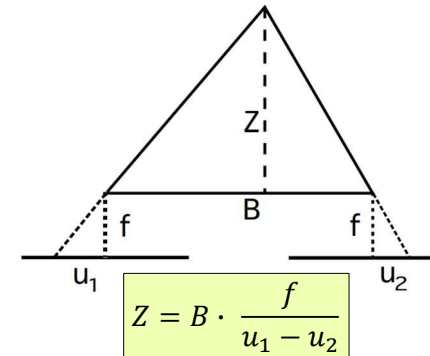


T. Moons et al. FTGV 2008

## I) Triangulation and passive stereo

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- Measure angles to a target from two sources with known baseline.
- In the stereo camera case, the angles are obtained from positions in two images.



$$Z = B \cdot \frac{f}{u_1 - u_2}$$



## I) Triangulation and passive stereo

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- Triangulation requires a known correspondence:  $u_1 \leftrightarrow u_2$
- In passive stereo, correspondence is obtained by searching through two images for matching points.



Images: M. Wallenberg

## I) Triangulation and passive stereo

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- The human visual system appreciates depth through a combination of passive stereo and a number of other features (shadows, perspective, focus, known size, motion).
- Passive light and stereo are unsuitable in many automation applications because there are a number of error sources, e.g. missing texture and repetitive patterns.

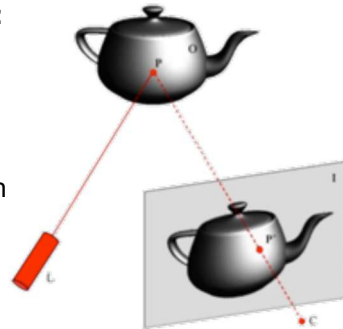


## II) Active light and triangulation

- Triangulation requires a known correspondence:

$$u_1 \Leftrightarrow u_2$$

- In active light and triangulation, the correspondence is given by replacing one camera with a light source.



T. Moons et al. FTICV 2003

## IIa) "Single spot" with triangulation

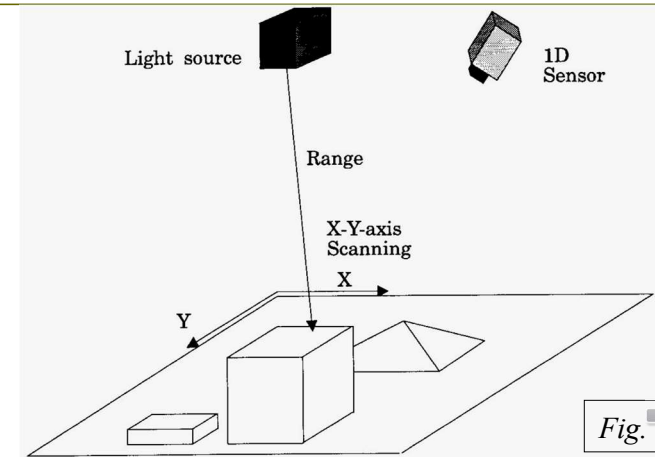


Fig. 1.3

## IIb) "Sheet-of-light" with triangulation

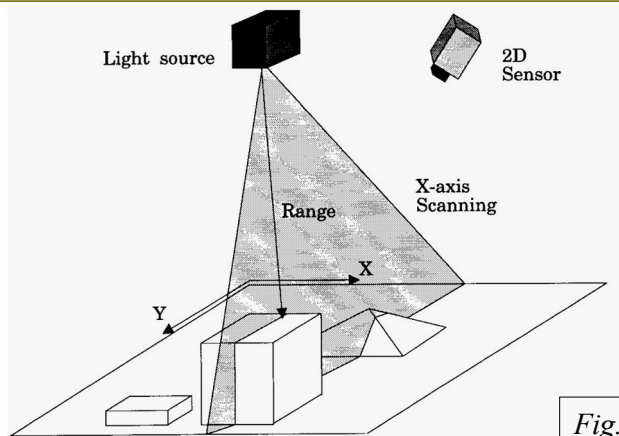


Fig. 1.4

## IIb) "Sheet-of-light" with triangulation

- An  $(x, y, r)$ -point on the object is desired.
- The position of the laser relative to the object gives  $x$ .
- The position of the laser point on the camera sensor  $(s, t)$  gives the  $(y, r)$ -coordinate.

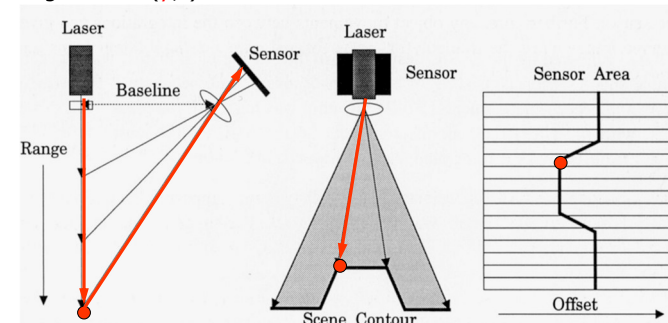
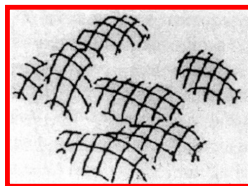


Fig. 1.6

## IIc) "Structured light" with triangulation

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- Here a grid pattern – a kind of precursor to KINECT 1.
- Disadvantage: The pattern of the objects cannot be too much wrinkled because then corresponding points cannot be determined.



potatoes

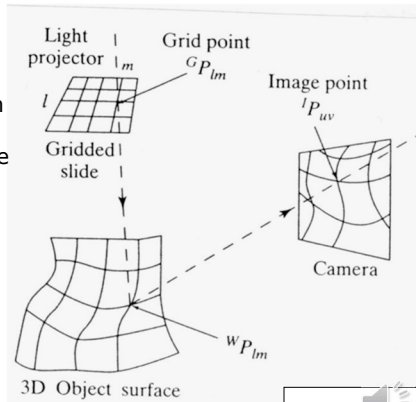


Figure 1.2

## IIId) "Gray coded patterns" with triangulation

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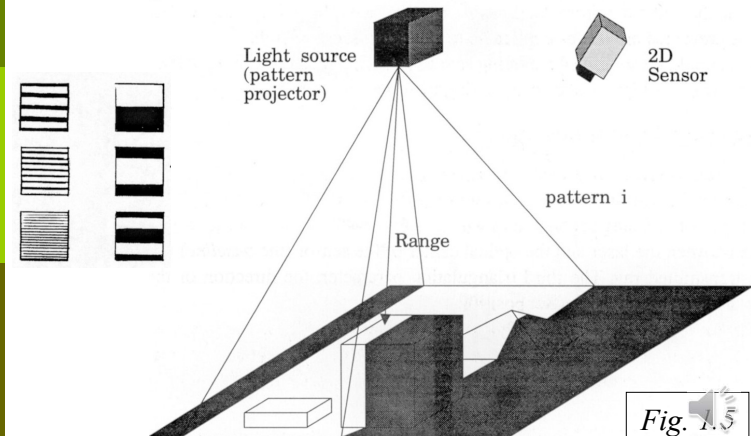
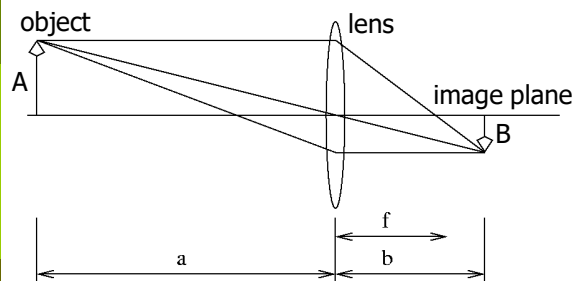


Fig. 1.5

## The Lens law (You should already know it.)

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The lens law:

$$\frac{1}{a} + \frac{1}{b} = \frac{1}{f}$$

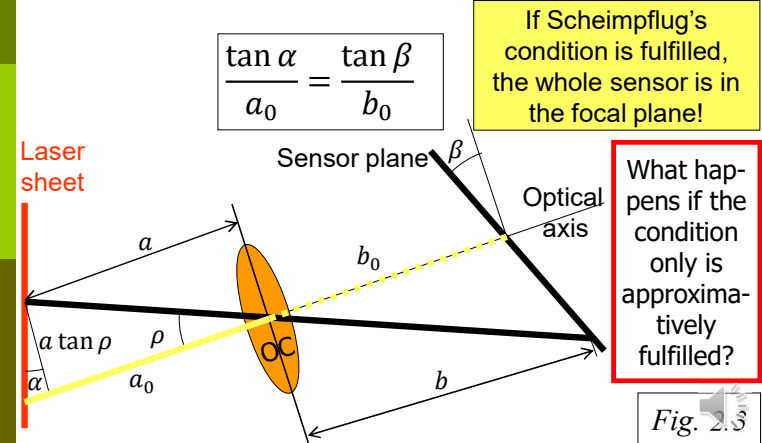
where f is the focal length

The lens law states that if the image plane is located at the distance b from the lens, then the object at distance a from the lens will give a sharp image.



## Scheimpflug's condition

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$$\frac{\tan \alpha}{a_0} = \frac{\tan \beta}{b_0}$$

If Scheimpflug's condition is fulfilled, the whole sensor is in the focal plane!

What happens if the condition only is approximately fulfilled?

Fig. 2.3

## Proof of Scheimpflug's condition, see Fig. 2.3

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We want the lens law  $\frac{1}{a} + \frac{1}{b} = \frac{1}{f}$  (1) to be valid.

We suppose:  $\frac{1}{a_0} + \frac{1}{b_0} = \frac{1}{f}$  (2)

Figure gives:  $\alpha = \frac{a_0}{1 + \tan \beta \tan \alpha}$  (3)

$b = \frac{b_0}{1 - \tan \beta \tan \alpha}$  (4)

Insert (3) and (4) into (1)  $\Rightarrow$

$$\frac{1 + \tan \beta \tan \alpha}{a_0} + \frac{1 - \tan \beta \tan \alpha}{b_0} = \frac{1}{f}$$

$$\tan \beta \left( \frac{\tan \alpha}{a_0} - \frac{\tan \alpha}{b_0} \right) + \frac{1}{a_0} + \frac{1}{b_0} = \frac{1}{f}$$

If this = 0 : (1) is valid everywhere



## Example of suitable values for $f$ , $b_0$ , $\alpha$ and $\beta$

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$f$ [mm]	$b_0$ [mm]	$\alpha$ [°]	$\beta$ [°]
18	18.4	45	1.43
75	76.8	45	1.36
18	18.4	63	2.81
75	76.8	63	2.67
18	18.4	85	15.98
75	76.8	85	15.21

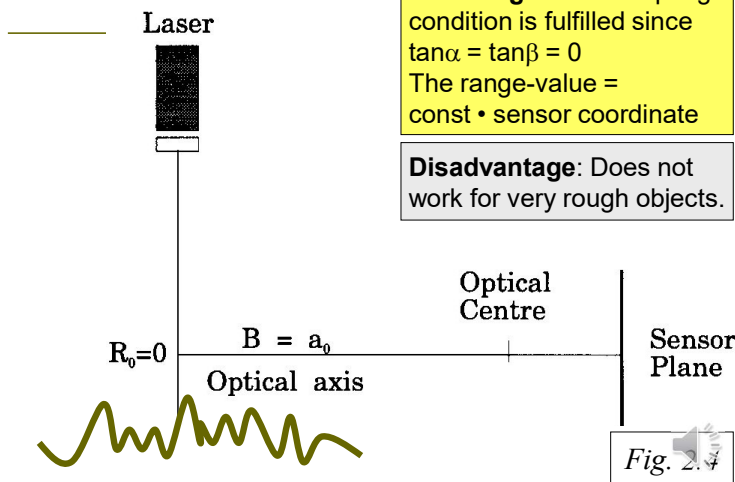
Table 3

On the following slides: 5 sheet-of-light arrangements with different geometry



## I Ib) Arrangement 1

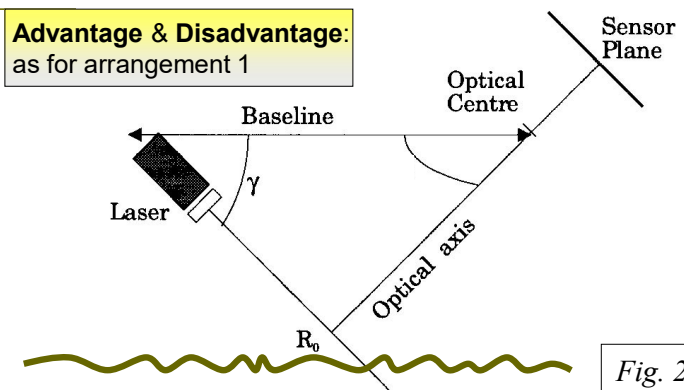
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## I Ib) Arrangement 2 = Arr. 1 rotated 45°

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**Advantage & Disadvantage:**  
as for arrangement 1



Can be used to measure the roughness on a metal sheet

## IIb) Arrangement 3

Works better for rough surfaces than Arr1 and Arr2.

**Advantage:**

Scheimpflug's condition is fulfilled since  $\tan\alpha = \tan\beta = 0$

### Disadvantages:

- The sensor has to be moved in the camera.
- Uneven illumination due to the  $\cos^4$  law.

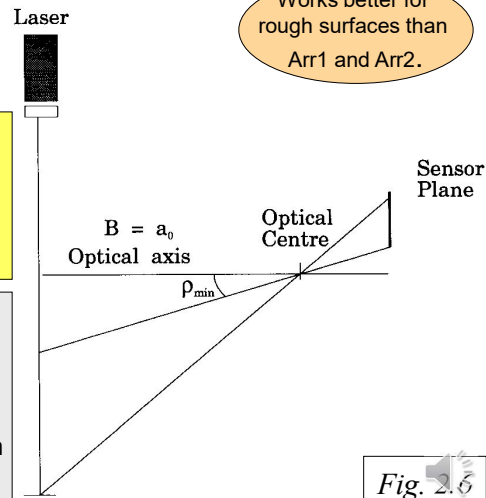


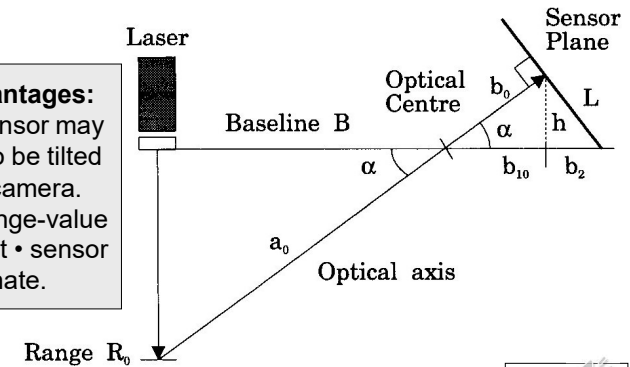
Fig. 2.5

## IIb) Arrangement 4

**SICK!**

### Disadvantages:

- The sensor may need to be tilted in the camera.
- The range-value  $\neq$  Const • sensor coordinate.



*Fig. 2.5*

## IIb) Arrangement 5

### Advantages:

The range-value  
=  
const • sensor  
coordinate

### Disadvantages:

- The sensor need to be tilted in the camera.
- Scheimpflug's condition is not fulfilled.

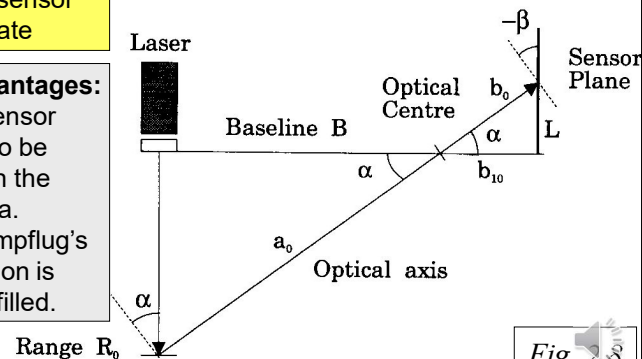
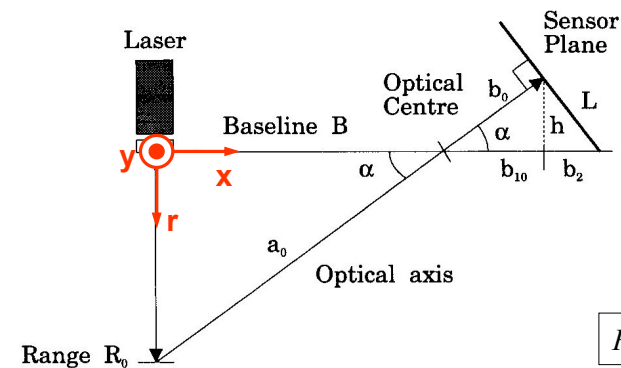


Fig. 2.8

### Determination of the coordinate x

- The x position is determined by the position of the laser sheet



*Fig. 2.5*

## Determination of the range coordinate $r$

$$r = \frac{B \cdot \left( \frac{b_0 \sin \alpha}{\cos(\alpha + \beta)} - s \right) \cdot \cos(\alpha + \beta)}{\frac{b_0 \cdot \cos \beta}{\cos(\alpha + \beta)} - \left( \frac{b_0 \cdot \sin \alpha}{\cos(\alpha + \beta)} - s \right) \cdot \sin(\alpha + \beta)} \quad \text{Eq. 2.15}$$

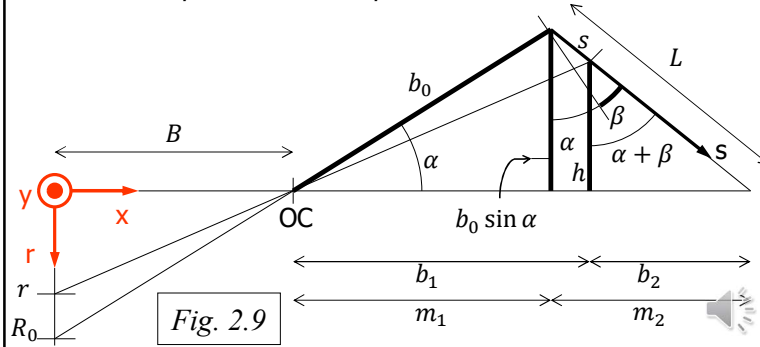


Fig. 2.9

## Determination of the width coordinate $y$

$$y = \frac{-t \cdot B}{\cos \alpha (b_0 + s \sin \beta) \left( 1 + \frac{s \cos \beta \tan \alpha}{b_0 + s \sin \beta} \right)} \quad \text{Eq. 2.21}$$

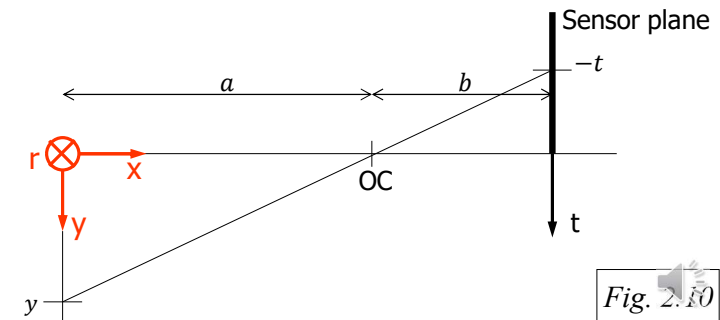


Fig. 2.10

## Range and width for $\beta=0$ (when the sensor is not tilted in the camera)

$$r = B \frac{b_0 \tan \alpha - s}{b_0 + s \tan \alpha} \quad \text{Eq. 2.17}$$

$$y = \frac{-t \cdot B}{b_0 \cos \alpha + s \sin \alpha} \quad \text{Eq. 2.22}$$



## Range and width for $\alpha=\beta=0$ (Arrangement 1 and 2)

$$r = -\frac{Bs}{b_0} \quad \text{linear range!} \quad \text{Eq. 2.16}$$

$$y = -\frac{t \cdot B}{b_0} \quad \text{linear width!}$$



## Calibration, different methods

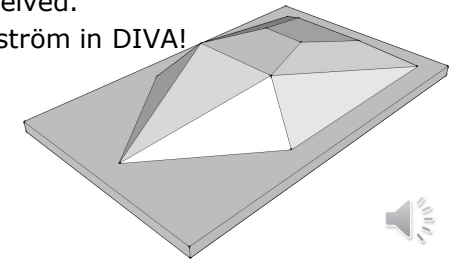
The unknown parameters,  $\alpha, \beta, b_o, s(0), t(0)$  have to be determined in some way.

- (Just measuring.)
  - Present known points  $(y_i, r_i)$  to the system and solve the parameters from Eq. (2.15) and (2.21). There exists only iterative methods.
  - Present known points  $(y_i, r_i)$  to the system and receive a polynomial approximation of Eq. (2.15) and (2.21).
  - Present known points  $(y_i, r_i)$  to the system and receive  $(s_i, t_i)$ . This gives a 2D table for  $(s, t)$ .
- 
- The projection of the laser plane to the image sensor is a **homography**. The complicated equations for the range coordinate  $r(s, t)$  and the width coordinate  $y(s, t)$  can be replaced by calibrating a homography (lab task).



## Calibration of Laser Triangulating Cameras in Small Fields of View (optional)

- An advanced very careful calibration method was developed in a Master Thesis work at SICK-IVP 2013.
- The movement of the object was involved in the calibration process, consequently a full 3D calibration was received.
- Search Daniel Rydström in DIVA!
- Calibration object:



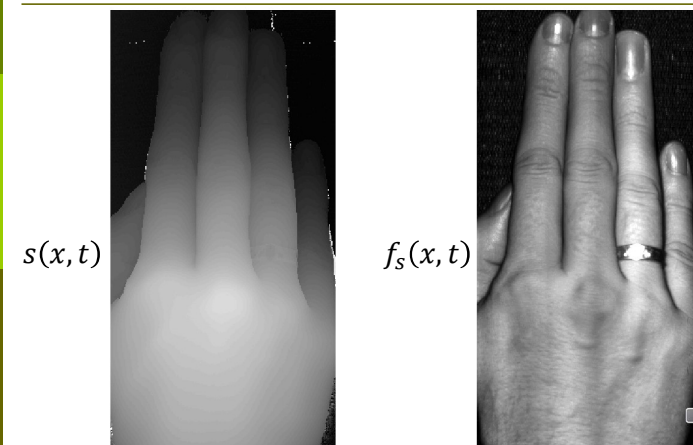
## Calibration of Laser Triangulating Cameras in Small Fields of View (optional)

$$U \sim D \left( HP \begin{bmatrix} R & t \\ 0^T & 1 \end{bmatrix} \tilde{Z} \right)$$

- $U = (u, v)^T$  are the pixel coordinates on the sensor.
- $D$  is the distortion function of the lens
- **$H$  is the homography from laser plane to real image plane**
- $P$  is the skew transformation onto the laser plane
- $R$  and  $t$  determine the positions and orientation of the calibration object relative the laser plane
- $\tilde{Z}$  are homogeneous 3D points that are defined in the calibration object coordinate system

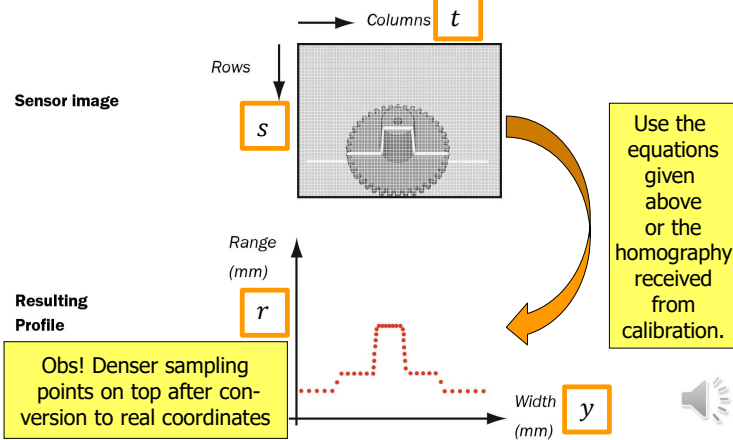


## A pseudo range image and its corresponding pseudo intensity image



## From pseudo-coordinates (s,t) to real coordinates (r,y)

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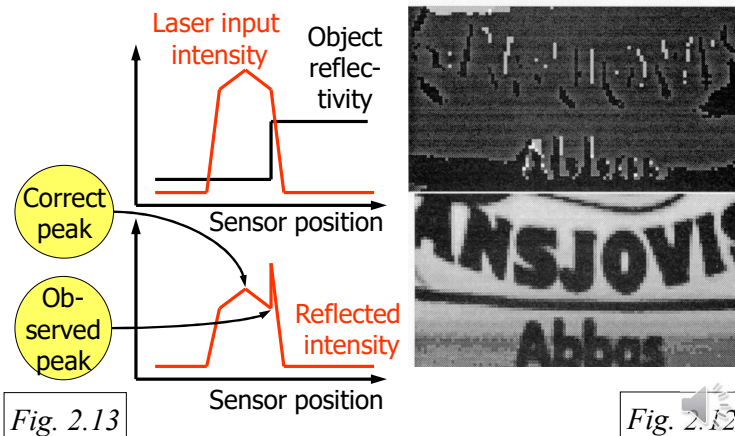
## Artefacts

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- Varying object reflectivity
- Occlusion
  - Laser occlusion
  - Sensor occlusion

## Varying object reflectivity

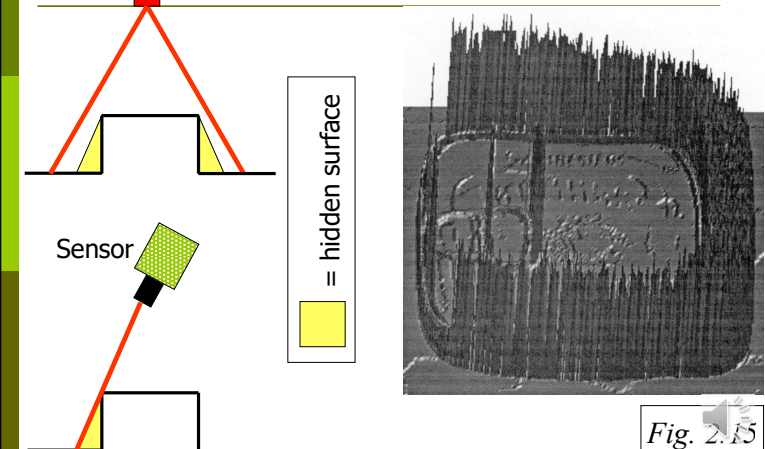
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Laser

## Laser & sensor occlusion

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## Detection of the laser line on the sensor

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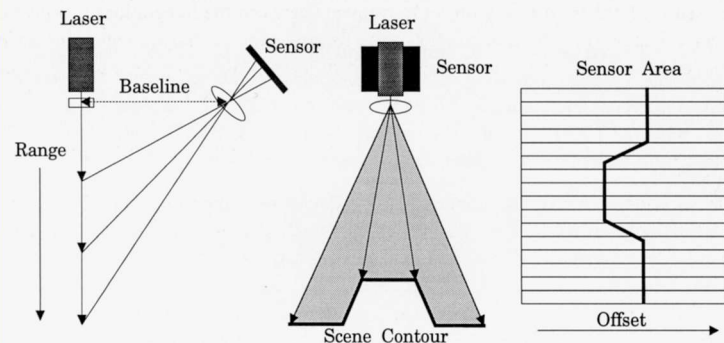


Fig. 1.6

## Detection of the laser line on the sensor

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- Max:  $\text{pos} = (a+b)/2$
- Thresh:  $\text{pos} = (n+m)/2$
- Cog:  $\text{pos} = [\sum x I(x)] / [\sum I(x)]$
- Derivate and search for the zero-crossing
- Sub-pixel correlation with a Gaussian function

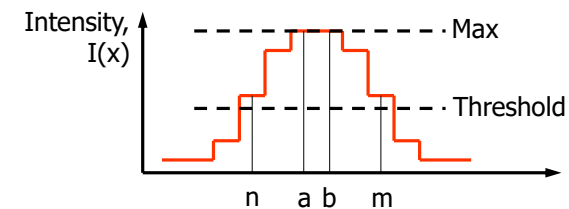
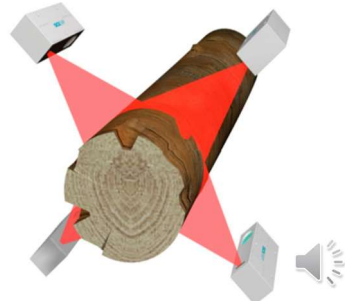


Fig. 1.7

## Application: Log Scanner

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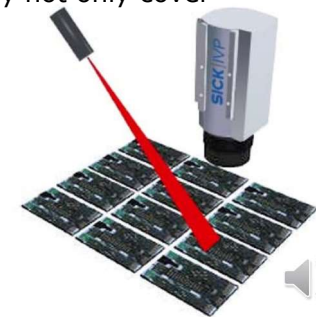
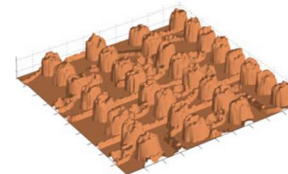
- The task is to measure the complete 3d-shape of the log and calculate the most optimal cutting pattern considering aspects like crook, bow, ovality, taper and log diameter.



## Application: 3D Solder Paste Inspection

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- Today, solder paste misprints are causing the majority of the faults found in finalized circuit boards. The range camera can measure the paste deposits in 3D, and thereby not only cover misaligned paste deposits, but also volume related print faults.

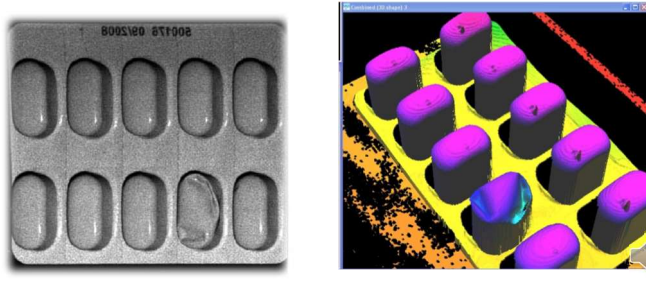


## Application: Blister Pack Inspection

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### □ Inspection Task:

- Each blister in every package should be checked for shape and integrity.
- Also it should be verified that the blister contains a pill.



## Application: Verification of Content in Praline Boxes

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### □ Inspection Task:

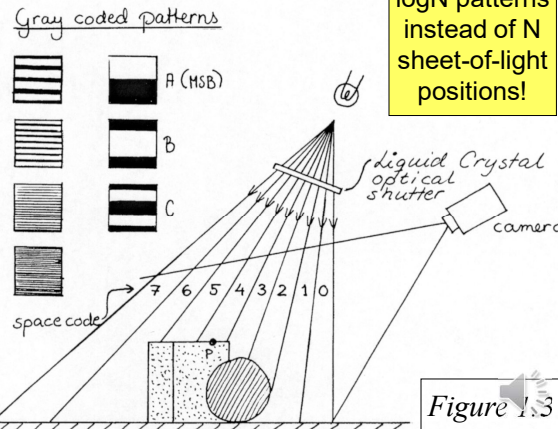
- 1. The shape of the pralines: are they shaped correctly?
- 2. The right position of the pralines in the box: is the right praline in the correct position?
- 3. The height of the pralines: have more pralines than required been added?



## Gray coded patterns instead of "sheet-of light"?

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The logN binary images can be combined to one image with coded positions in every pixel. Consequently N different codes are possible.



## Why Gray code instead of binary code?

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Normal binary code

0	0	0
0	0	1
0	1	0
0	1	1
1	0	0
1	0	1
1	1	0
1	1	1

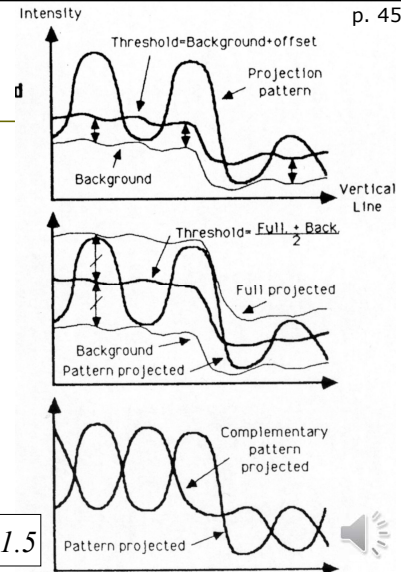
Gray code

1	0	0
1	0	1
1	1	1
1	1	0
0	1	0
0	1	1
0	0	1
0	0	0

Advantage: Because only one binary position changes at the time in the Gray code, one error does not give a big effect.

## Detection of patterns

- Background offset
- Local thresholding
- Complementary patterns



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## Microsoft Kinect 1

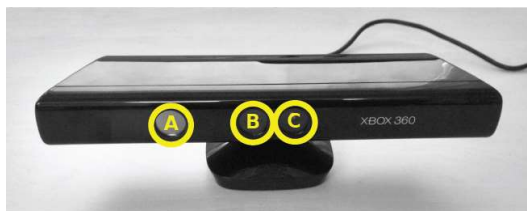
- Not a sales success, but an interesting technique.
- Based on structured light with random dots and triangulation.
- User interface to Xbox 360
- Arrived in Sweden November 10, 2010



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## Microsoft Kinect 1: RGB-D sensor

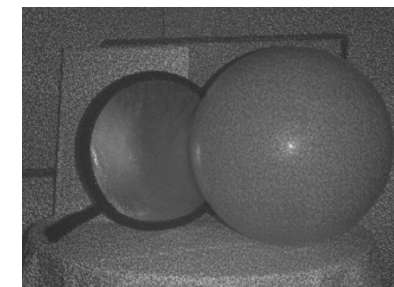
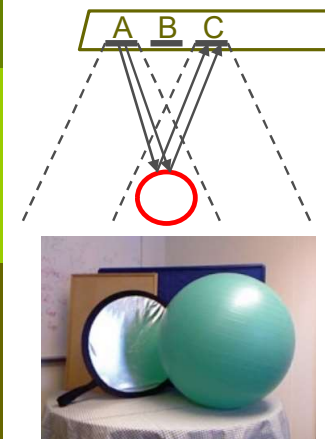
- A - NIR-laser projector
- B - CMOS colour camera
- C - CMOS NIR camera



- Active, due to the built-in IR-light source
- Problematic in strong light, e.g. outdoors.
- Problematic on rough surfaces.

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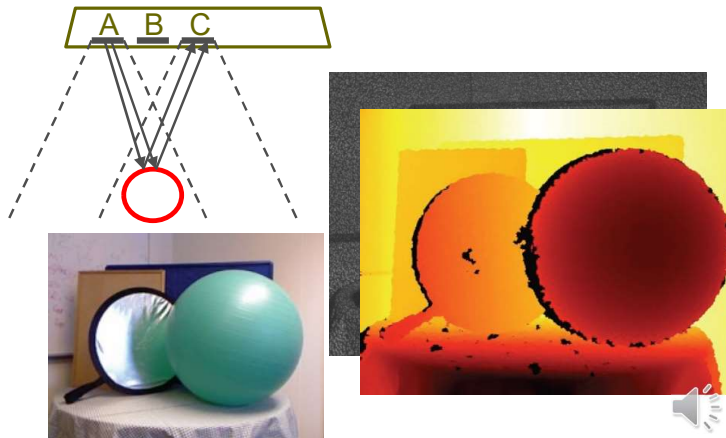
## Microsoft Kinect 1: Depth from triangulation



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## Microsoft Kinect 1: Depth from triangulation

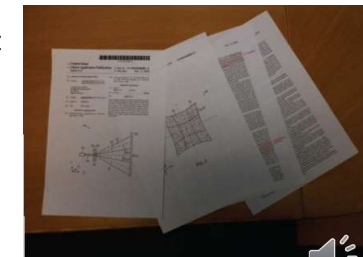
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## Microsoft Kinect 1 and others. Patent.

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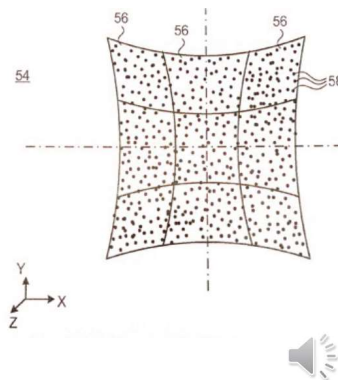
- Based on structured light with random dot pattern according to a patent from the Israeli company PrimeSense.
- Many variants: Microsoft Kinect, Asus Xtion, PrimeSense, Carmine...



## Microsoft Kinect 1: Structured light with random dot pattern

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- The dot pattern is designed to have as low an autocorrelation as possible:
  - for all shifts larger than the point size and ...
  - in the interval of disparities that the system needs to deal with, i.e. along the base-line.
- Corresponding points are received by correlation with pattern patches.
- Depth is then received from triangulation.
- Reduced detail resolution due to the correlation with pattern patches.



## IIIa) Time-of-flight. Light pulse and time measurement

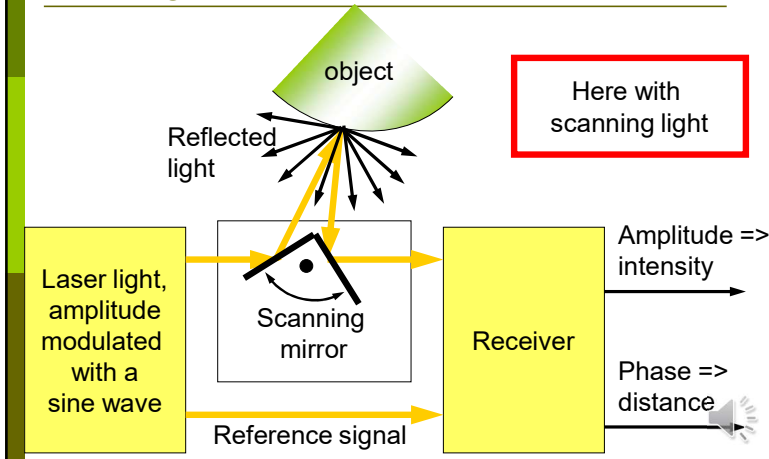
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- Same idea as RADAR: send out a light pulse and measure the time it takes for it to come back:  $s = v \cdot t$ , distance =  $s/2$ .
- Sometimes called LIDAR or LADAR, (light+RADAR)
- Demands an accurate clock, since  $v = 3 \cdot 10^8$  m/s

Clock accuracy	Depth accuracy
1 ms	$\pm 300$ km
1 ns	$\pm 3$ dm
1 ps	$\pm 0.3$ mm

### IIIb) Time-of-flight. Amplitude modulated light and phase shift measurement

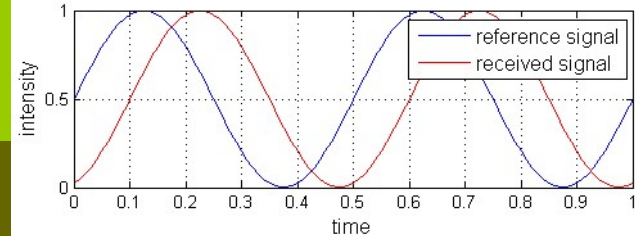
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### IIIb) Time-of-flight. Amplitude modulated light and phase shift measurement

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- The phase difference between the reference signal and the received signal gives the time difference, which gives the range.
- There is an ambiguity in phase/time difference. In the figure, time difference can be 0.1 or 0.6.



Note that the frequency of light is MUCH larger than the amplitude modulation frequency.

- In theory: Two amplitude modulated signals with frequencies with no common factor can measure all ranges.

### A simple method to measure phase

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- Subtract 0.5 from both signals.
- Call the received signal  $r(t) = \cos(\omega t - \phi)$ .
- Call the reference signal  $s_1(t) = \cos(\omega t)$ .
- Also use another reference signal  $s_2(t) = \sin(\omega t)$ .
- The period time is  $T = 2\pi/\omega$ .
- Multiply and integrate ("correlate"), compute the phase  $\phi$ :

$$v_1 = \int_T s_1(t)r(t)dt = \frac{\cos \phi}{2},$$

$$v_2 = \int_T s_2(t)r(t)dt = \frac{\sin \phi}{2}$$

$$\phi = \arg(v_1 + iv_2)$$

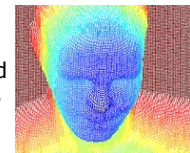
- Three measurements are resistant to noise and bias, see lecture Range Cameras 2.



### IIIb) Time-of-flight. Amplitude modulated light and phase shift measurement

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- The MESA camera SR-3000, SR-4000, SR-4500
- See the datasheet on SR-3000 for more information.
- **No scanning.** Sends out amplitude modulated IR-light in many directions at the same time.
- Catches a 3D scene in real time.
- 176 X 144 sensor elements.
- Non-ambiguous range: 7.5m.
- Distance resolution:  $\approx 1\%$  of range.
- Not for sale anymore, but the principle is similar to Kinect 2, see last slides.



## Microsoft Kinect 2 for the Xbox One

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- Time-of-flight instead of structured light as Kinect 1



## Microsoft Kinect 2

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- Time-of-flight method: Amplitude modulated light and phase shift measurements.
- Three different frequencies are used. They are sampled with 3 samples per period.
- My colleagues at CVL work with range cameras. On the next lecture on Range cameras, we will learn more.

