3D Vision System Development

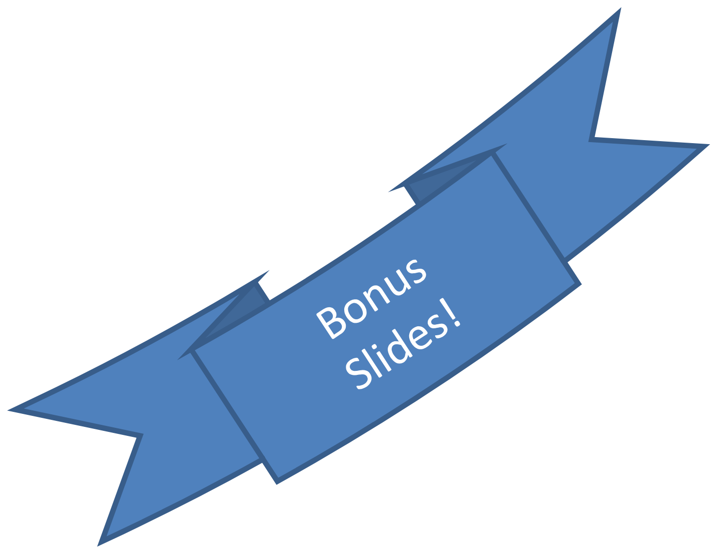
Mattias Johannesson

Expert, 3D Vision

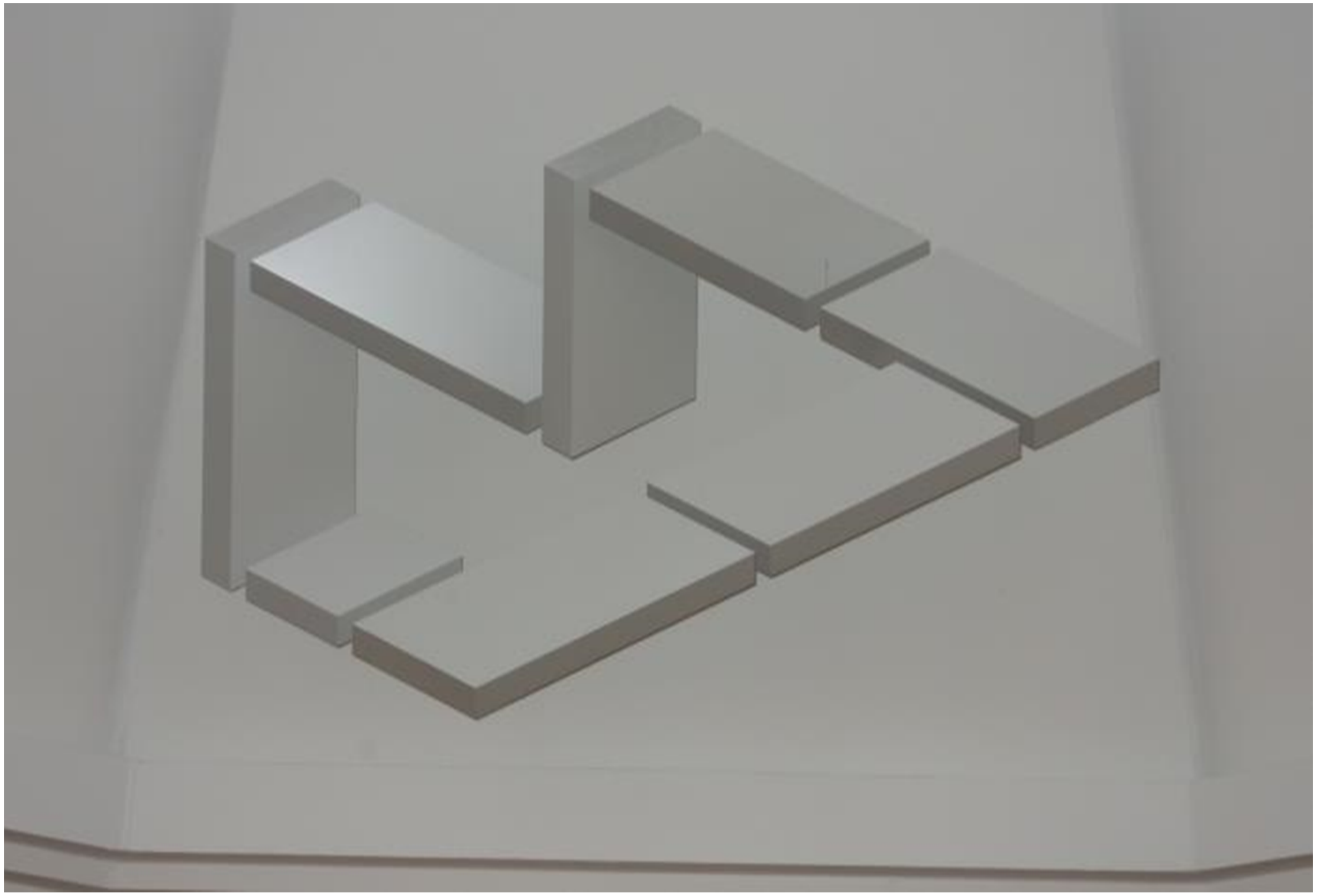
SICK

Agenda

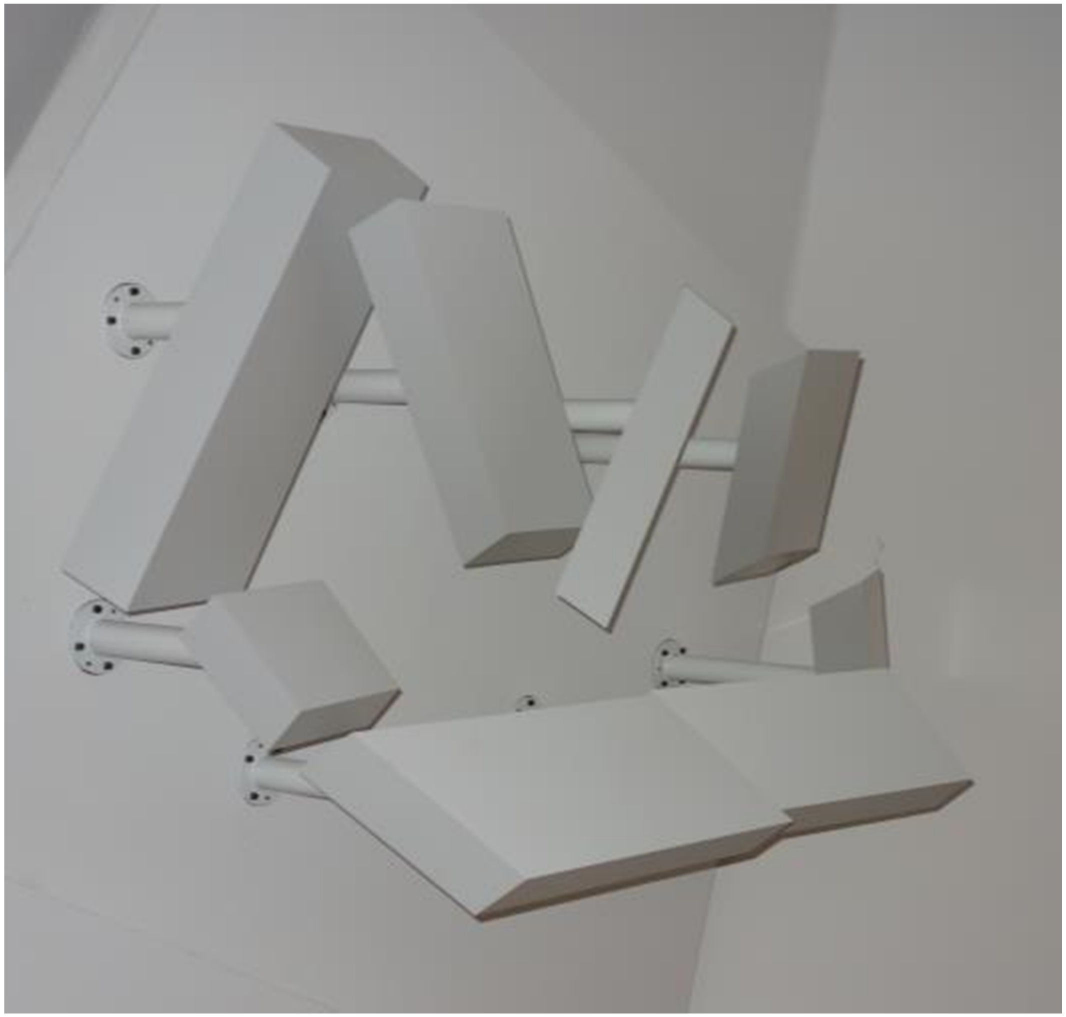
- Why do we need 3D Vision?
- Definitions in 2D & 3D Vision
- 3D Techniques and Applications
  - What fits where?
- Conclusions
- ….and bonus slides!



Why 3D?

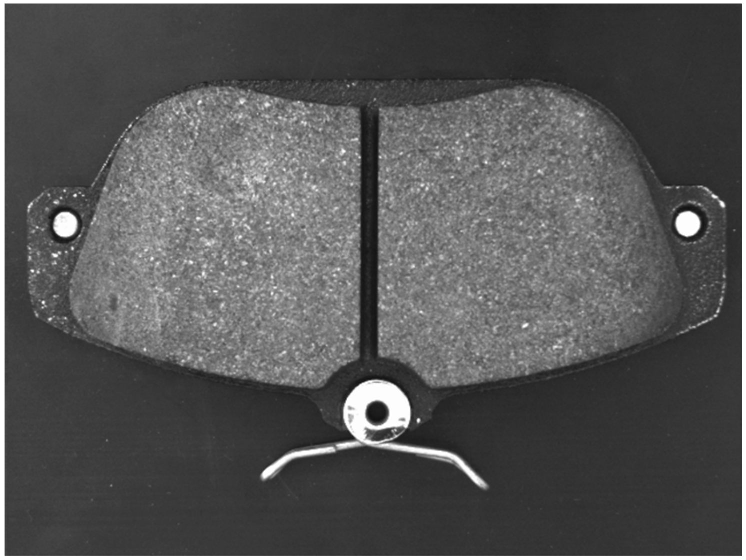


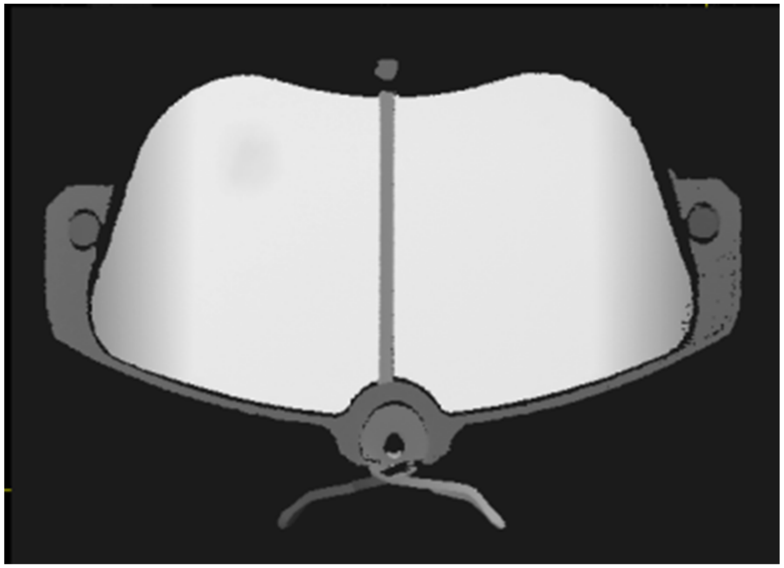
Why 3D?

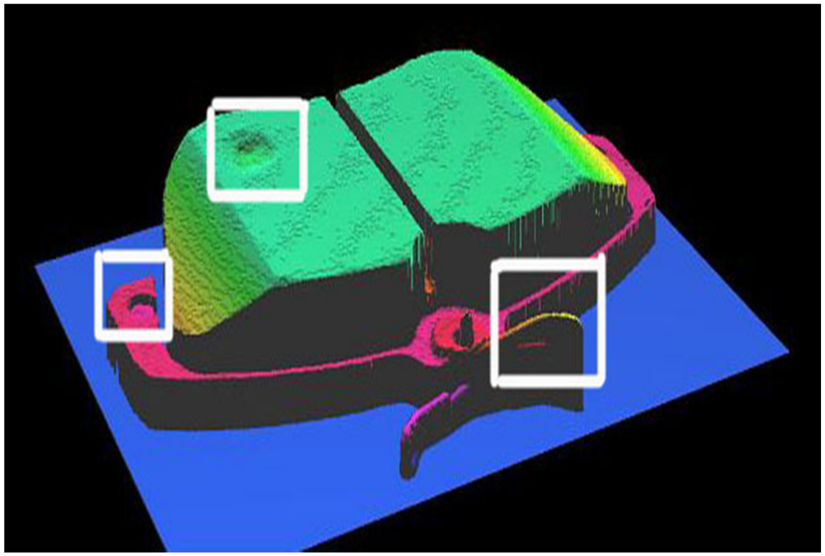


Why 3D?

Why 3D?

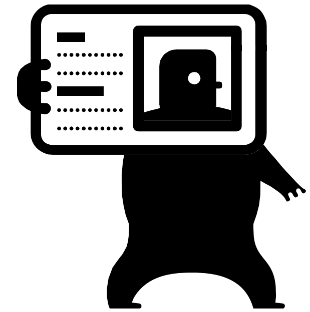


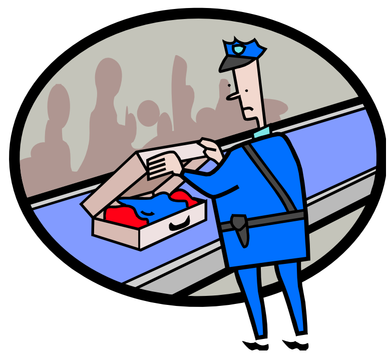


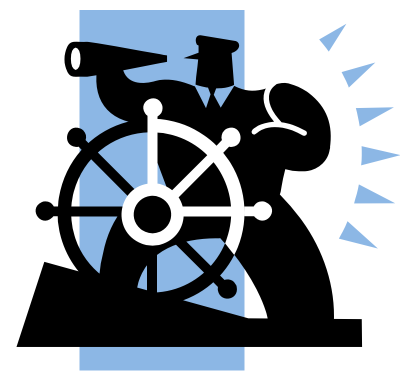


3D Vision Use

- To measure
- To locate
- To identify
- To inspect
- To navigate



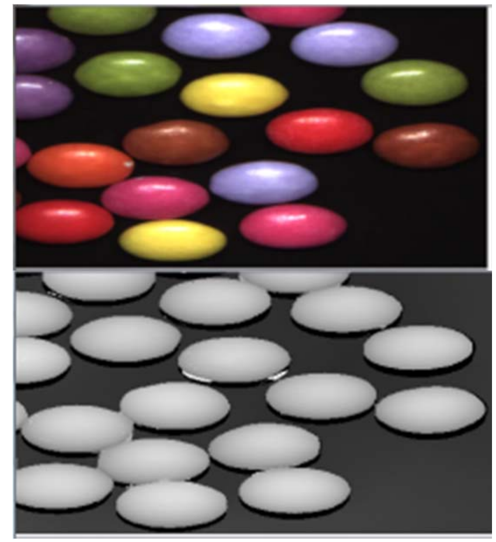


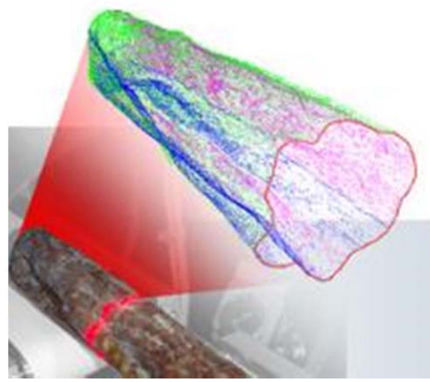


- 3D more difficult than 2D
  - Get good “image”
    - Illumination more critical than in 2D
  - Use capable SW package
    - Avoid reinventing the wheel

Data Types

- 2D intensity
  - 2D array of brightness/color pixels
- **2.5 D range**
  - **2D array of range/height pixels**
  - **Single view-point information**
- 3D surface range data
  - Surface coordinates [x,y,z]
  - Point cloud data





- 3D "voxel"
  - A volume [x,y,z] of densities
  - e.g., CT scan

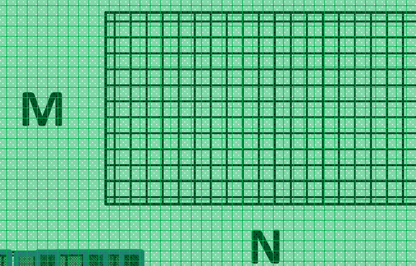
Ranging Techniques

- Passive range imaging
  - No dedicated light source
  - Very, very difficult in a real world...

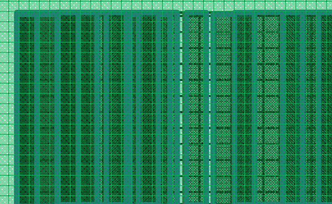
- Active range imaging
  - Dedicated illumination
  - Typically defined spatially *Where*
    - Triangulation
  - Or defined temporally *When*
    - Time of flight principles

Acquisition Speed

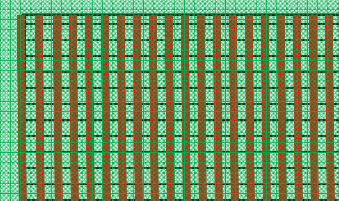
- Range imaging is typically not snapshot as 2D cameras
- Snapshot **O(1)**
  - Stereo
  - Primesense / "Kinect"
  - Time-of-flight array camera



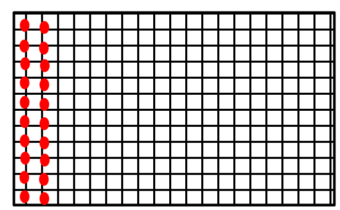
- "Almost" snapshot **O(log(N))**
  - Structured light projection
  - Moving camera stereo



- 1D scanning **O(N)**
  - Linear movement of object / illumination
  - 1D scanning (depth from focus, interferometry)

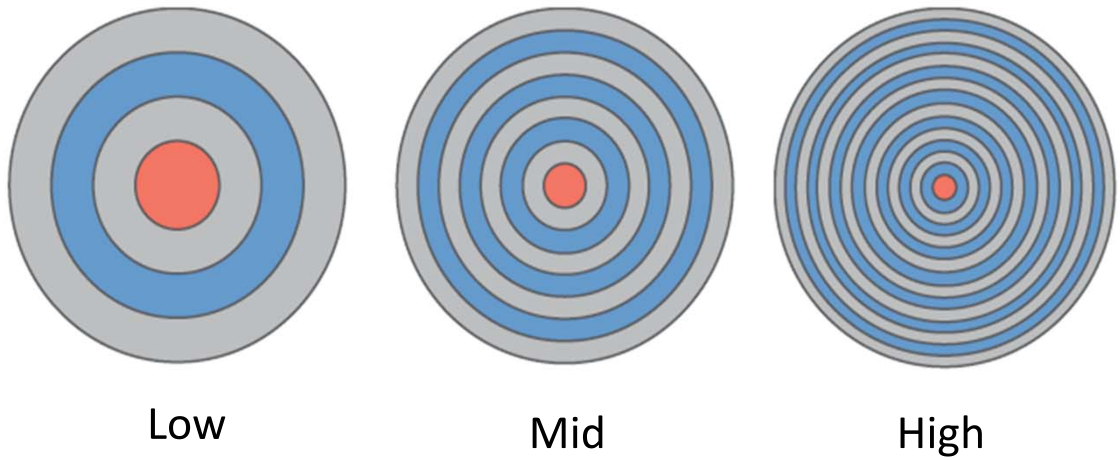


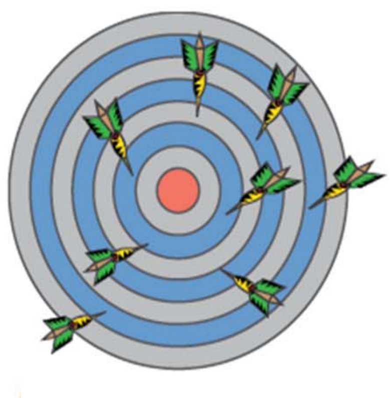
- 2D scanning motion **O(N*M)**
  - 2D scanner
  - Linear movement of object + 1D scanning



Accuracy

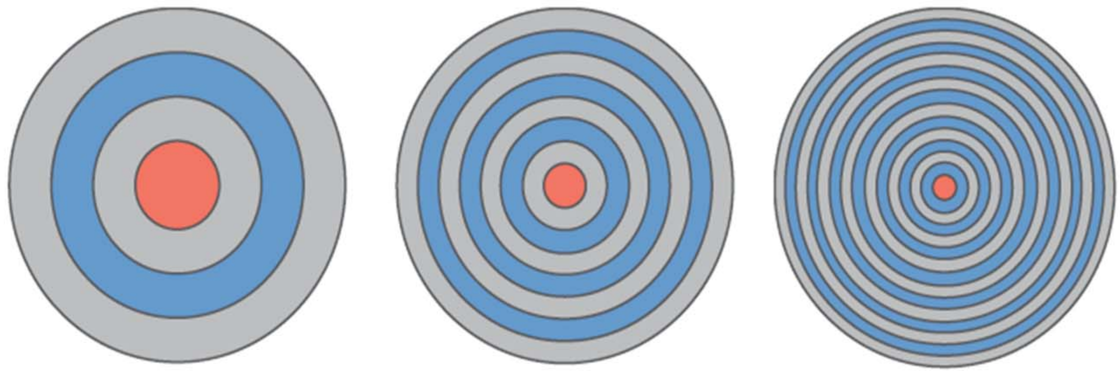
- Resolution
  - Pixel size ΔX, ΔY
  - The min ΔZ
- Repeatability
  - First step to accuracy



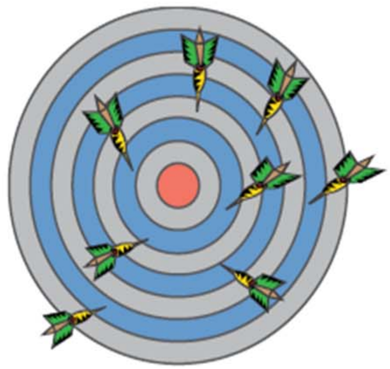


Accuracy

- Resolution
  - Pixel size ΔX, ΔY
  - The min ΔZ
- Repeatability
  - First step to accuracy

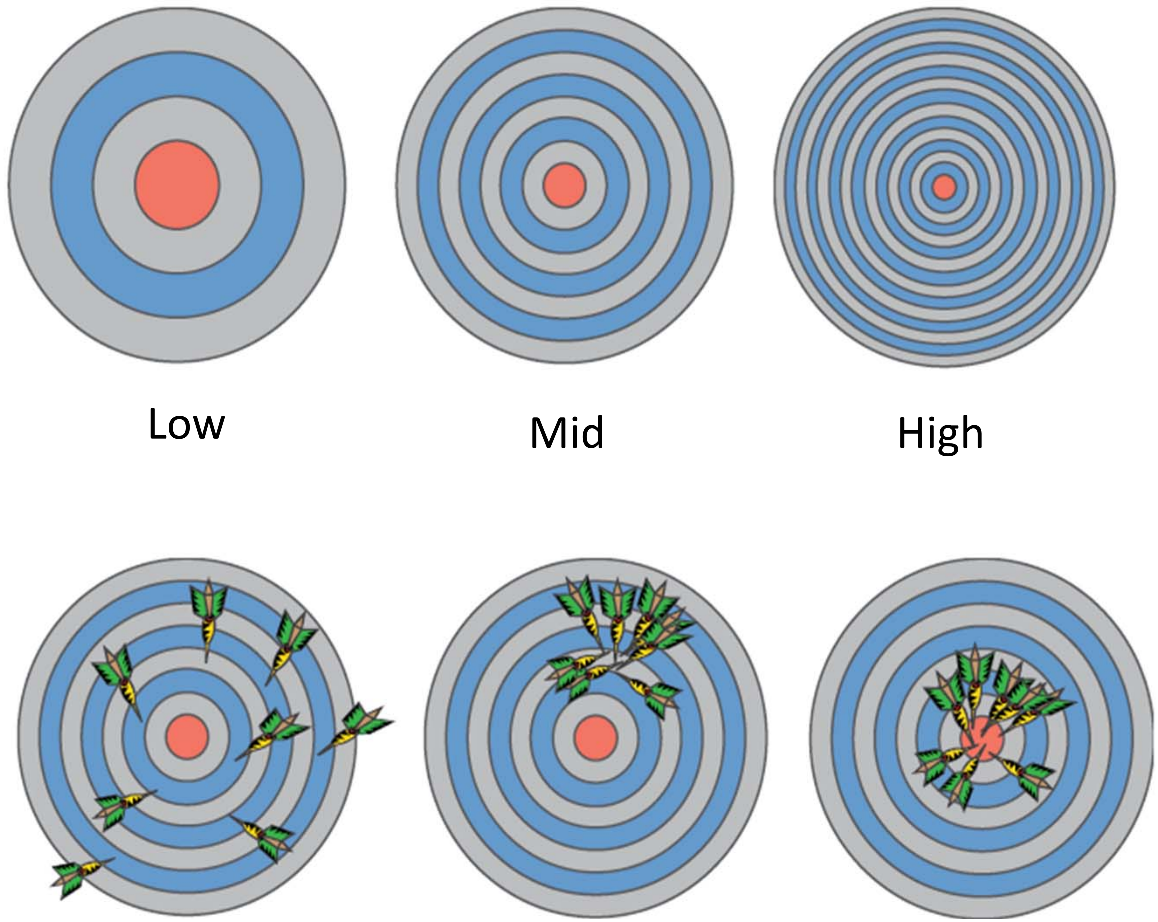


Low Mid High



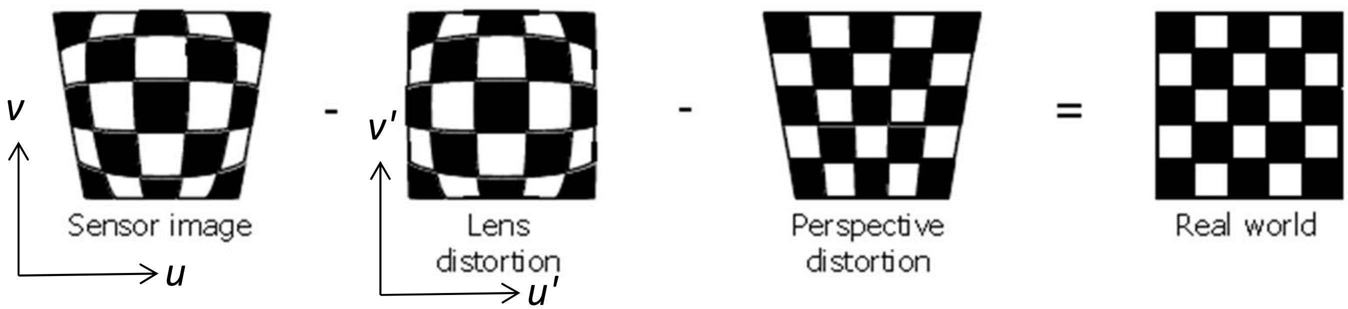
Accuracy

- Resolution
  - Pixel size ΔX, ΔY
  - The min ΔZ
- Repeatability
  - First step to accuracy
- Accuracy
  - If the system is repeatable then accuracy is "just" calibration



Calibration

- Map Relative image coordinates to World coordinates
  - Lookup Table or Model



$$u' = u + u_0\left(c_1 r^2 + c_2 r^4\right) + 2c_3 u_0 v_0 + c_4\left(r^2 + 2u_0^2\right)$$

$$v' = v + v_0\left(c_1 r^2 + c_2 r^4\right) + 2c_4 u_0 v_0 + c_3\left(r^2 + 2v_0^2\right)$$

$$u_0 = u - u_c$$

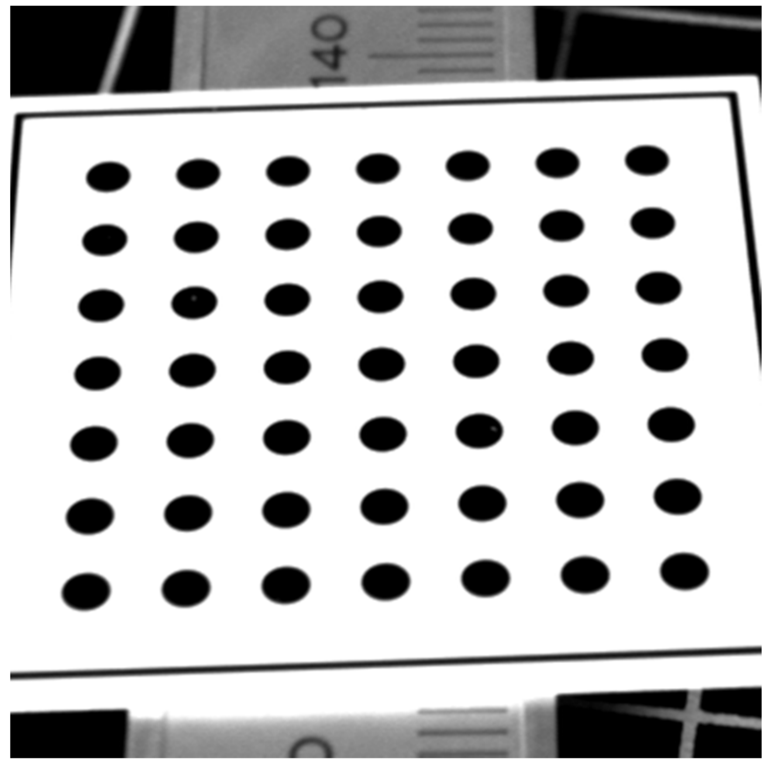
$$v_0 = v - v_c$$

$$r = \sqrt{u_0^2 + v_0^2}$$

$$\begin{pmatrix} X \\ Z \\ s \end{pmatrix} = H \begin{pmatrix} u' \\ v' \\ 1 \end{pmatrix} = \begin{pmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{pmatrix} \begin{pmatrix} u' \\ v' \\ 1 \end{pmatrix},$$

Calibration Procedure

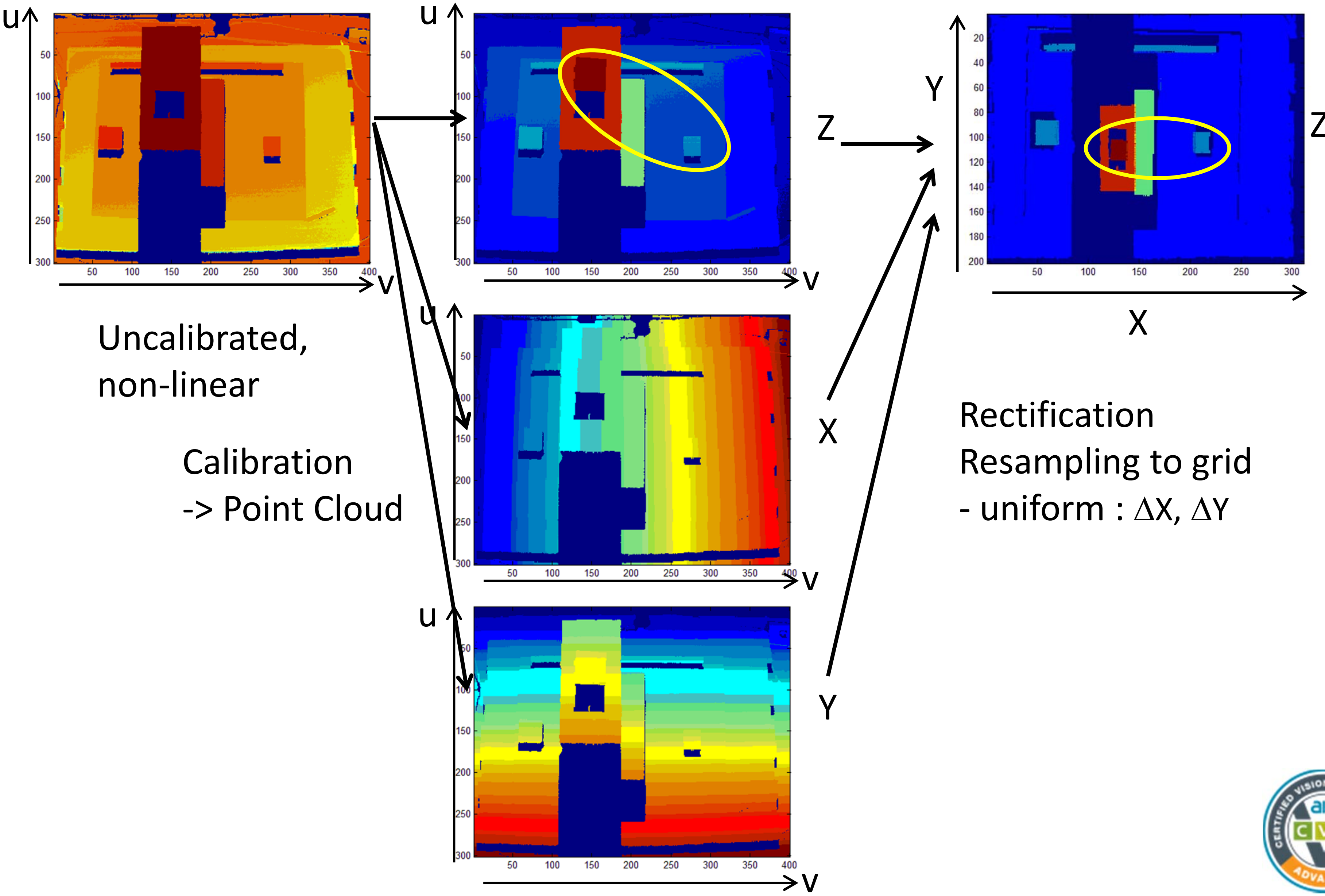
- Measure a known target, let the SW crunch the data...



Calibration – Rectification

- Calibration gives world coordinate point cloud
  - Z image plane distorted
- Rectification gives image fit for "standard" processing
  - 1 Z value for each “integer” {X,Y} coordinate

Calibration – Rectification



Uncalibrated,
non-linear

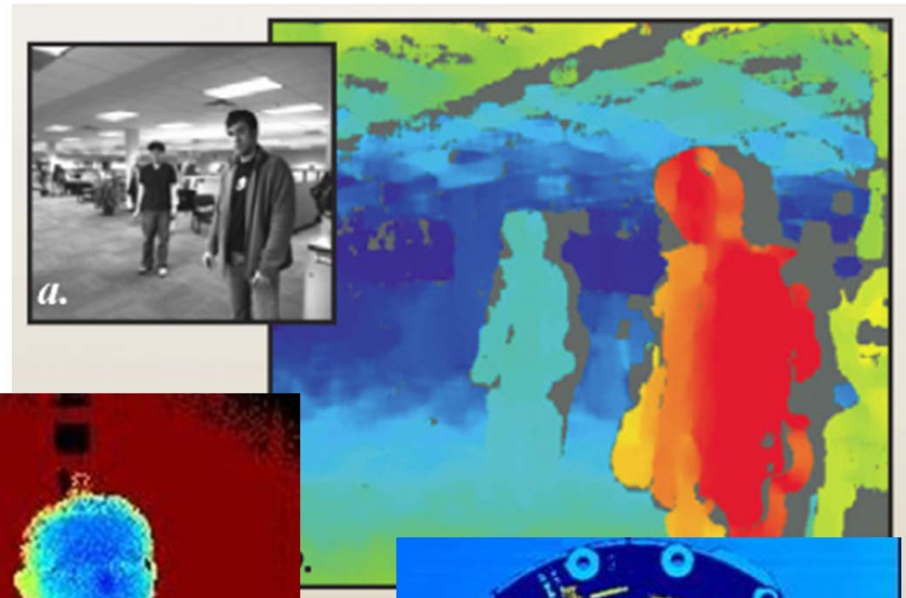
Calibration
-> Point Cloud

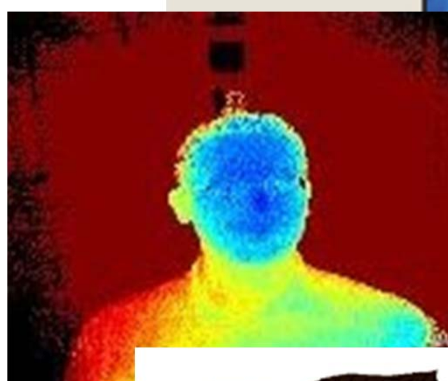
Rectification
Resampling to grid
- uniform : ΔX, ΔY

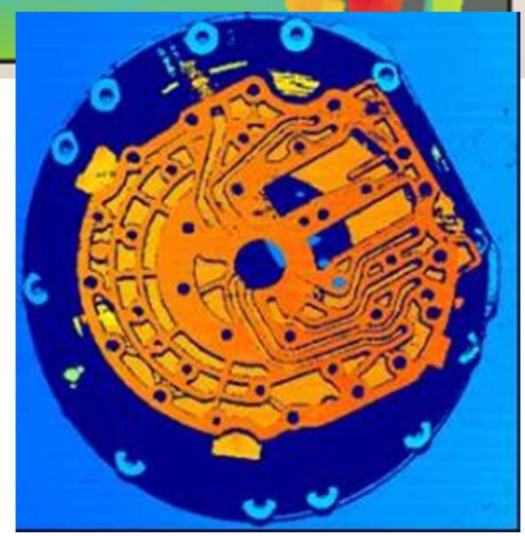
3D Imaging Methods

- Triangulation
  - Stereo
  - Structured light
    - Sheet-of-light
    - Projected patterns
- Time-of-flight
- Misc.
  - Focus
  - Shading
  - Interferometry
  - Light field

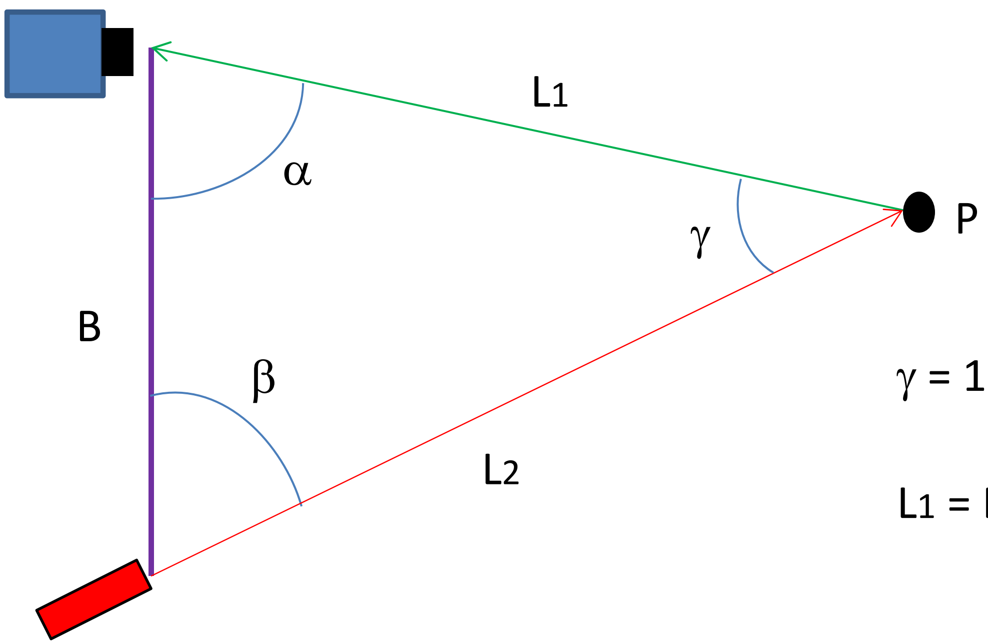
Bonus Slides!







Triangulation Principle



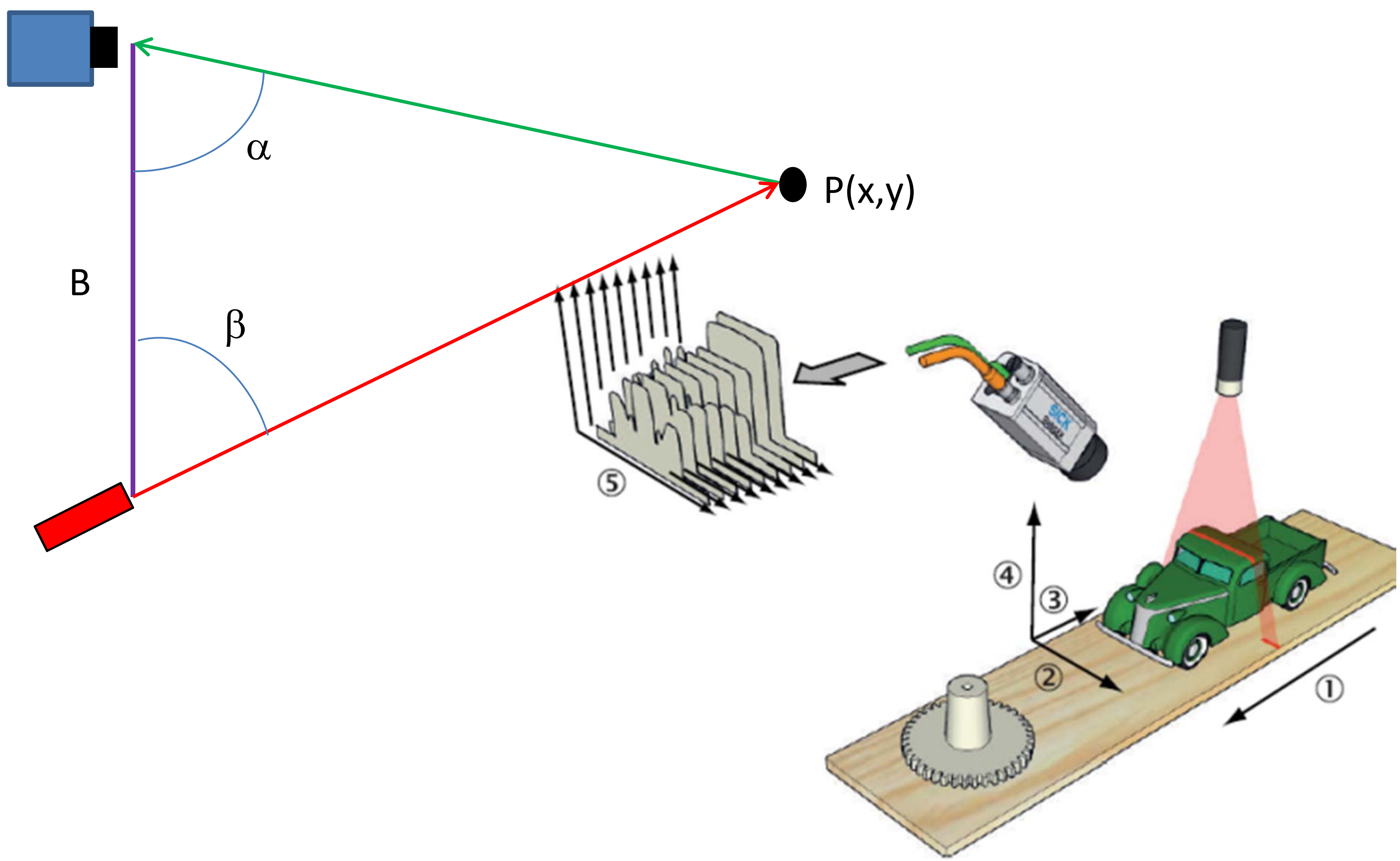
$\gamma = 180 - \alpha - \beta$

$L_1 = B * \sin\beta / \sin\gamma$

Robustness:
- Large B
- Large γ

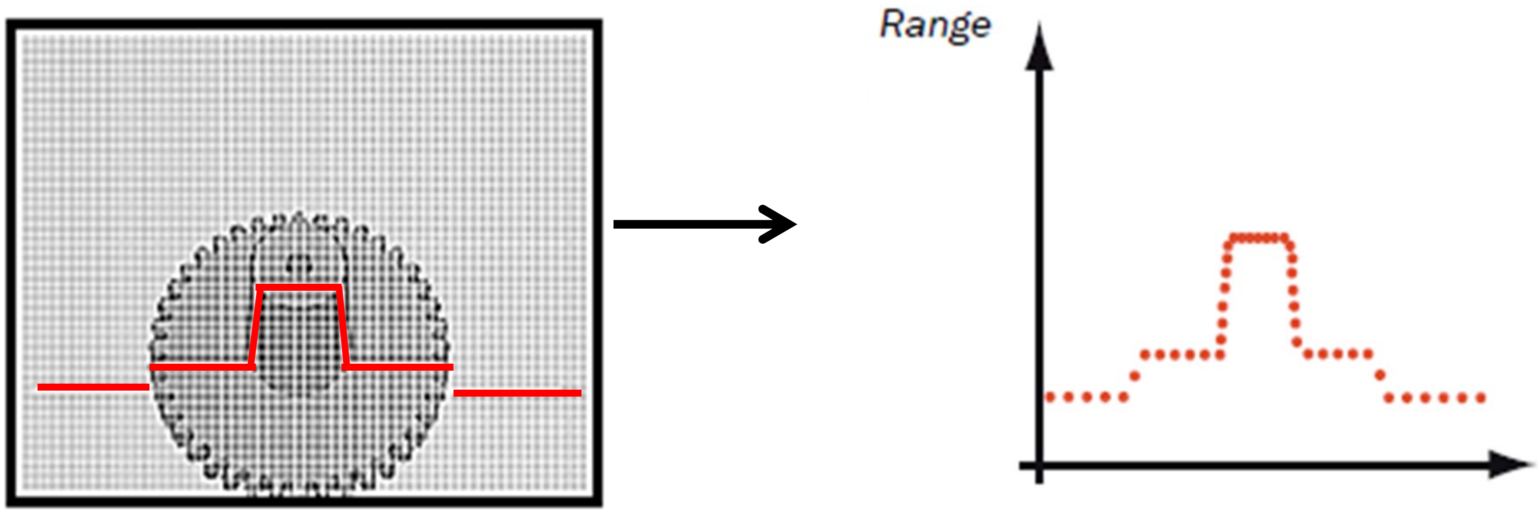
Laser Line Triangulation

- "Simple" special case of "structured light"



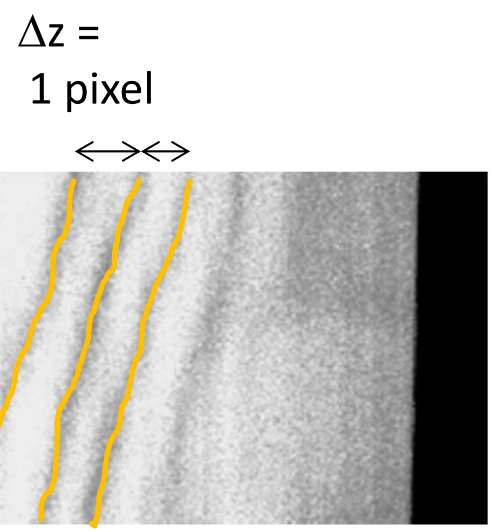
Laser Line Triangulation 1

- 2D sensor + laser line
- Each 2D intensity image -> 1 3D profile
  - sensor/camera processing -> early data reduction
- Find peak position / column
  - High sub-pixel resolution is possible, e.g.
    Center-Of-Gravity,
    Interpolated peak position, etc.



Laser Line Width

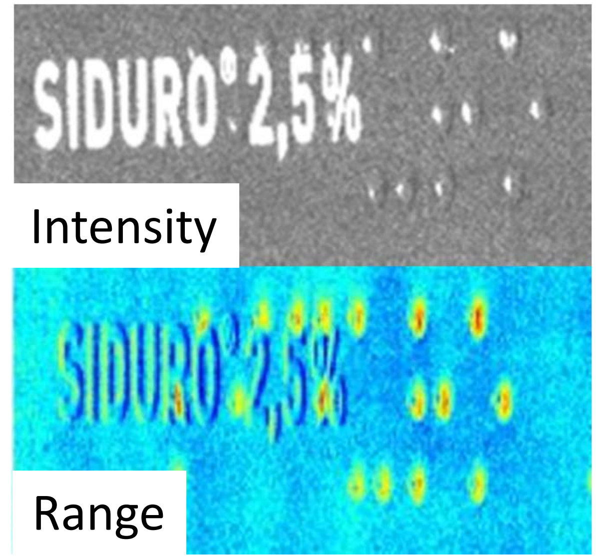
- Wide line - high-resolution sub-pixeling
  - Typical at least 3-5 pixels needed
  - Wide line can give edge artifacts
- Narrow line – less edge artifacts on range
  - Intensity modulation effects
  - Poor sub-pixel resolution



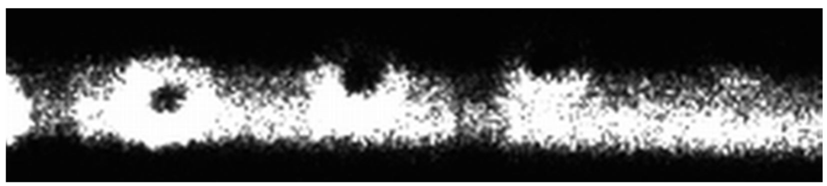
Intensity image from laser line

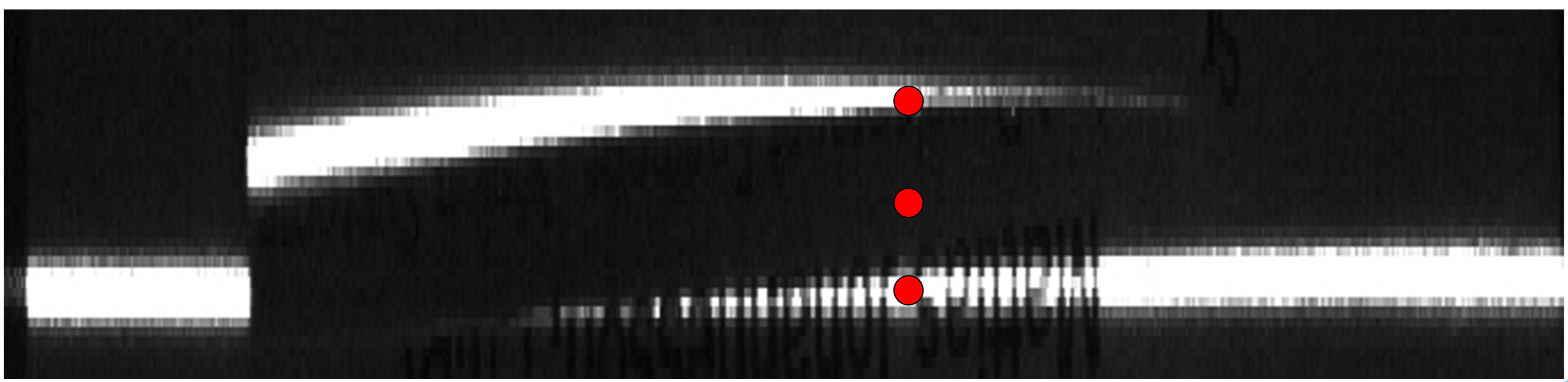
Peak Finding Issues

- The laser covers multiple pixels
  … and can hit a distance transition
  or intensity modulation



- Laser speckle gives noise on the peak



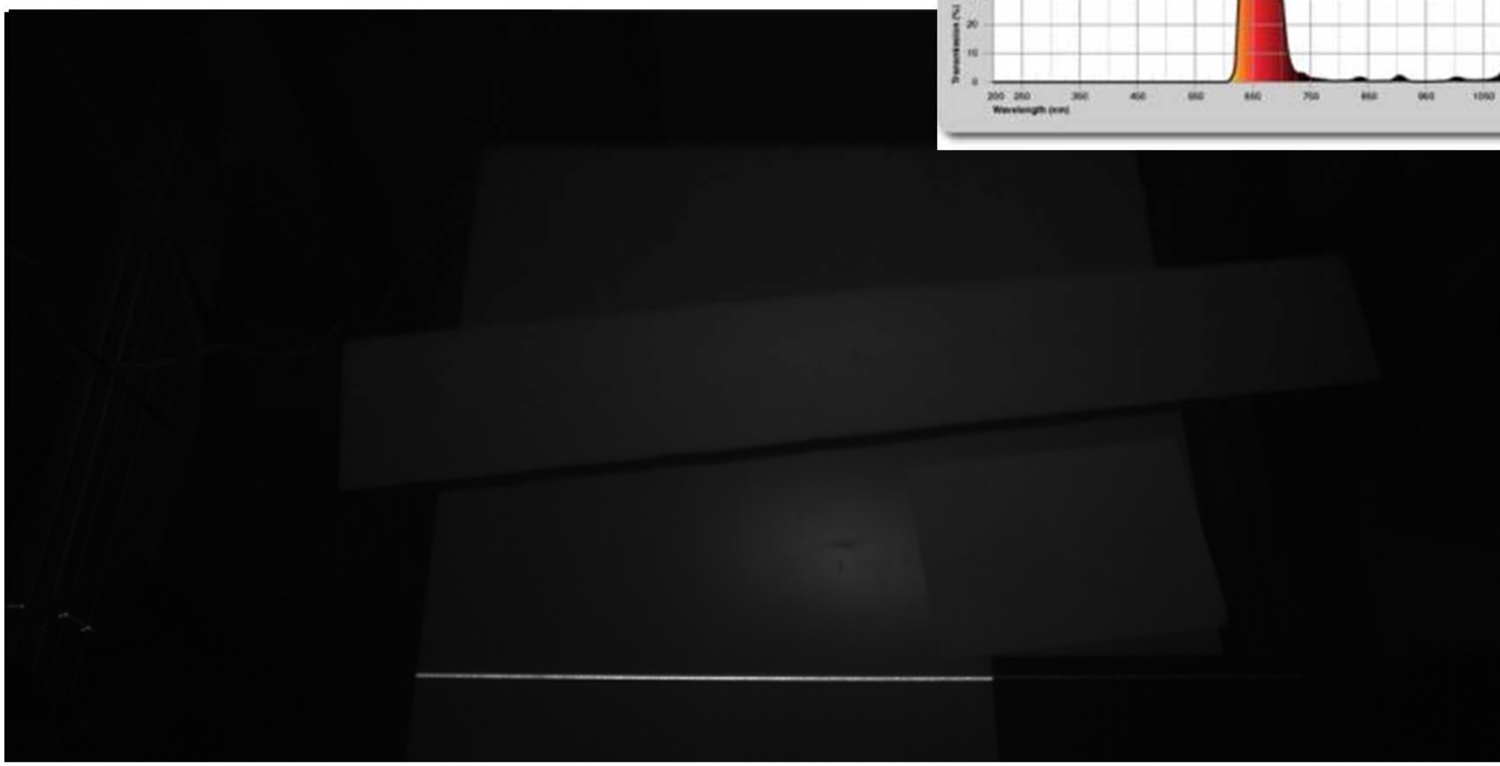


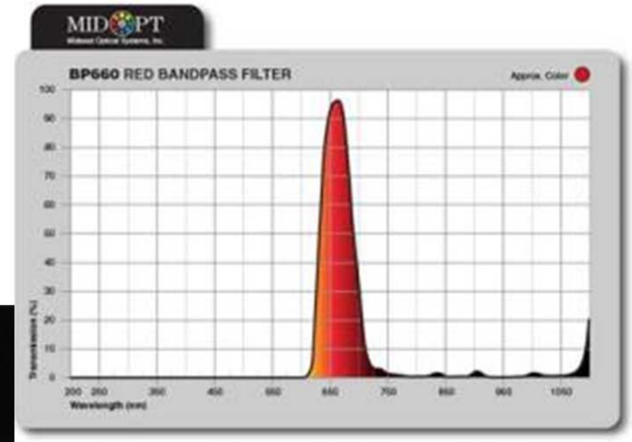
Ambient Handling

- Ambient light not good !

Ambient Handling

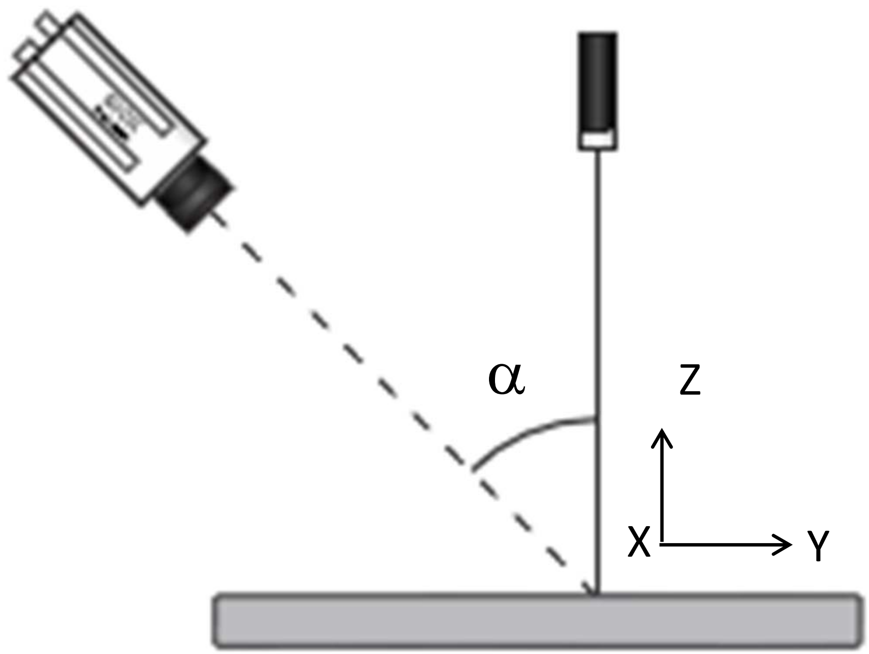
- Ambient light not good
  - Interference filter on camera





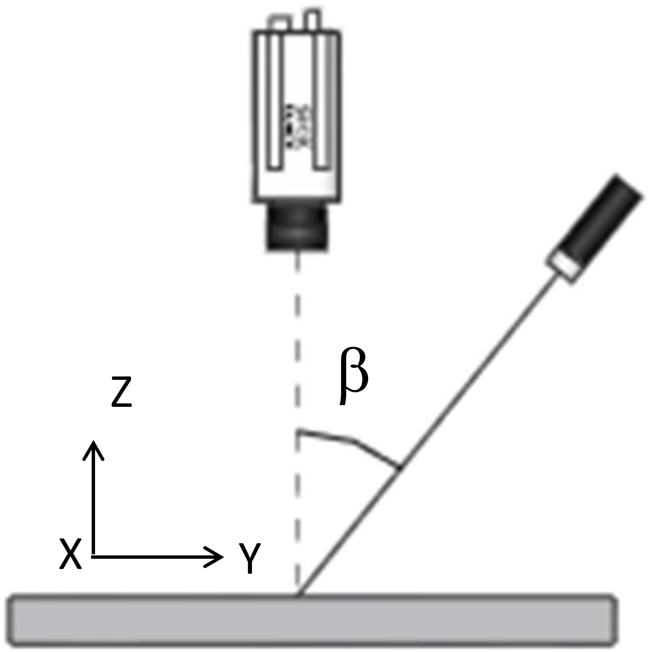
Geometry Options 1(2)

- Vertical laser gives "natural slicing"
- $\Delta z \sim \Delta x/\sin(\alpha)$ Δx is pixel resolution in width
- $\Delta z > \Delta x$



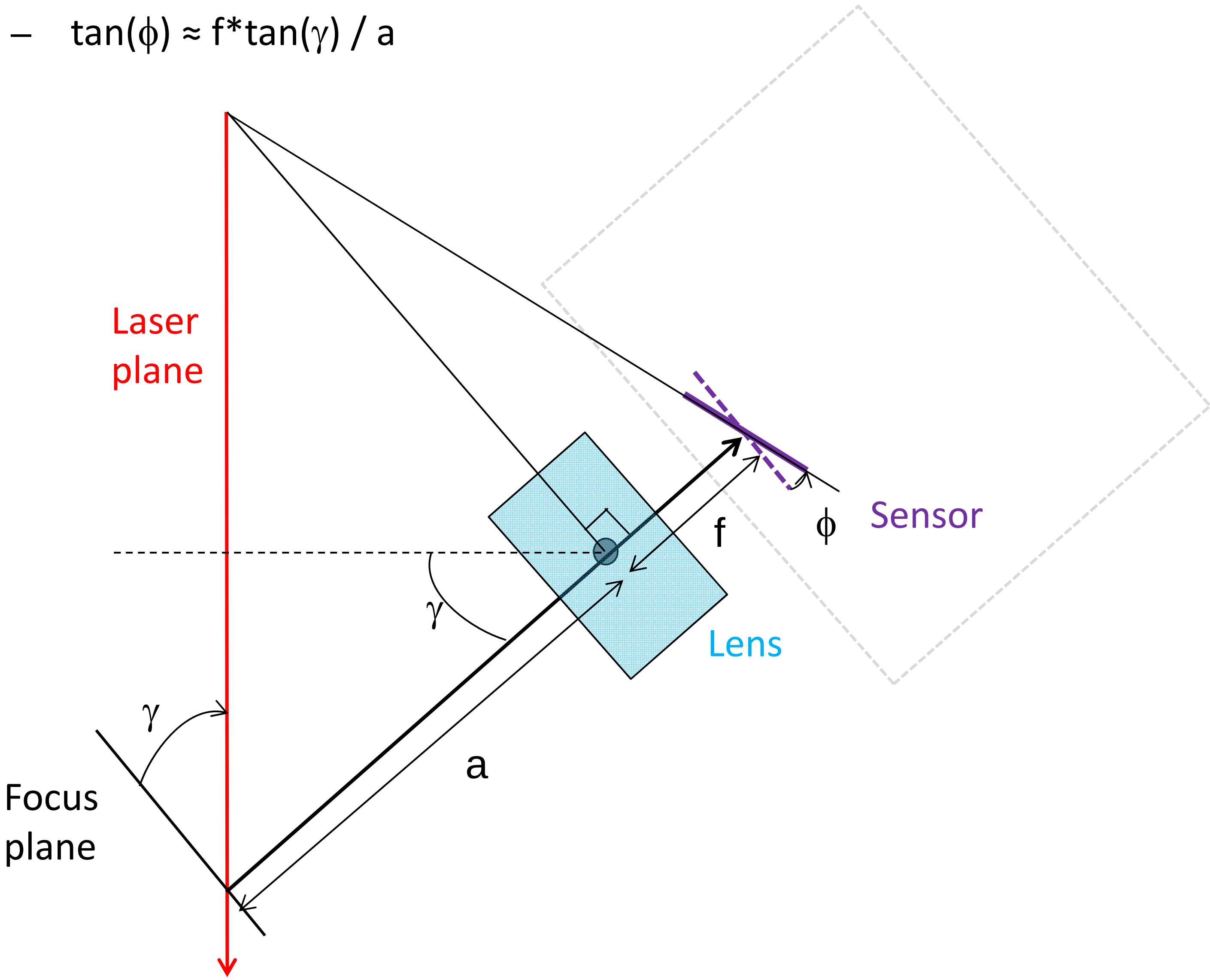
Geometry Options 2(2)

- Vertical camera gives good 2D imaging options
  - can give very high Z resolution
- $\Delta z \sim \Delta x/\tan(\beta)$ Δx is pixel resolution in width
- $\Delta z > \Delta x$ for $\beta < 45$
- $\Delta z < \Delta x$ for $\beta > 45$



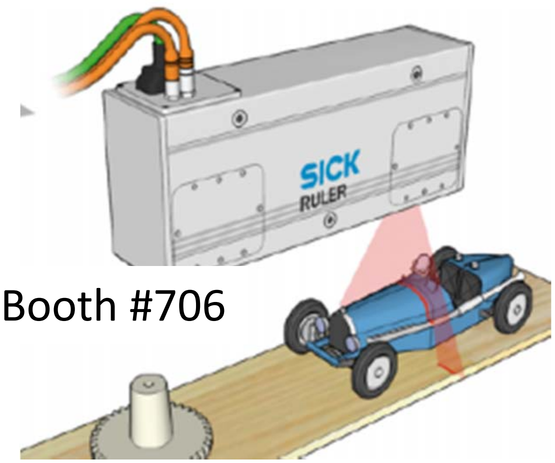
Scheimpflug Focussing

- Tilt sensor to focus laser plane
  - $\tan(\phi) \approx f{*}\tan(\gamma) / a$



Laser Triangulation Products

- Product examples
  - Algorithm support in vision SW packages
  - SICK Ranger/Ruler/IVC — - Proprietary CMOS sensor, multi scanning/color
  - Automation Technology — - Fast CMOS sensors and FPGA processing
  - Photonfocus — - Fast CMOS sensors + Lin-Log response



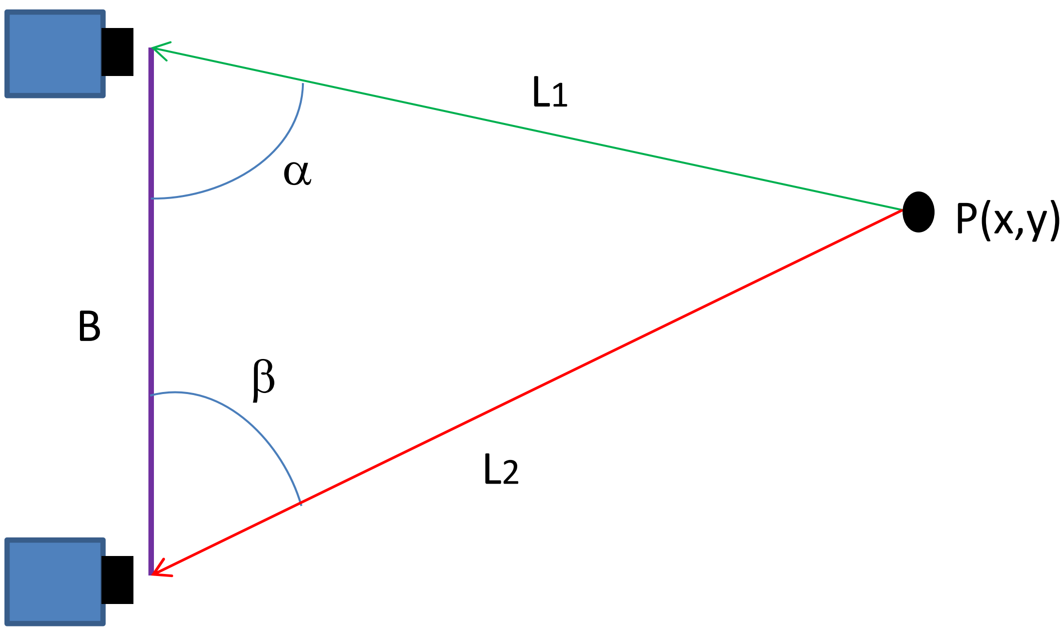
Booth #706

Booth #500

Laser Triangulation Conclusions

- Benefits
  - "Micrometer to mm" resolution scalability
  - Fast and robust
  - Moving objects -> No additional scanning needed
- Limitations
  - Occlusion
  - Not suitable for large outdoor applications (~ > 1 m FOV)
  - Not snapshot
- Typical applications
  - Log/board/veneer wood inspection
  - Electrical components / solder paste
  - Food and packaging

Stereo Imaging 1

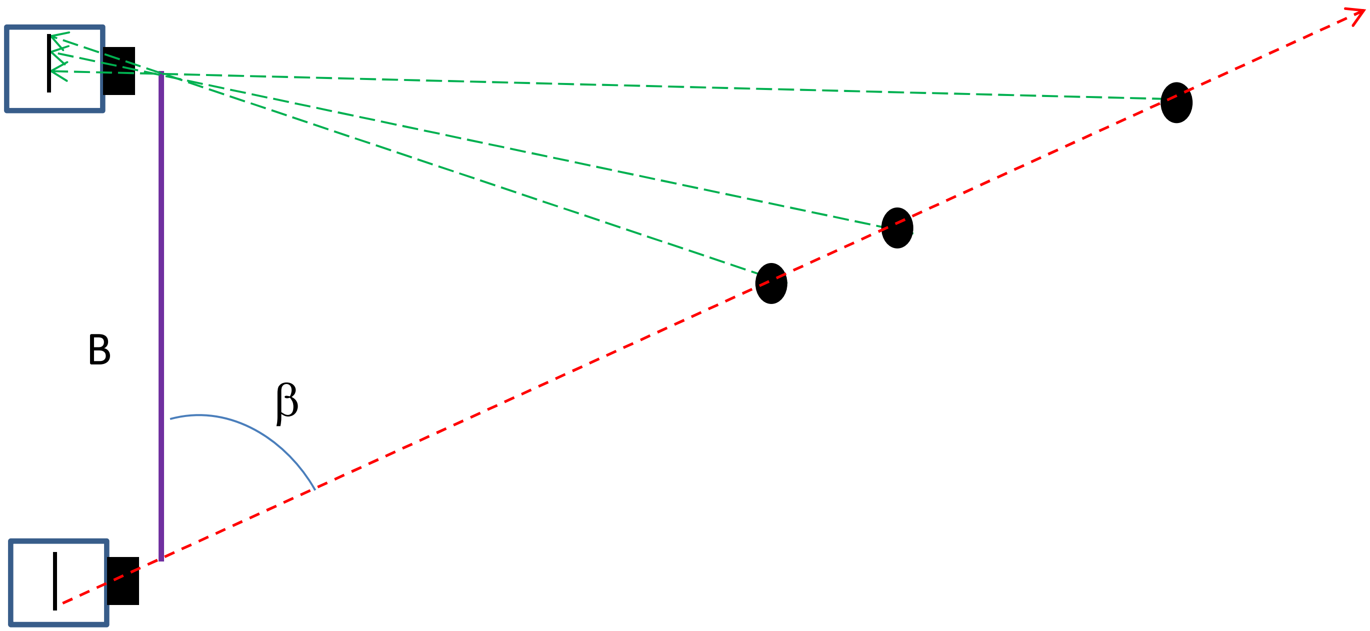


Stereo Imaging 2

- Stereo is based on (at least) 2 views of a scene
  - Human vision….
- Key is matching between the images
  - But pixels are not at all unique so …
    - Either patches of pixels are matched or
    - Distinct features/landmarks are matched
- So, *where* do we match ?

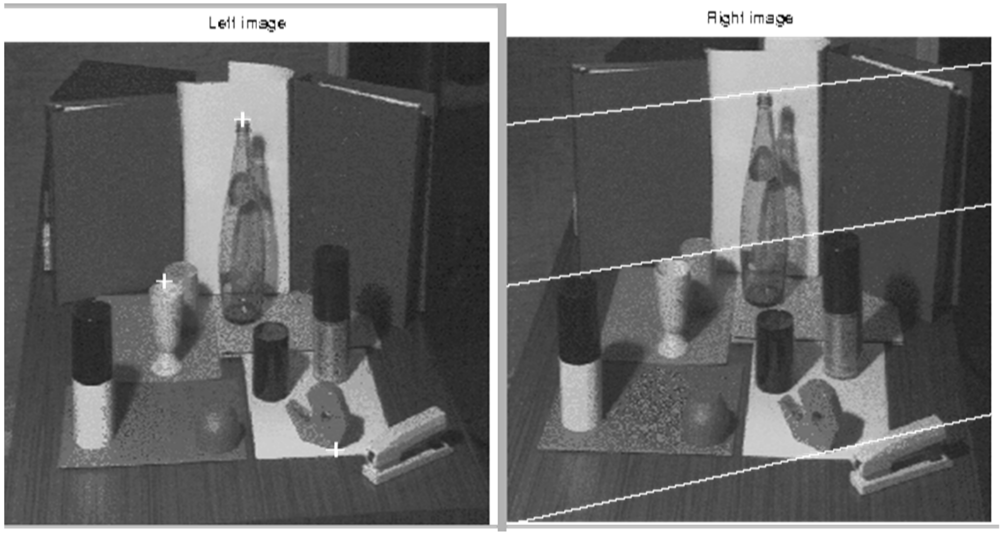
Where to Match?

- Simple 1D case : Along a line in the plane



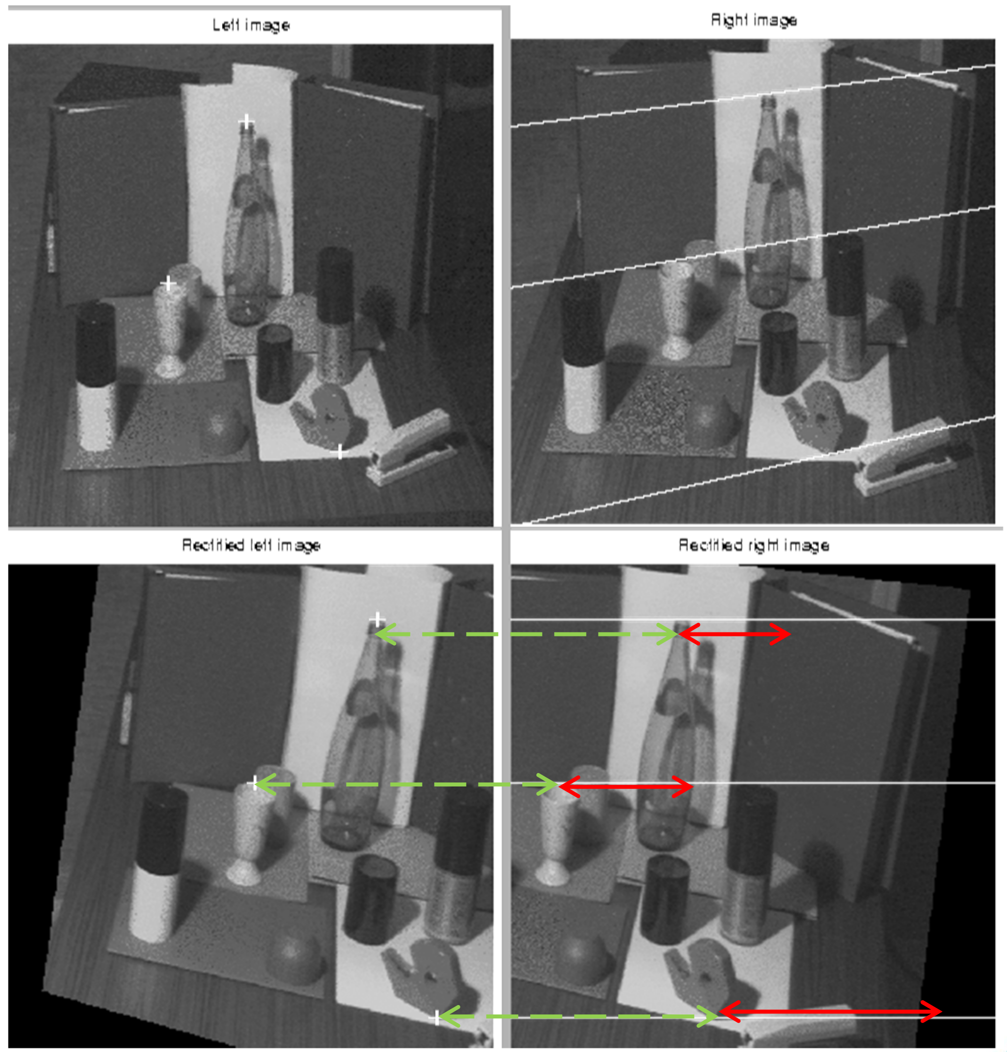
Epipolar Lines

- Unrectified
  - tilted/curved
  - epipolar lines



Epipolar Lines

- Unrectified
  - tilted/curved
  - epipolar lines
- Rectified
  - aligned epipolar and matching
- Find *Disparity*
  - Difference in position



Disparity Matching

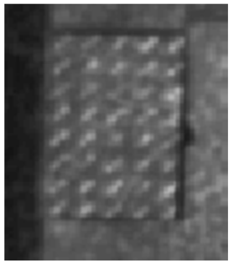
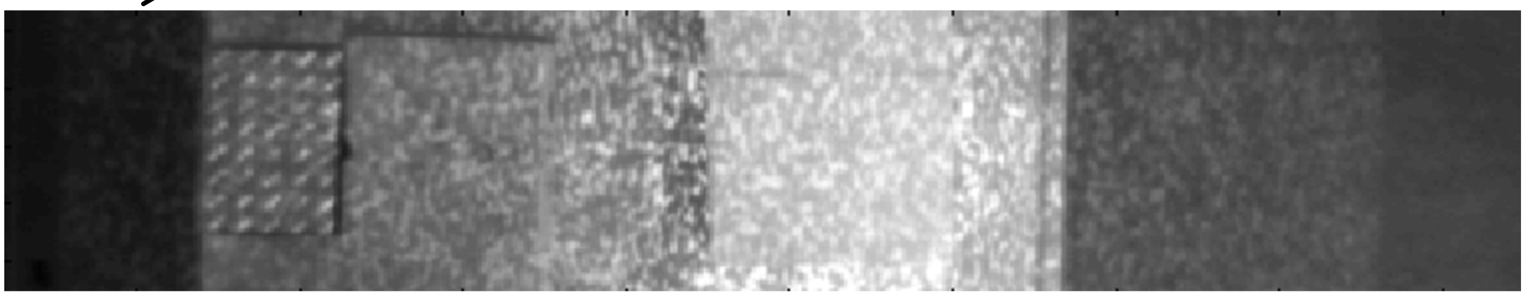


Image Patch : **f**(u,v)

disparity

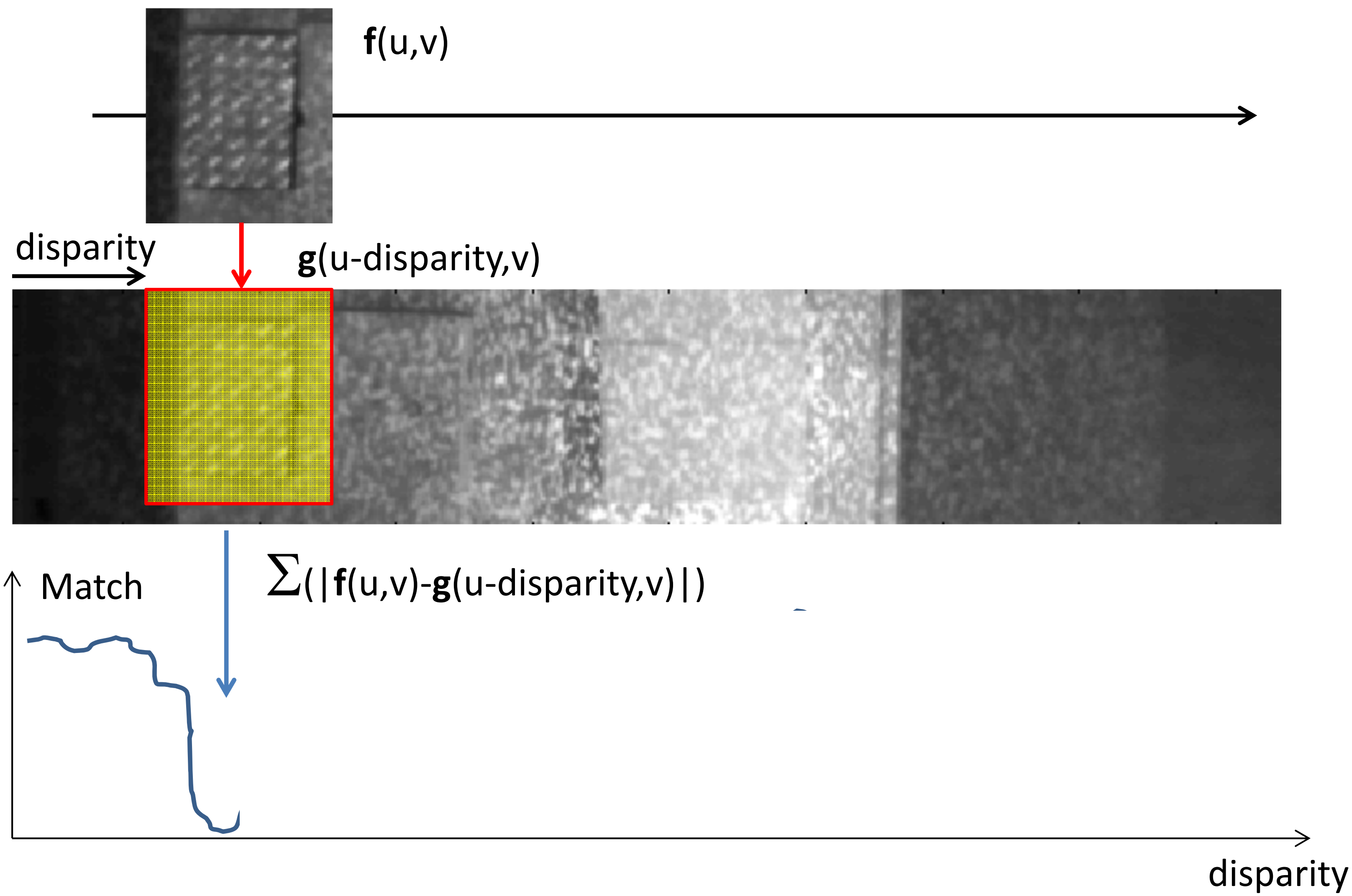
Epipolar swath : **g**(u-disparity,v)



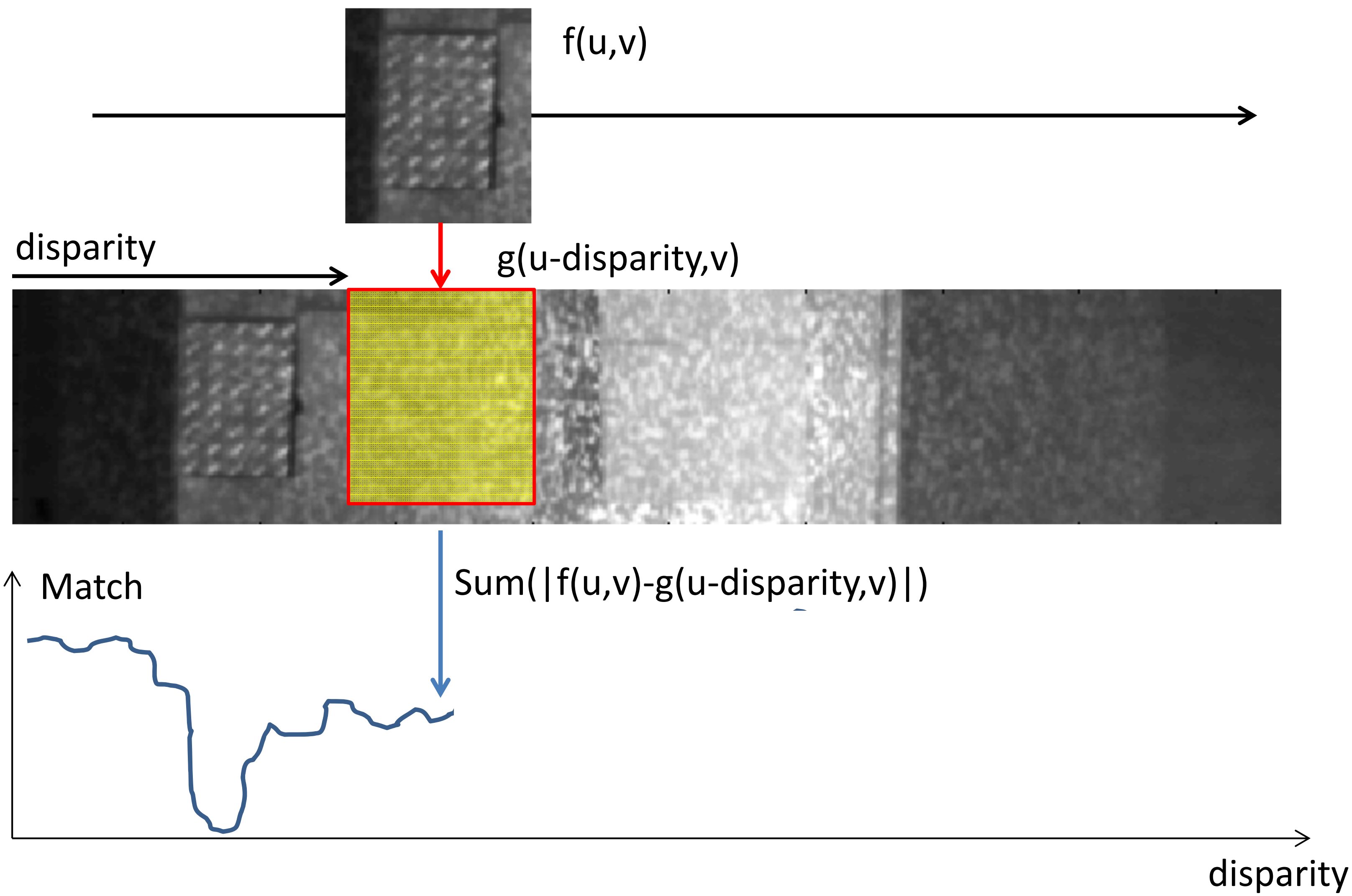
Matching Function : Sum of Absolute Difference, SAD

$\sum(|\mathbf{f}(u,v)-\mathbf{g}(u\text{-}disparity,v)|)$

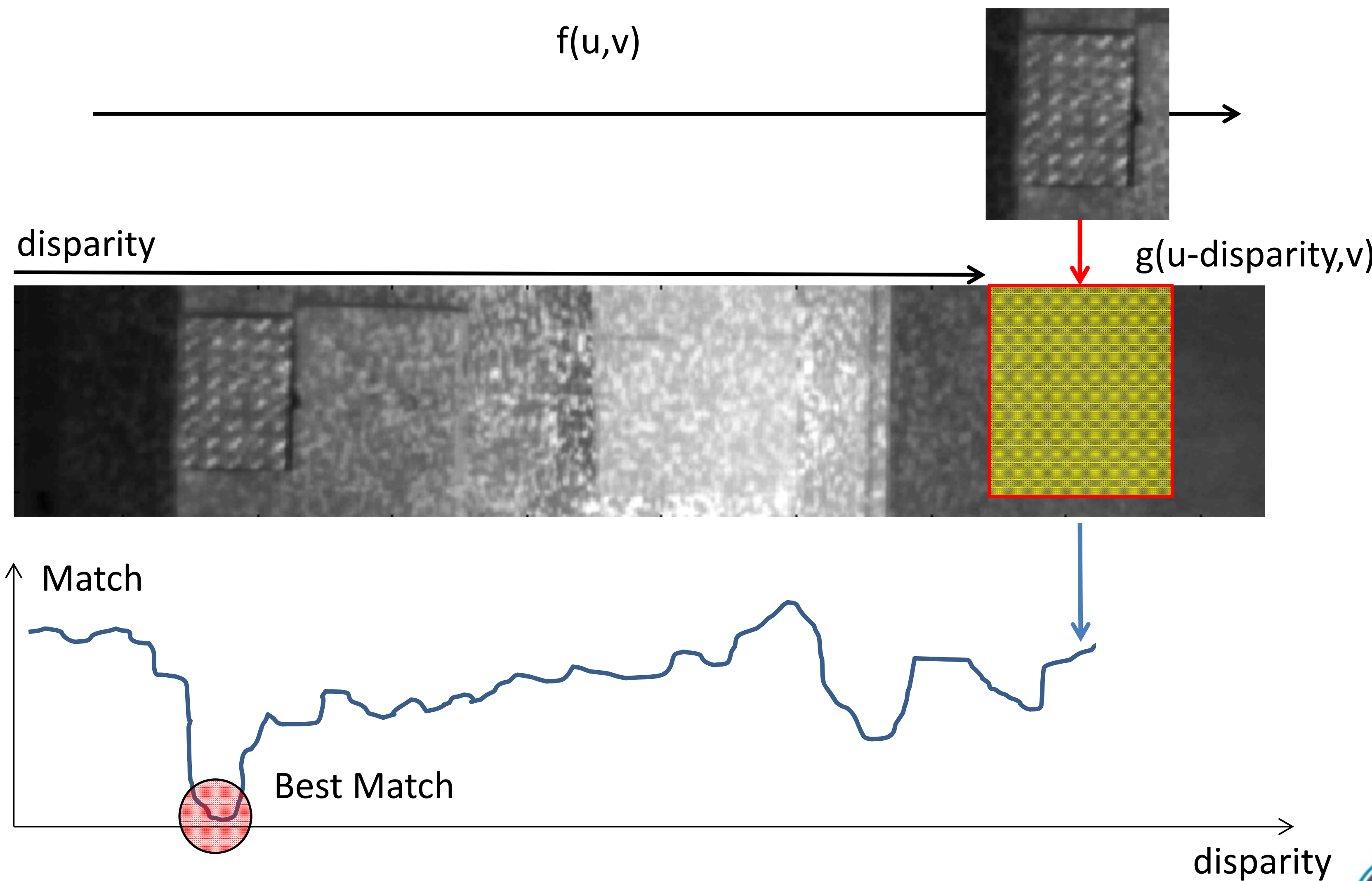
Disparity Matching



Disparity Matching

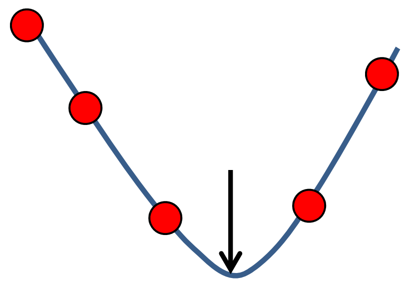


Disparity Matching



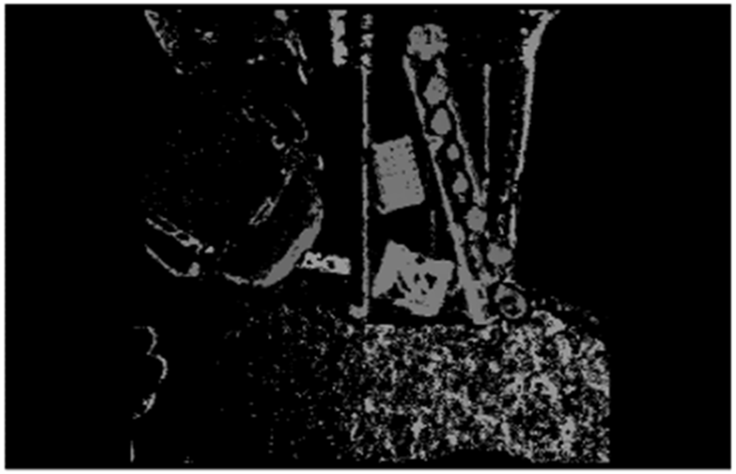
Disparity Matching

- Matching algorithm is key
  - SSD/SAD correlation are common
    - Brightness matching -> High Pass Filter
- "Coarse" pixel correlation positions
  - Interpolate to find sub-pixel matching position



- Feature matching algorithms gives sparse image data
  - High precision on found features
- Middelbury Stereo Vision Pages

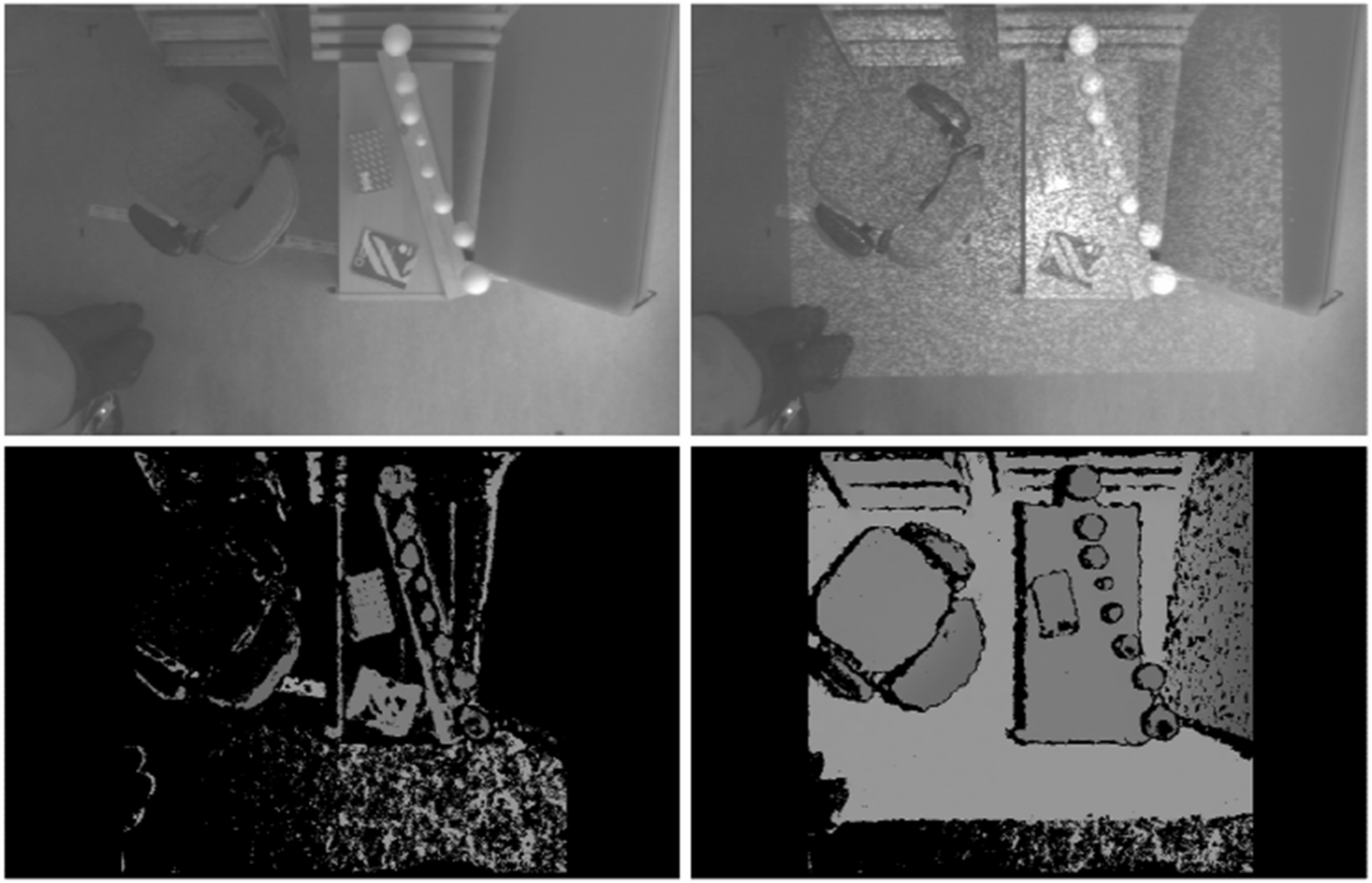
No Structure – No 3D



Structure – 3D

No Structure – 3D

No structure | Active structure



Stereo Products

- IDS - Ensenso with “Kinect” illumination
- Point Grey - SAD correlation, 2/3 cameras
- Chromasens – line scan color
- Most vision SW packages
- And many others…

Booth #520

Booth #516

Booth #611

Stereo Conclusions

- Benefits
  - Standard cameras
  - Can “freeze” a moving object/scene
  - Real snapshot
  - Good support in vision SW packages

- Limitations
  - No structure - no data -> illumination constraints
  - Low detail level in X & Y – typically ~1:10 compared to pixels
  - Poor accuracy in Z

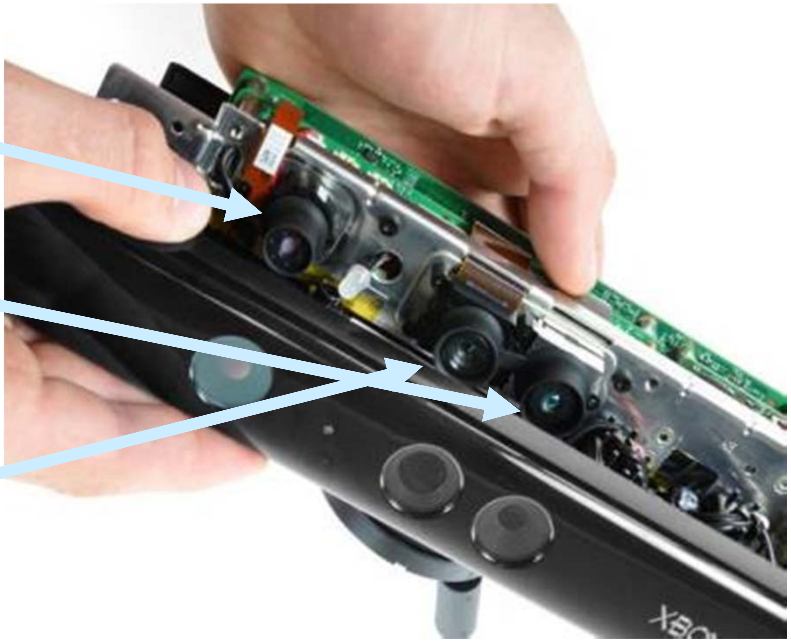
- Typical applications
  - Traffic tolls – vehicle classification
  - Robot bin picking
  - Automotive safety/navigation

Structured Light Technology

- 2D Sensor to grab 3D “snapshot”
  - Pattern defines illumination angle beta
- For each pixel the illumination ray must be identified
  - With a single pattern this gives poor angular definition
    - Or usage of multiple pixels to define the illumination
  - Multiple patterns increase resolution in all dimensions

Fixed Pattern - Primesense (Kinect)

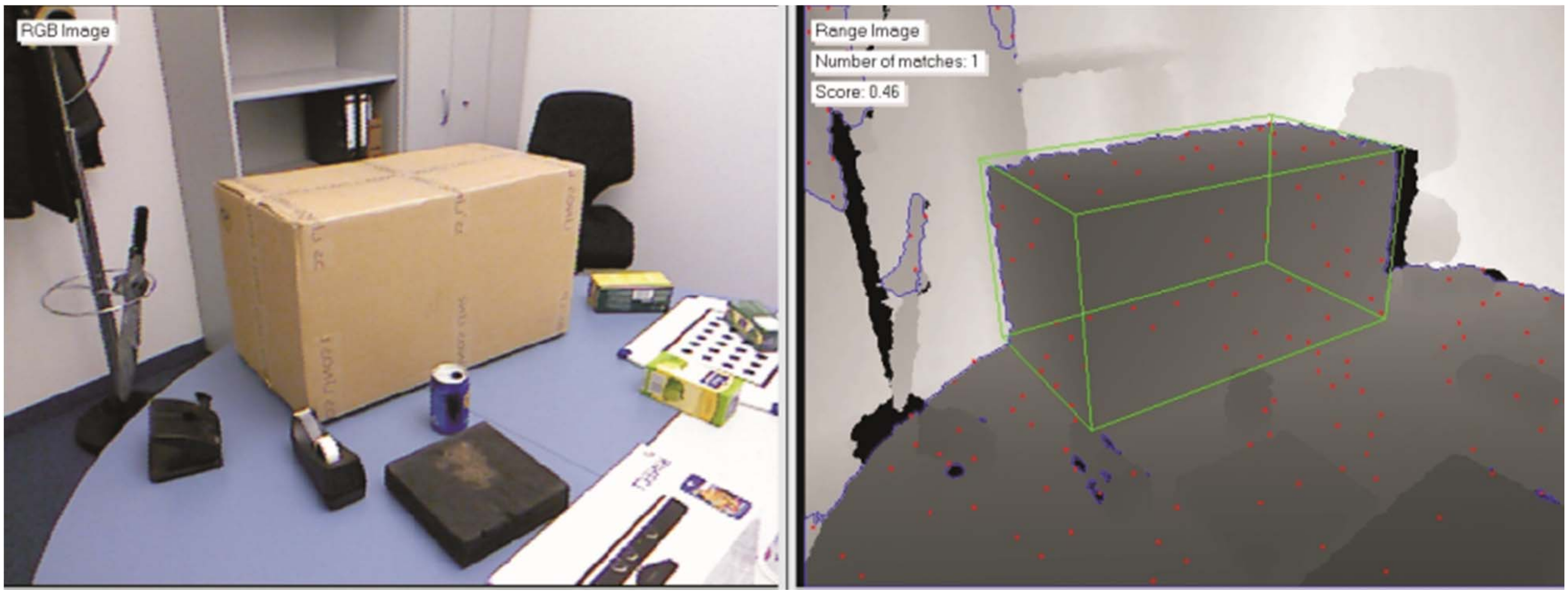
- Projected pattern
  - Fixed “random” pattern
  - Pattern designed to be unambiguous
  - IR laser diode
- Grayscale sensor for 3D triangulation
  - Generates 640 × 480 pixels image
  - 30 fps
- Additional standard RGB sensor
  - 640 × 480 pixels
  - For face recognition, etc.
- A few mm depth resolution
  - As stereo - not independent per pixel
- Other vendors, e.g. Asus
  - Future with Apple ??



Kinect Application Sample

Bonus – Slide!

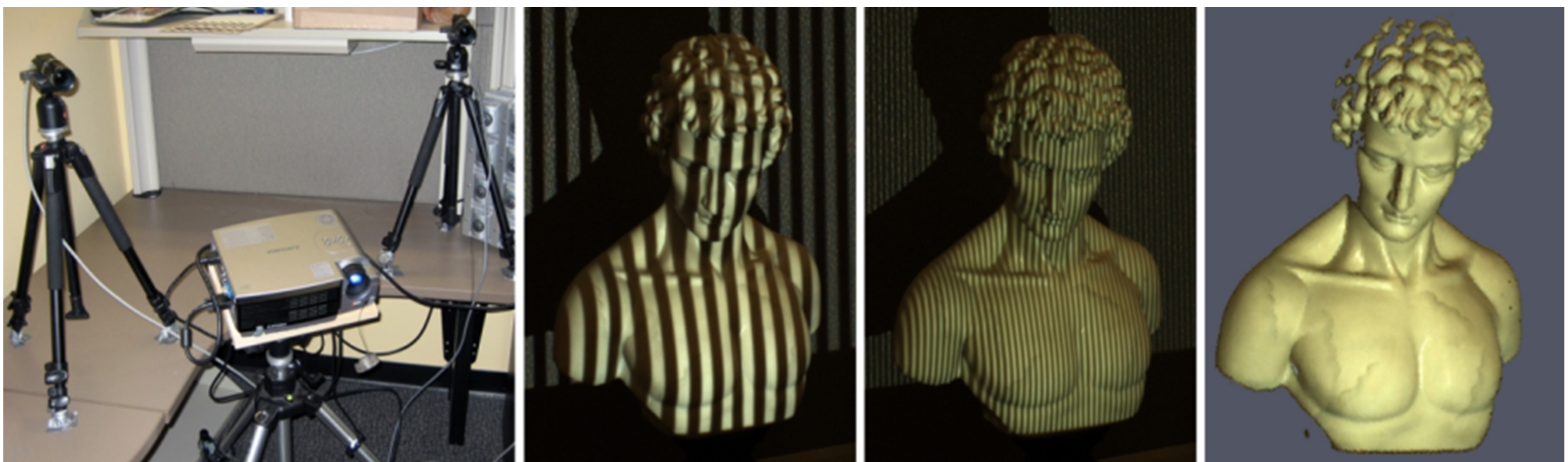
- MVTec HALCON image processing SW example – finding box



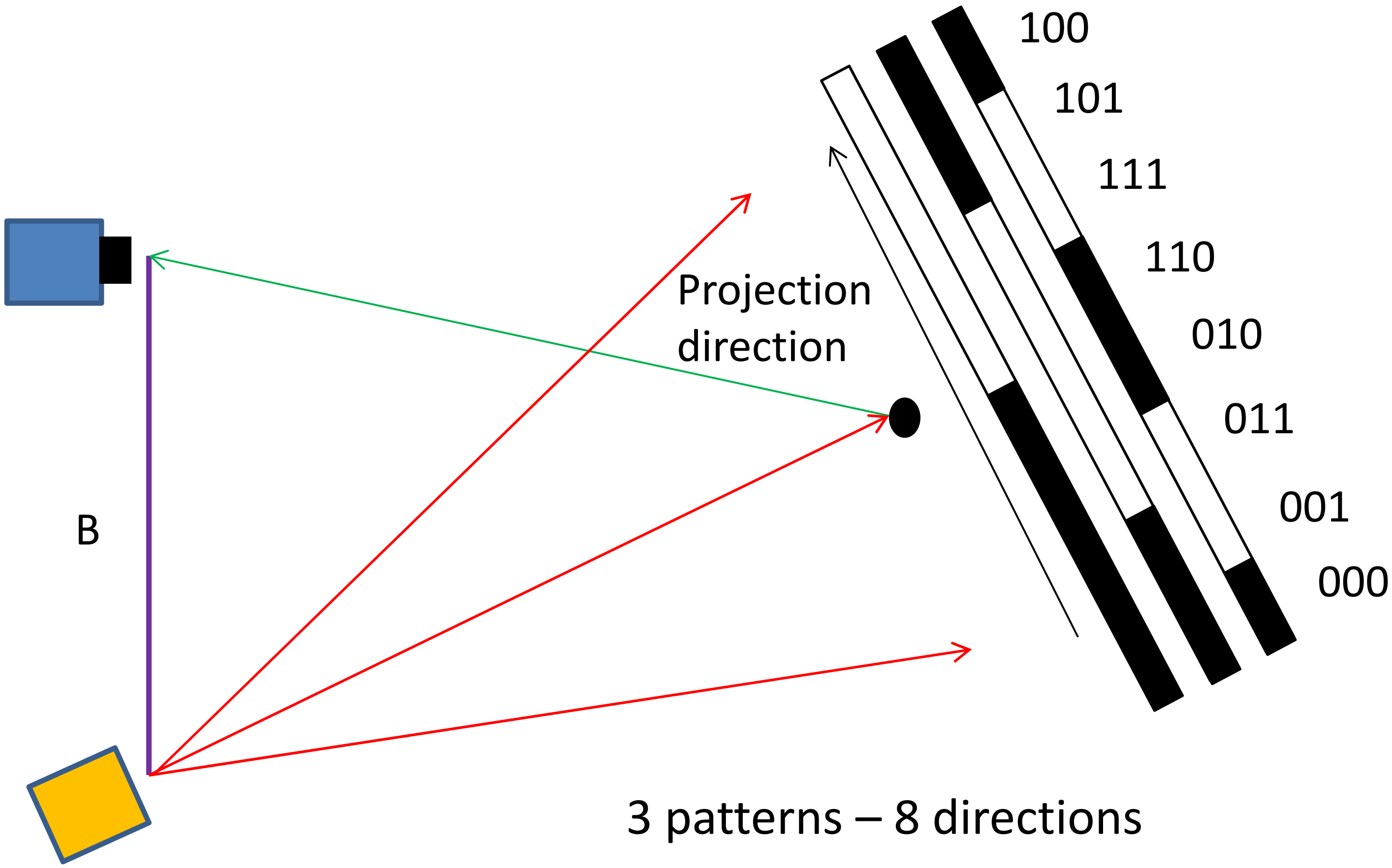
Booth # 301

Spatio-temporal Coded Light

- Generally called Digital Fringe projection or simply "structured light"
- Light modulation :
  - Binary [Gray coded]
  - Continuous phase shift - "sinus"



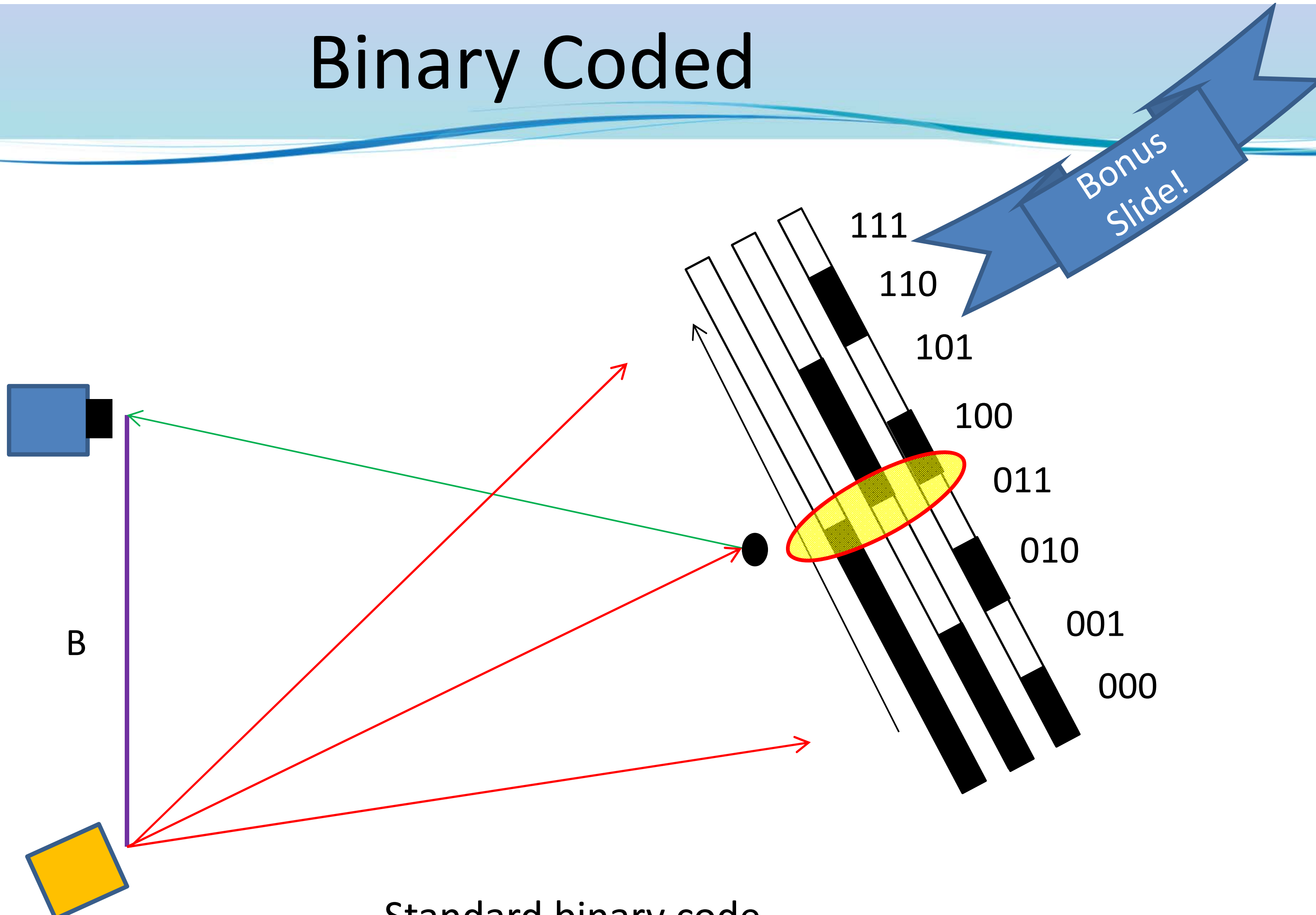
Binary Coded



3 patterns – 8 directions

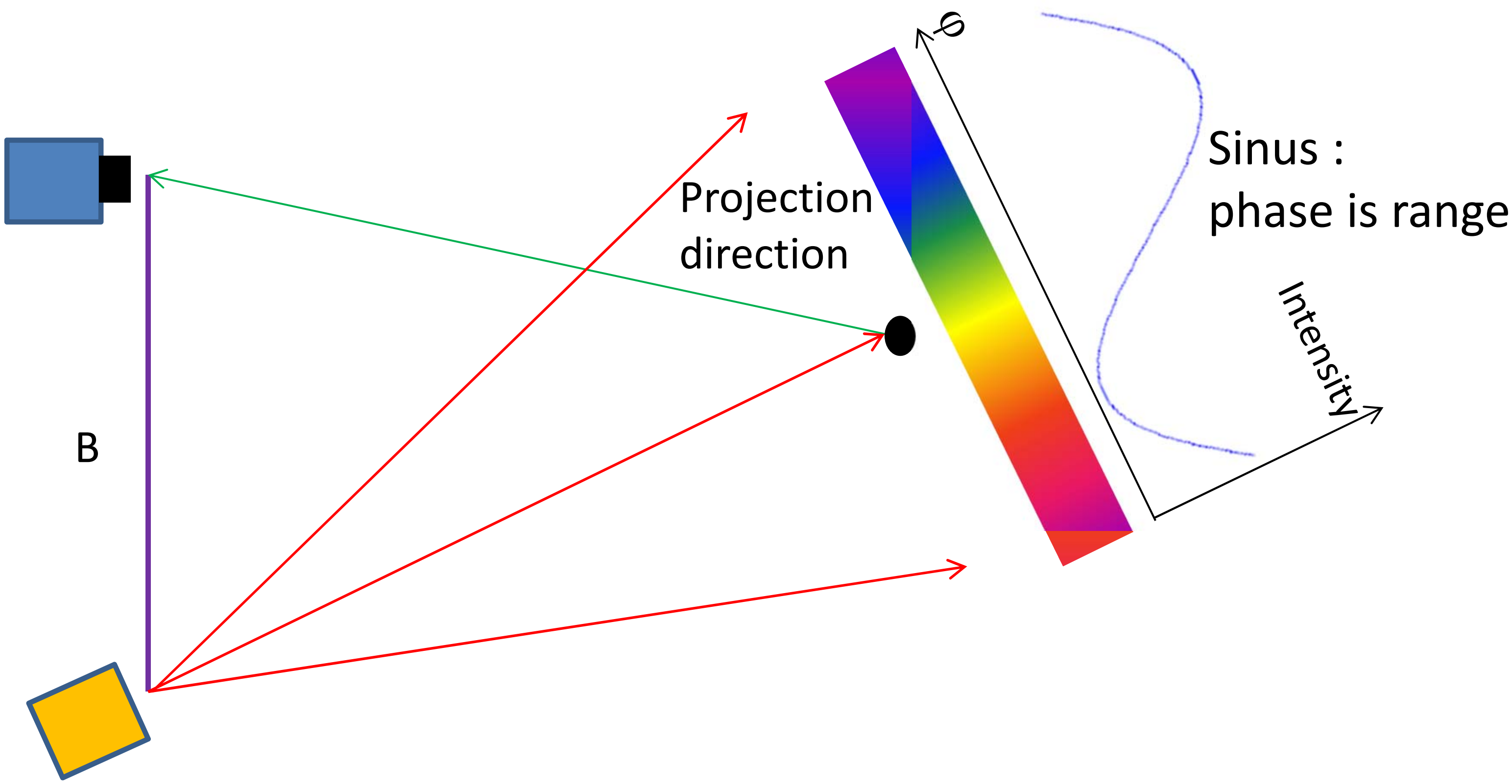
Gray code minimizes error impact

Binary Coded

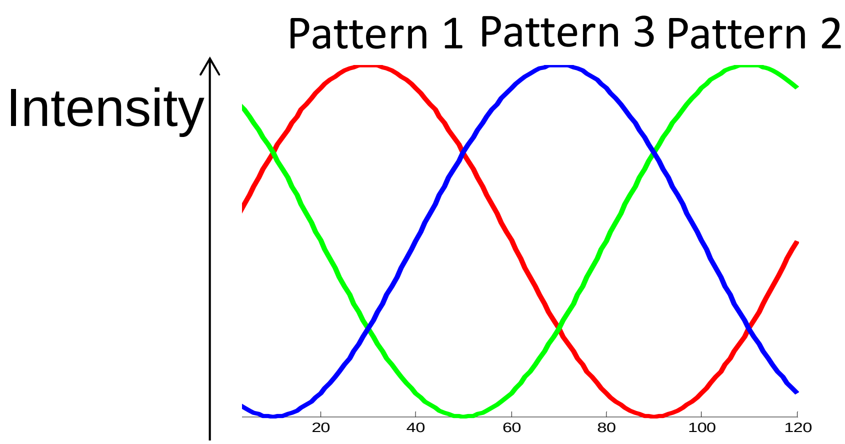


Standard binary code
- Many bits switch at same position

Phase Coded 1



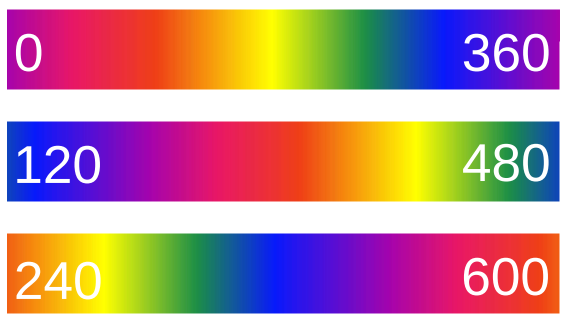
Phase Coded 2



3 unknown:

I(x,y,t) = I(x,y)+ I'(x,y)*cos(φ(x,y,t))

Analytical expression in each pixel
-> range, modulation, background



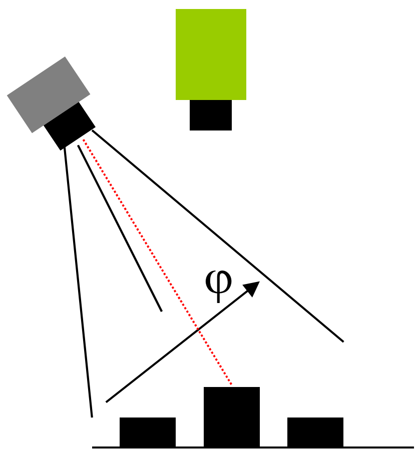
Pattern 1 : Shift 0

Pattern 2 : Shift 120 degrees

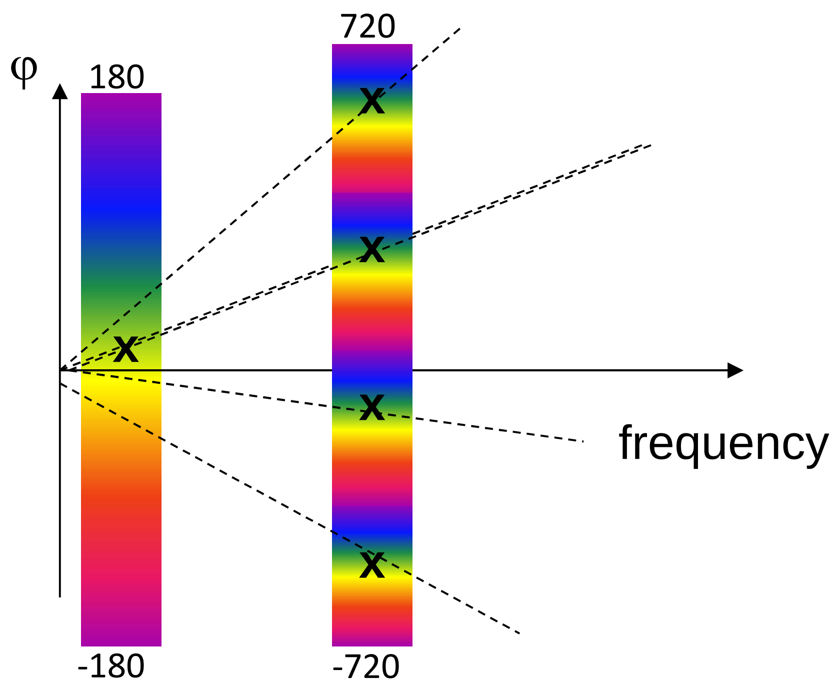
Pattern 3 : Shift 240 degrees

4 patterns with 90 degree separation
-> Simpler math & more robust

Phase Unwrapping



- High frequency-> High accuracy – Ambiguous
- Low frequency – Low accuracy – Unambiguous
- Combine results to unwrap
- In theory 2 frequencies are typically enough
- Typically 4-5 frequencies -> ~ 15-20 images / “snap”
- Coarse binary patterns
  + high frequency phase coded common

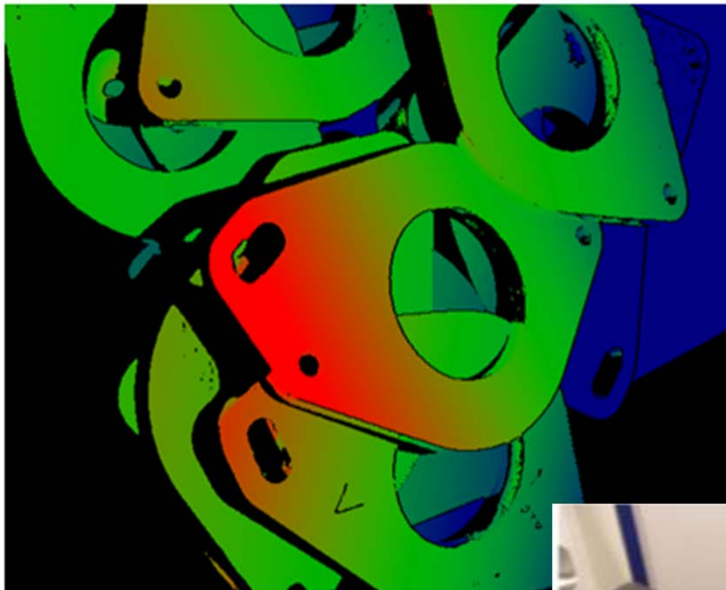


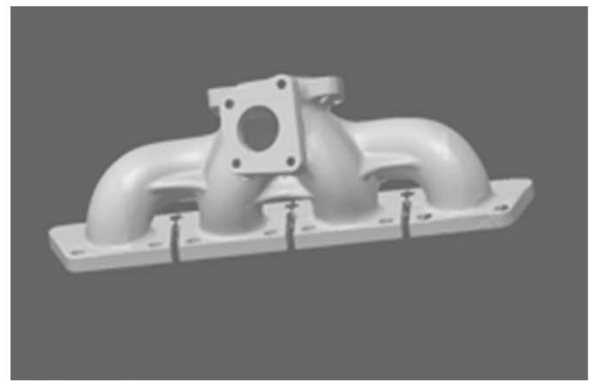
Spatially Coded Light Conclusions

– True individual pixel processing -> high X-Y resolution

- Binary pattern easy to decode
  - Use pattern + inverse or “floodlight / dark” references to increase detection capability
  - Log(N) patterns give N different ray directions
  - The resolution of the image/pattern limits N
  - Some pixels will be on the black-white borders
- Phase coded gray patterns gives better performance
  - High Z resolution
  - 3 shifted phase images needed to decode the phase, intensity and modulation
  - Pixel modulation -> quality measure
  - High frequency gives high resolution
    - ambiguous due to wrap around
  - Maximum pattern frequency limited by system resolution/sharpness

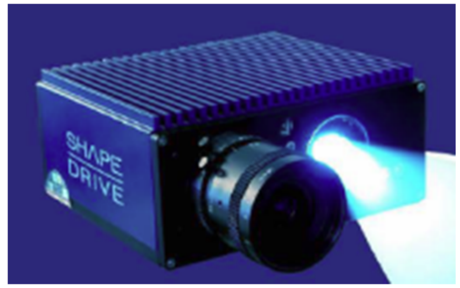
Examples Coded Light





Conclusions Coded Light

- Commercial system examples
  - ViaLux Z-snapper
  - LMI Gocator
  - Numetrix
  - Shape Drive



- Benefits
  - Very good 3D measurements, with quality measure
  - Independent measurement in each sensor pixel
  - Fast – “almost snapshot”

- Limitations
  - Needs static scene during multiple projection capture
  - The dynamic range in each pixel must be enough to make the phase calculation
    - Ambient, low/high reflection and specularities limit
    - Large FOV difficult to realize.

- Typical applications
  - Reverse engineering shape capture
  - Medical imaging
  - Electronics inspection

Triangulation General

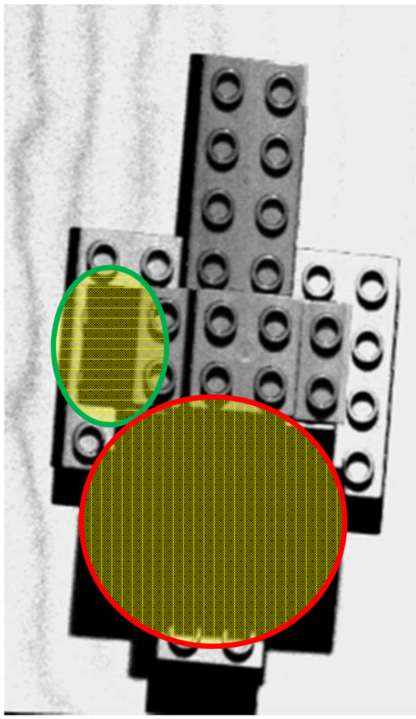
- Discussion on
  - Baseline - accuracy
  - Occlusion
  - Wavelength

Baseline vs Accuracy

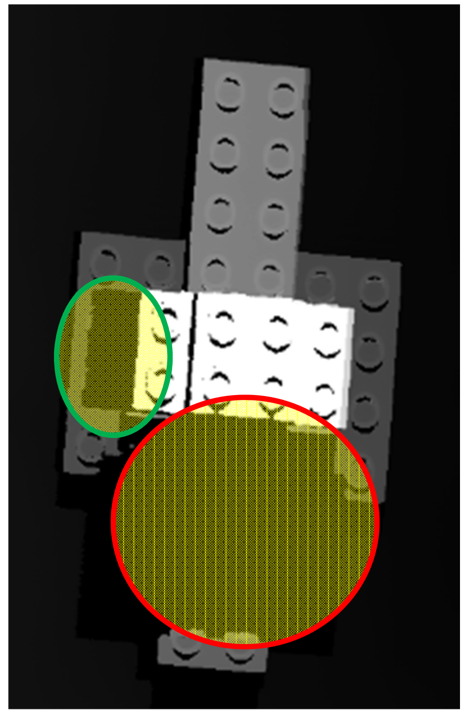
- Baseline is distance between sensor and illumination or between cameras
- A larger baseline gives larger displacement per Δz
  - Better resolution / accuracy
- A larger baseline gives more differences between the “views”
  - More areas not seen by both cameras - occlusion
  - Less accurate matching, especially for rounded structures and tilted surfaces

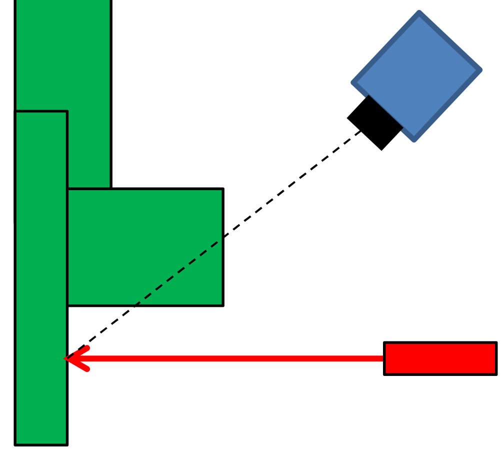
Occlusion Illustration

Intensity

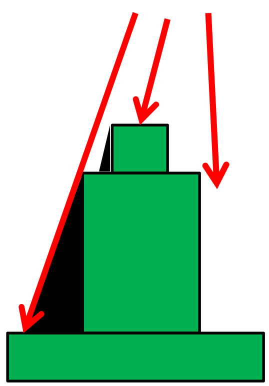


Range





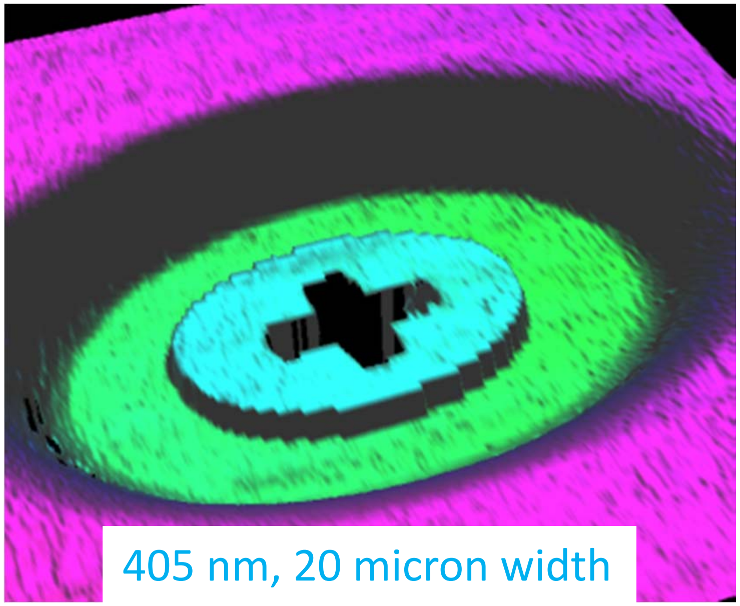
Camera
Occlusion



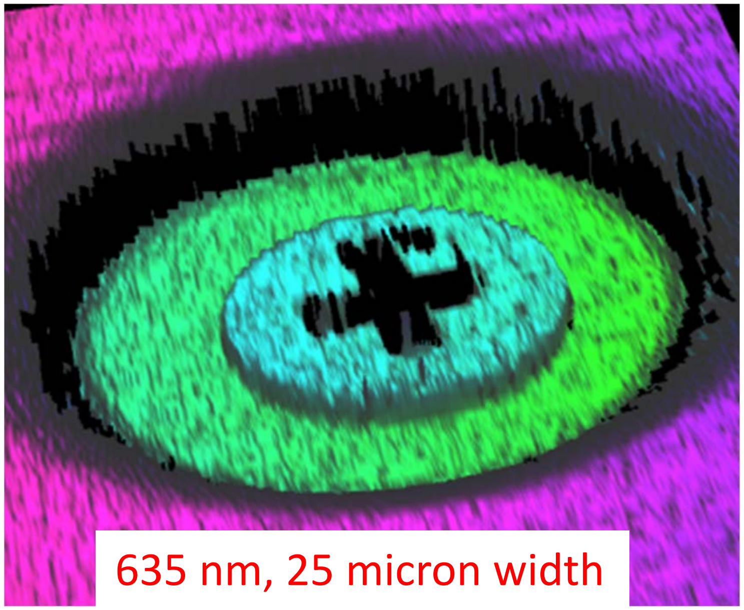
Illumination
Occlusion

Wavelength

- Focussing limits proportional to wavelength
  - Speckle size too
- IR : Invisible, but poor focussing
- Red : Cheap lasers, high CMOS/CCD sensitivity, high ambient
- Blue : Good focussing, less ambient, expensive
- Comparison laser triangulation:



405 nm, 20 micron width



635 nm, 25 micron width

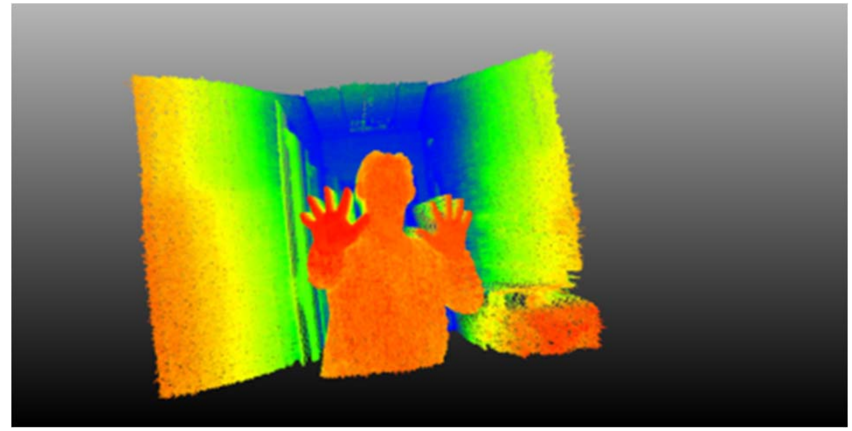
General Conclusions Triangulation

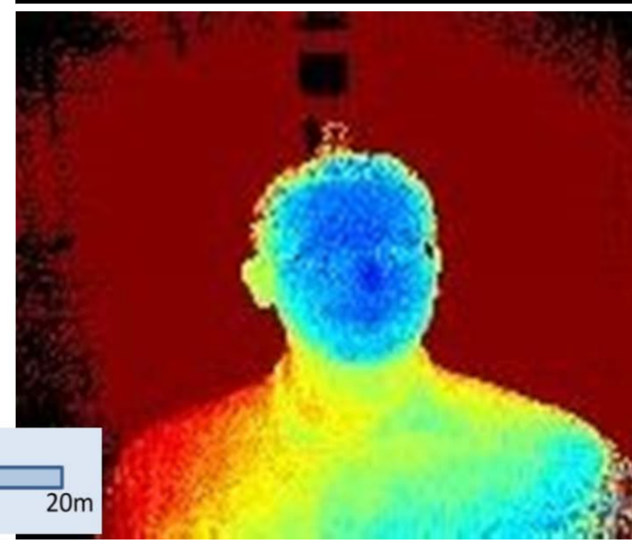
- Most common 3D principle
  - "Simple" methods
  - Robust if active
  - Reasonably fast

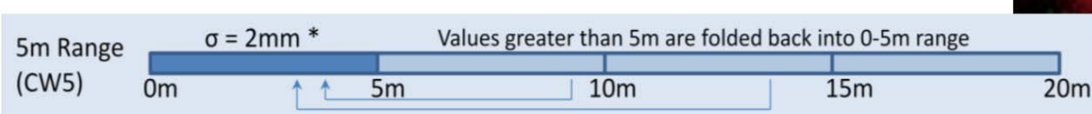
- Difficult to scale to distances more than a meter or 2 ... which leads us to

Time-of-flight

- Pulsed
  - Send a light pulse – measure the time until it comes back
  - Light speed 0.3 Gm/s …
    at 1 m it comes back after ~7 ns
  - ~Millimeter resolution in laser scanners
  - Shutter-based used in imagers
- CW - Continuous Wave
  - Modulated continuous illumination
  - Phase shift ~distance
  - Used in most TOF imager arrays
  - Low resolution due to complex pixels
  - Similar ambiguity problem as
    phase coded structured light



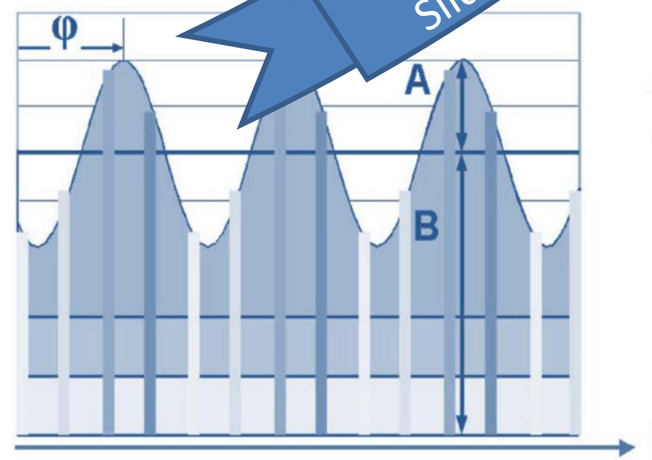




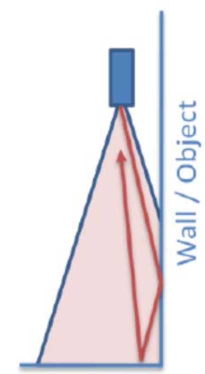
TOF with CW Modulated Light Source

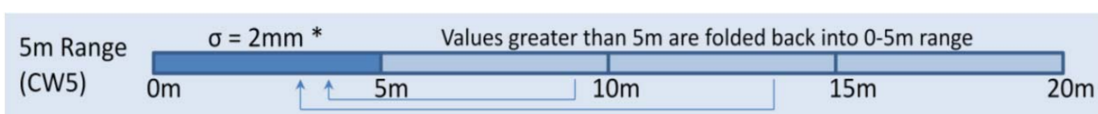
Bonus Slide!

- Modulate the light source
  - e.g., f = 30 MHz => 5 m range ambiguity limit
- 4 capacitors per pixel
  - integrating one 90° phase interval each
- Integrate for many cycles
  - e.g., 20 ms => 5 ms/capacitor
- Find phase φ from the 4 values
  - φ_0 from pixel with direct optical feedback
- Wrapping problem for distances larger than 5 m
- Problems with ambient, reflections, saturation, motion …

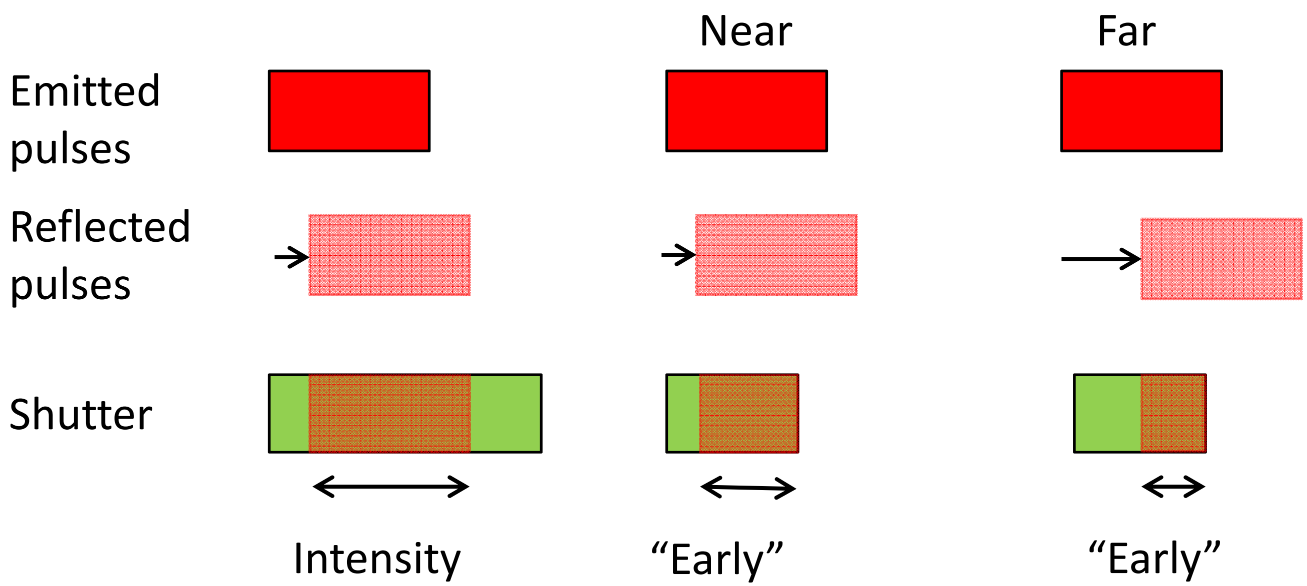


$$d = c\frac{\varphi - \varphi_0}{4\pi f}$$





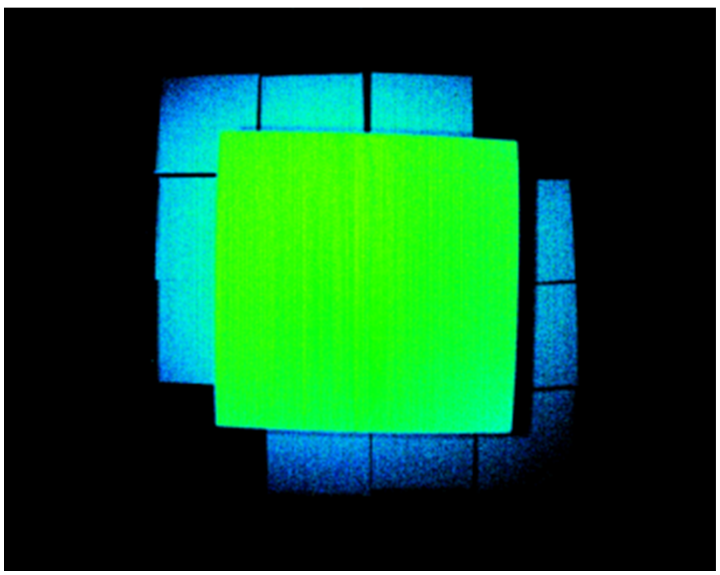
Pulsed TOF Shutter Principle



Relationship between “Early” and Intensity gives range

Pulsed TOF Camera

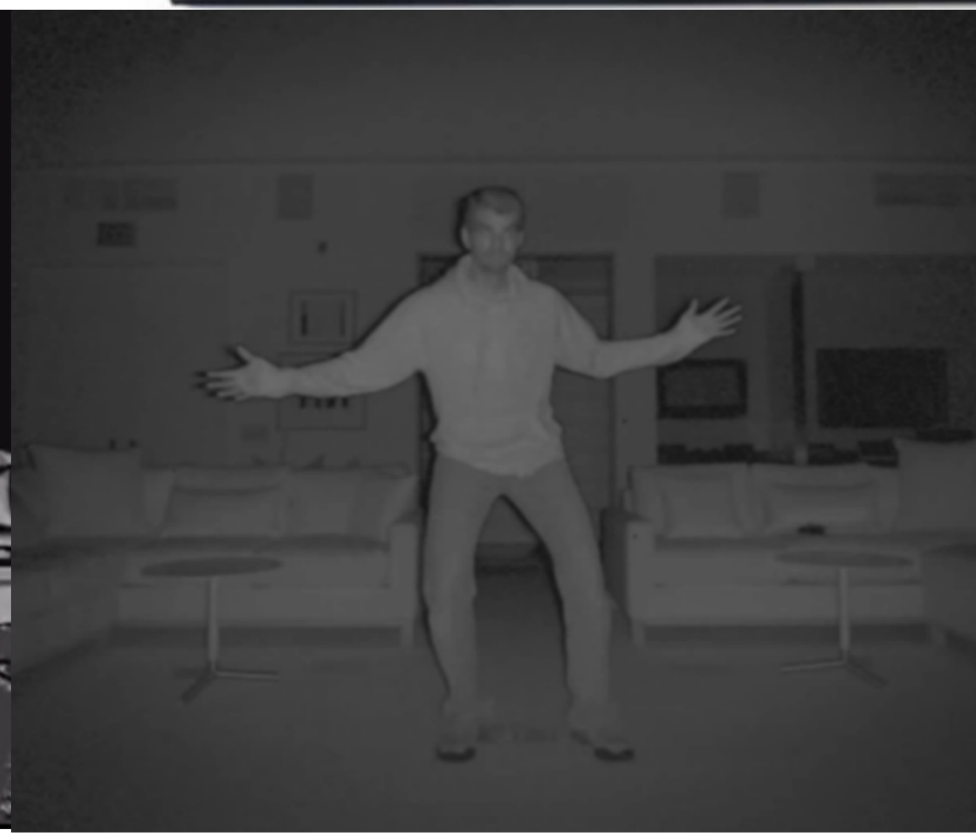
- Odos imaging has new 4 Mpixel pulsed TOF camera
  - Z accuracy 2-12 cm
  - up to 470 fps



Booth #202

Kinect One

- Now with TOF !
- ~500x400 pixels
- CW / pulsed ?

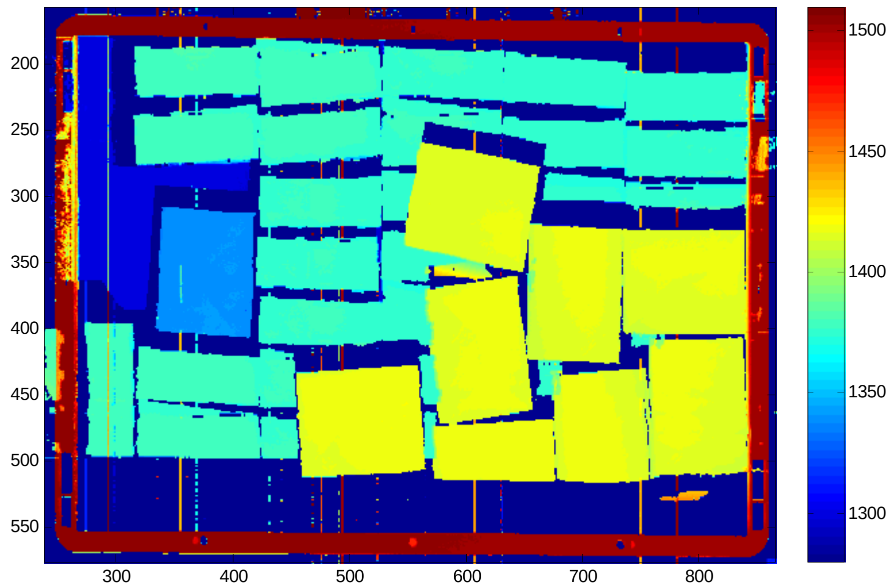


TOF Array Conclusions

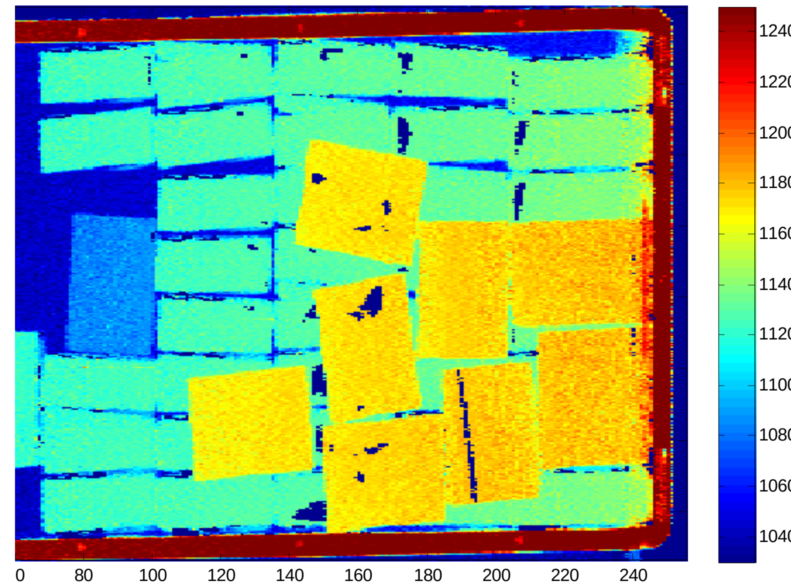
- Pulsed 2D array : Odos, 4 Mpixel
- CW 2D array “3D cameras”
  - Mesa Swiss Ranger ~150x150 pixels
  - IFM –”smart camera” ~60x50 pixels
- Benefit
  - Snapshot
- Basic limitations
  - Z resolution > cm
  - X-Y resolution (CW)
  - Secondary reflections (CW)
  - Fast movements (?)
  - Ambient light (?)
- Typical applications :
  - People counting
  - Automatic milking machine

Technology Compare 1

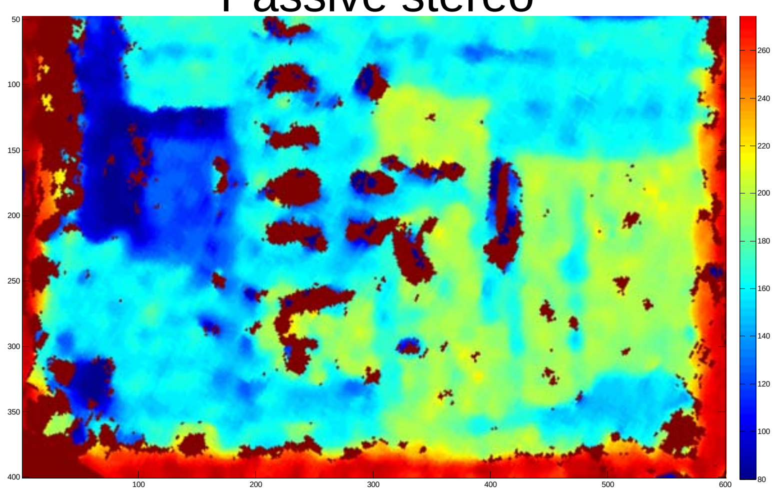
Laser triangulation

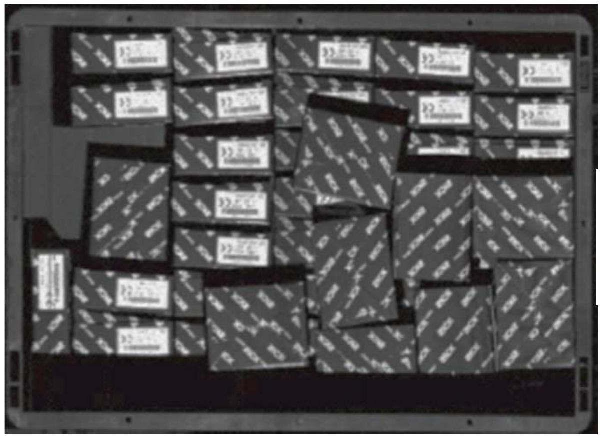


Scanned TOF (Phase)



Passive stereo

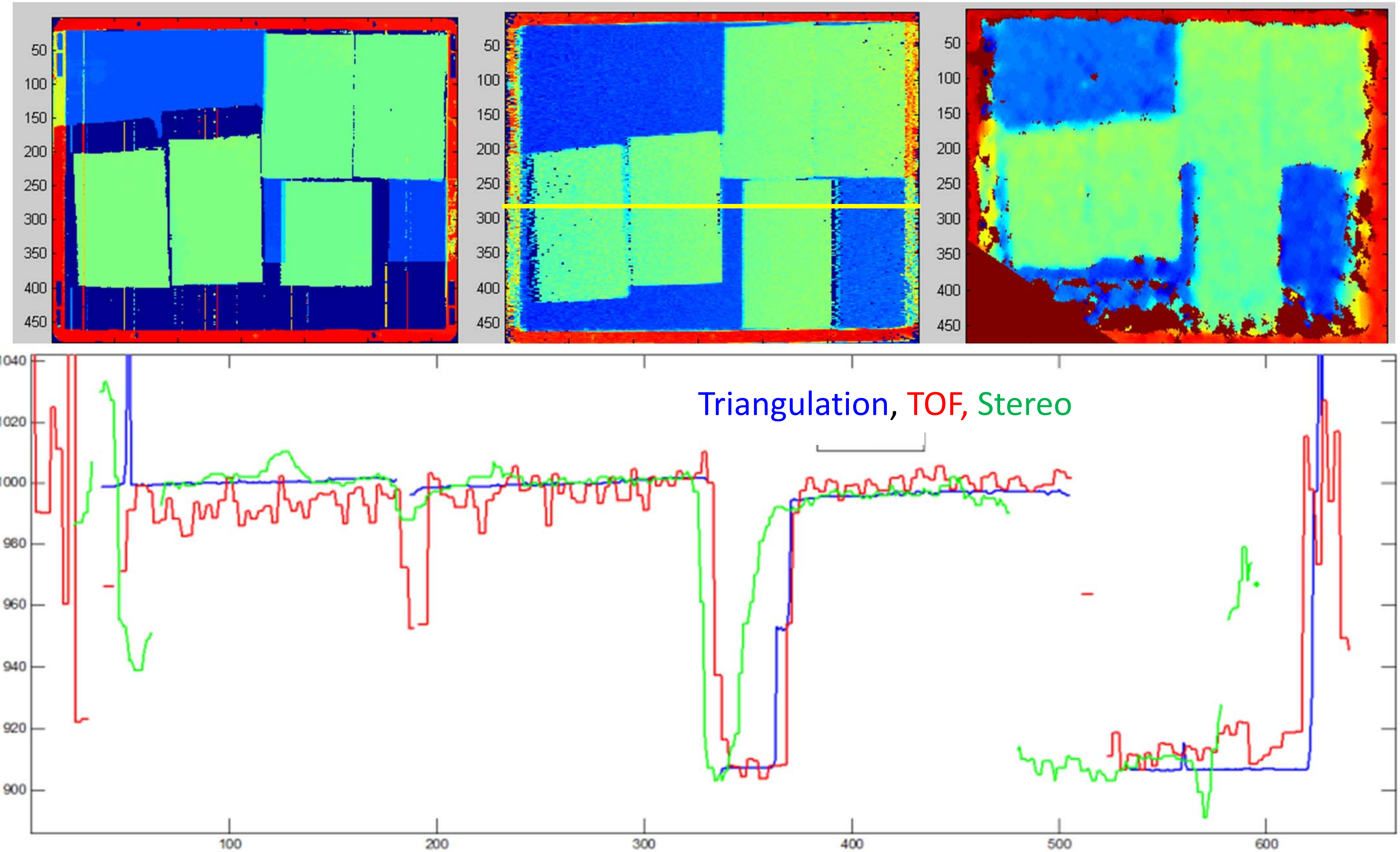




Laser intensity

Technology Compare 2

Laser triangulation | Scanned TOF (phase) | Active stereo



Misc. 3D Methods

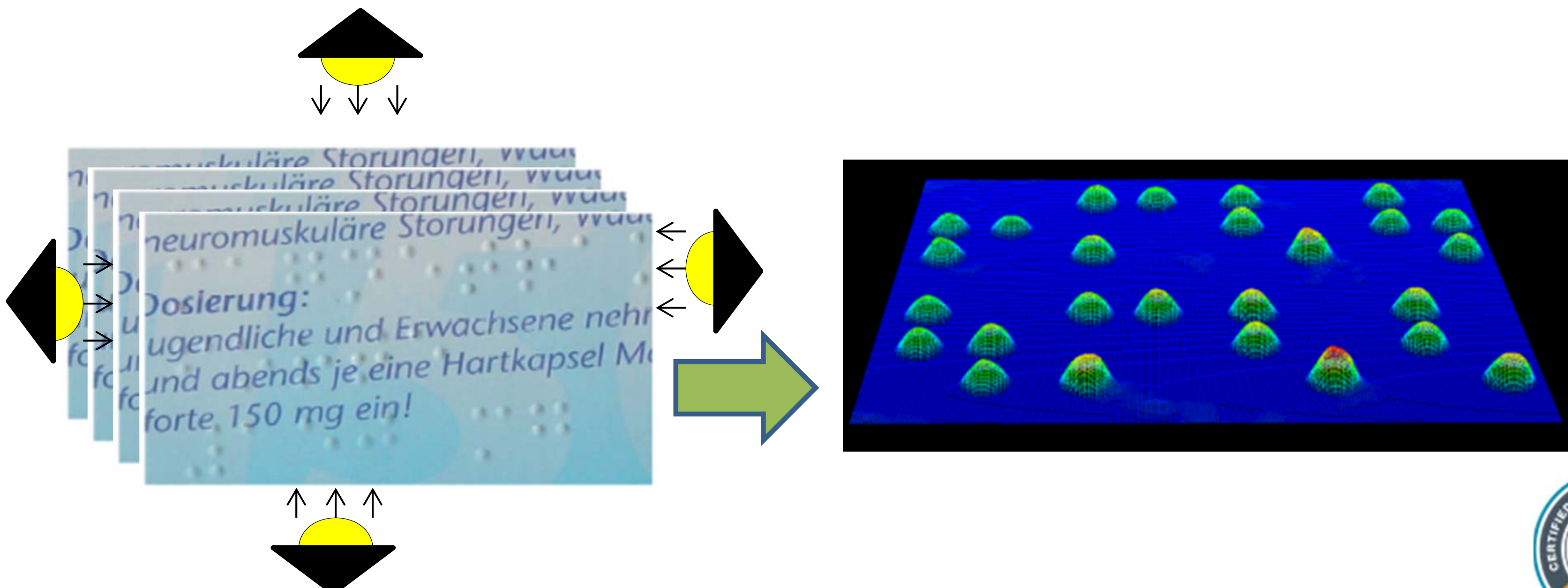
- Less common
  - Interesting theory
  - Special cases
  - On Bonus Slides !

Bonus Slide!

Shape from Shading

Bonus Slide!

- Gives shape information, but not real distance
  - Shade from different directions of illumination gives surface orientation information
  - Integrating the orientation gives depth variations
- Limitations
  - Only surface orientation, no actual depth
  - No discontinuities allowed



Light-Field 3D 1

Bonus Slide!

- Micro lens array used to create "4D" light-field image on standard image sensor
  - 2D direction "subpixels" in each 2D "pixel"

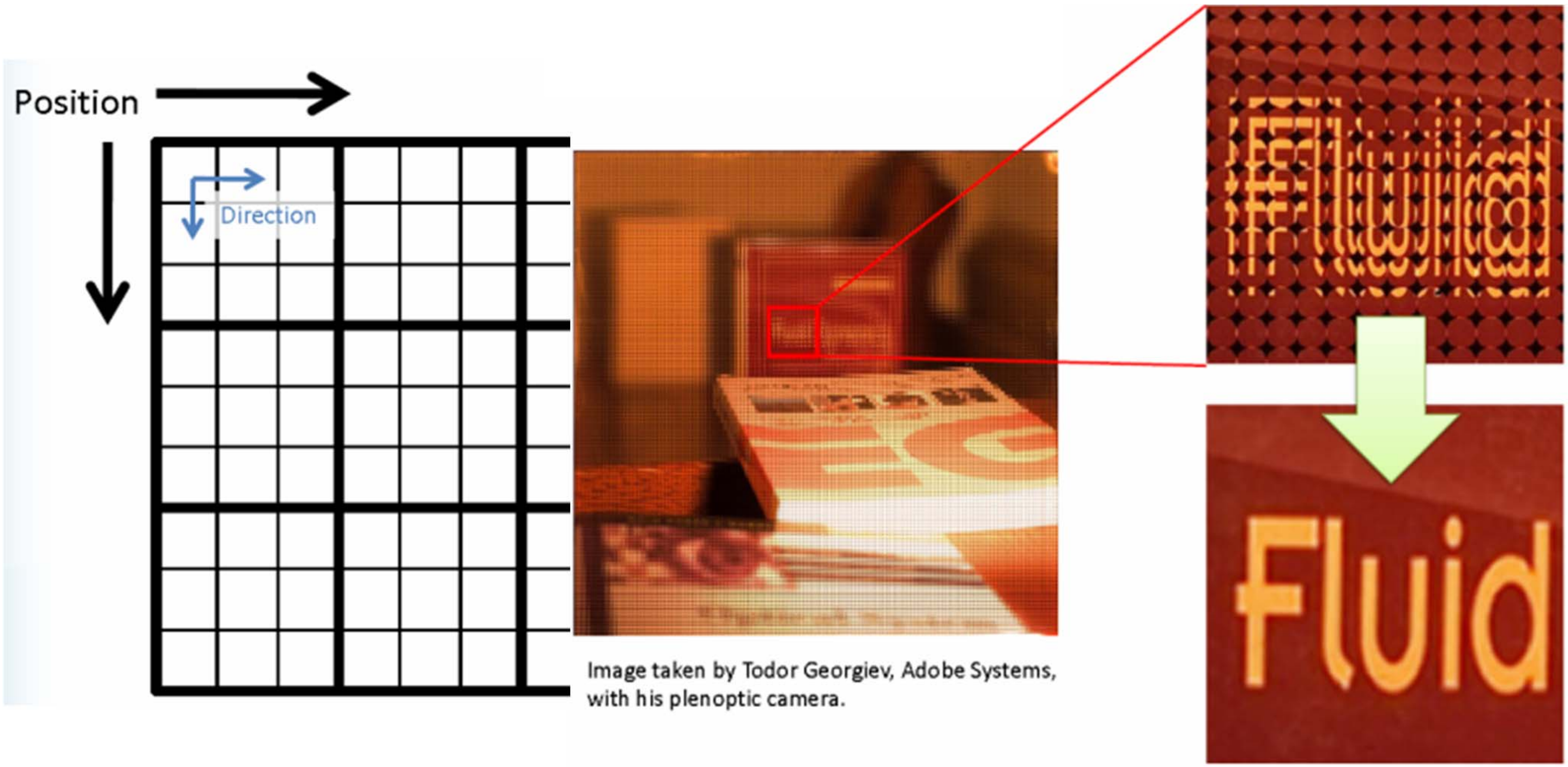
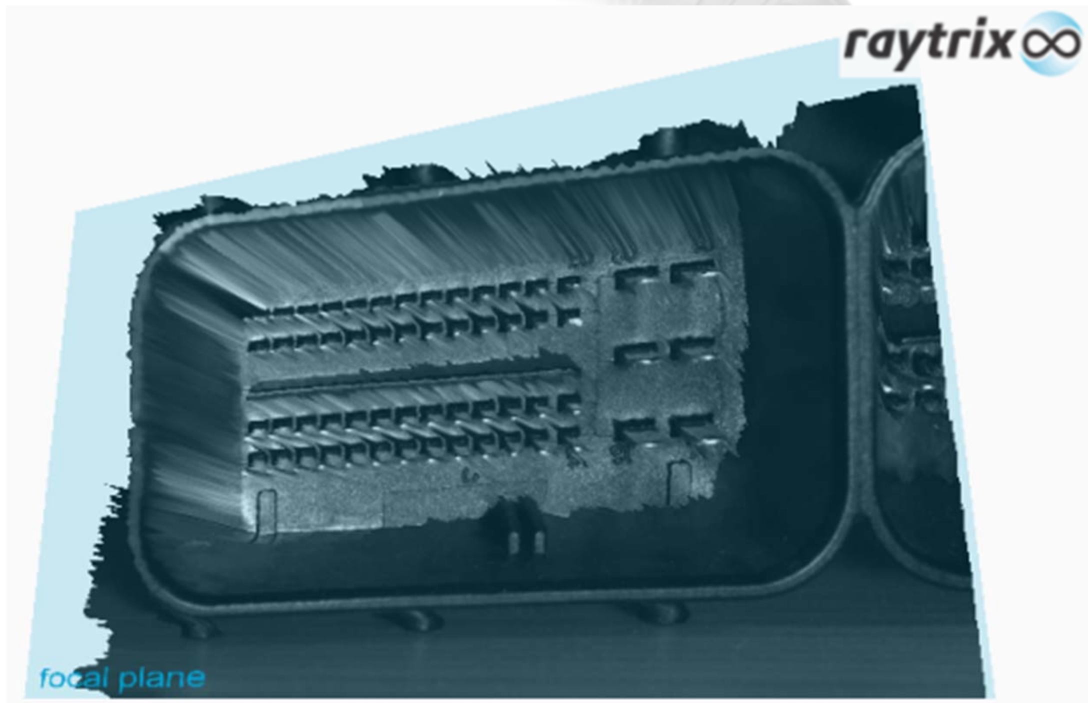


Image taken by Todor Georgiev, Adobe Systems, with his plenoptic camera.

Light-Field 3D 2

Bonus Slide!

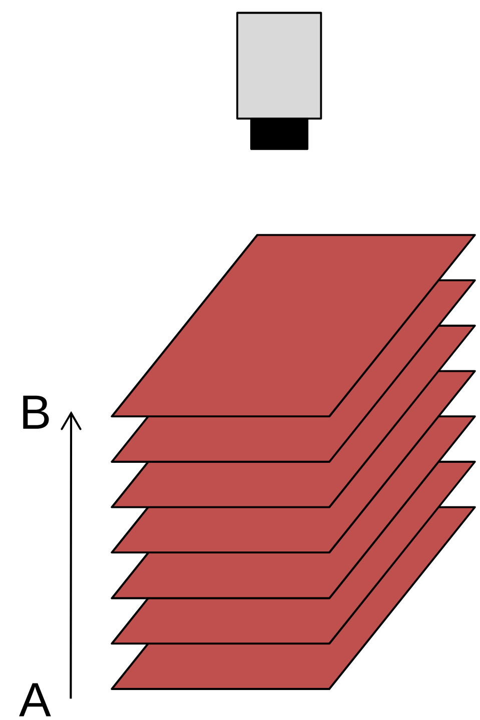
- Processing of light-field image
  - Refocussing
  - 3D calculation
- Cameras – Raytrix (Lytro)
- Features
  – "No occlusion"
- Limitations
  – Depth accuracy "lens aperture triangulation"
  – Special cameras
  – Complex processing
  – Lytro : no 3D, not industrial



Depth from Focus

Bonus Slide!

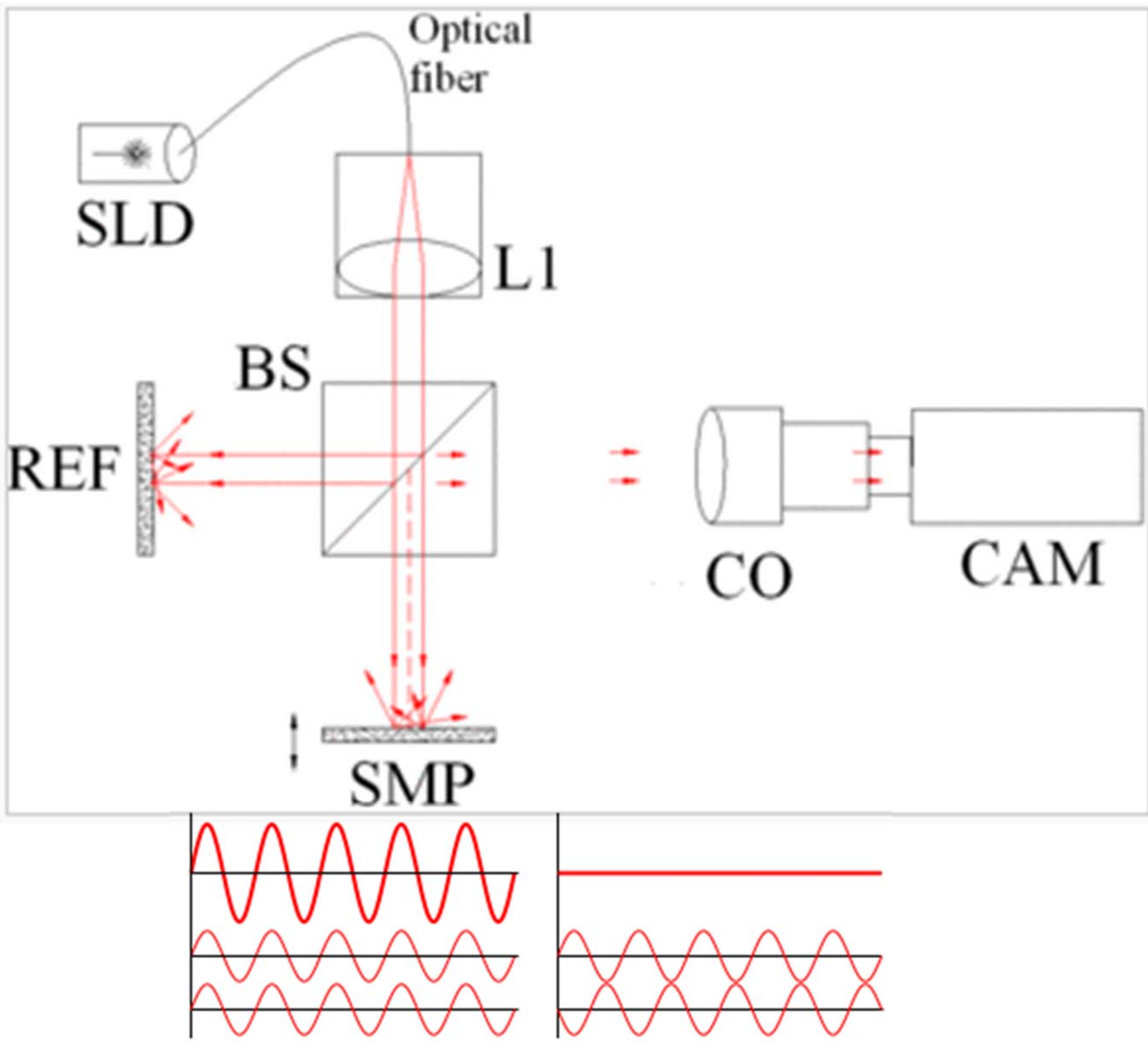
- Grab a sequence of images focused from A to B
- Scan through the stack and find where local focus is maximized
  - That gives the range



- Features
  - No occlusion
  - No structured illumination needed
- Limitations
  - Slow
  - Needs structure to estimate focus
  - Pixel regions needed to estimate focus
  - Poor accuracy
    - "Triangulation using lens aperture"

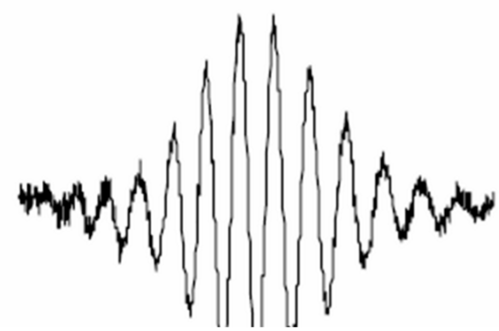
Interferometry 1

Bonus Slide!



Coherent (Laser) Light
- Periodic Interference
-> Flatness measurements

Incoherent (White) Light
- Interference @ same distance
-> Shape measurements



Interferometry 2

Bonus Slide!

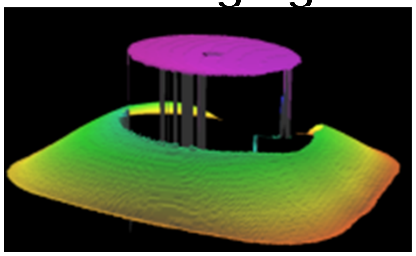
- Features
  - Sub-micron accuracy
- Limitations
  - Complicated scanning mechanics
  - Static scene needed during scan

3D Camera Standard?

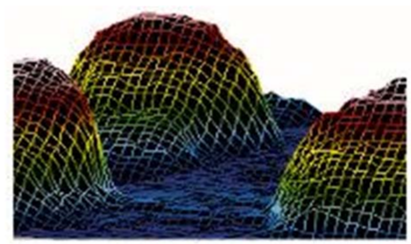
- Explicit 3D support in vision standards underway!
- Companies working include:
  - Cameras:
    SICK, LMI, Point Grey, Automation Technology, Odos
  - SW (Cameras):
    MVTec, Matrox, Teledyne DALSA, STEMMER

3D Applications

Packaging



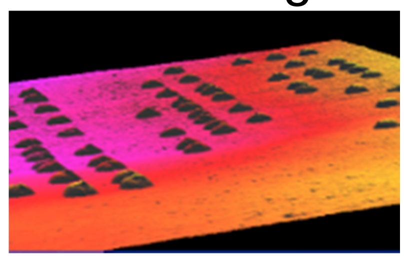
Electronics



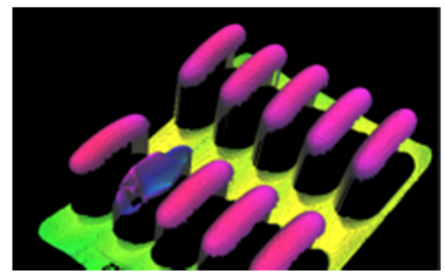
Wood

Robotics

Printing



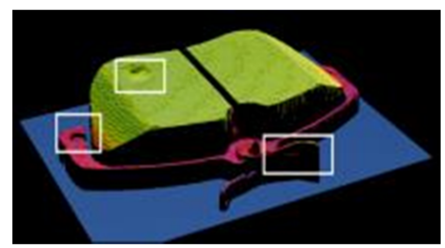
Pharmaceutical



Logistics

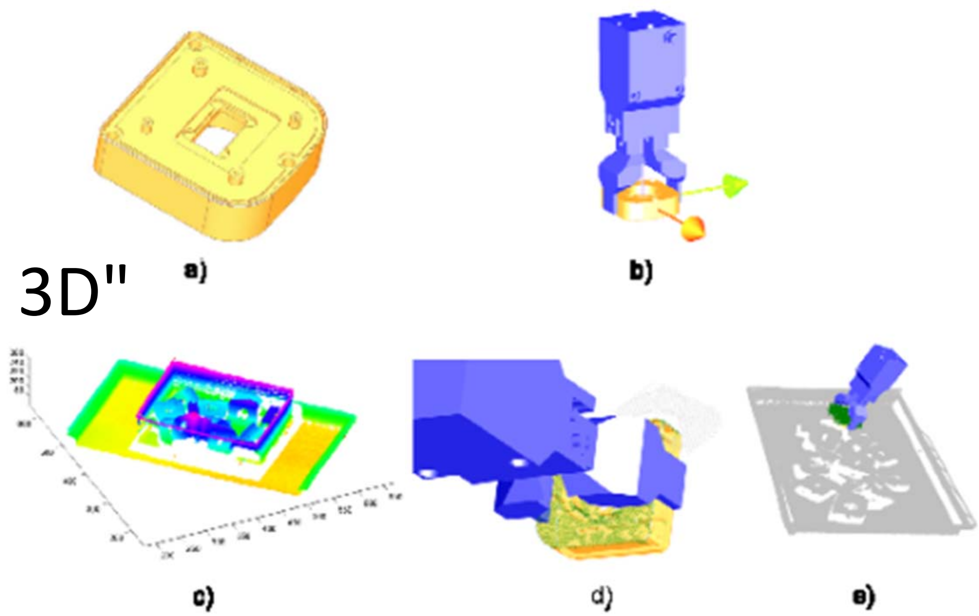
Food

Automotive



Robot Vision and 3D

- Random bin picking an old "Holy Grail"
- Main problems:
  - Object location / description
    - Geometrical primitives
    - CAD models
  - Finding pick point
  - Controlling robot
- Overhead 3D vs "hand 3D"
- ... Finally, general systems coming



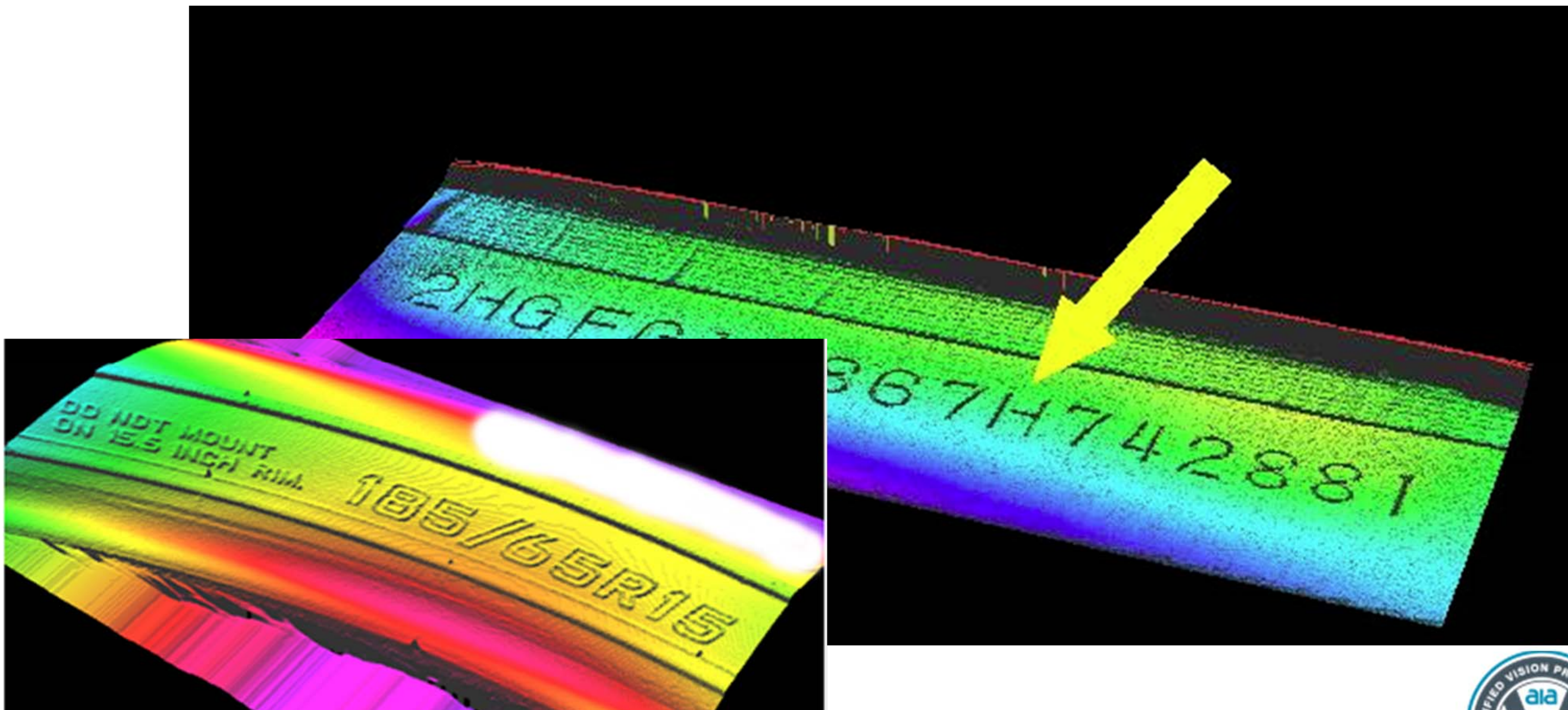
3D Bin Picking System Example

- Scanning ruler sweeps laser over the scene
  - Complete 3D image
- Bin-picking application
  - Co-register coordinate system of camera system and robot
  - Estimate pose of picking candidates in 3D data
  - Ensure collision free gripping of the part

Video - Random Bin-picking

3D OCR / Code Reading

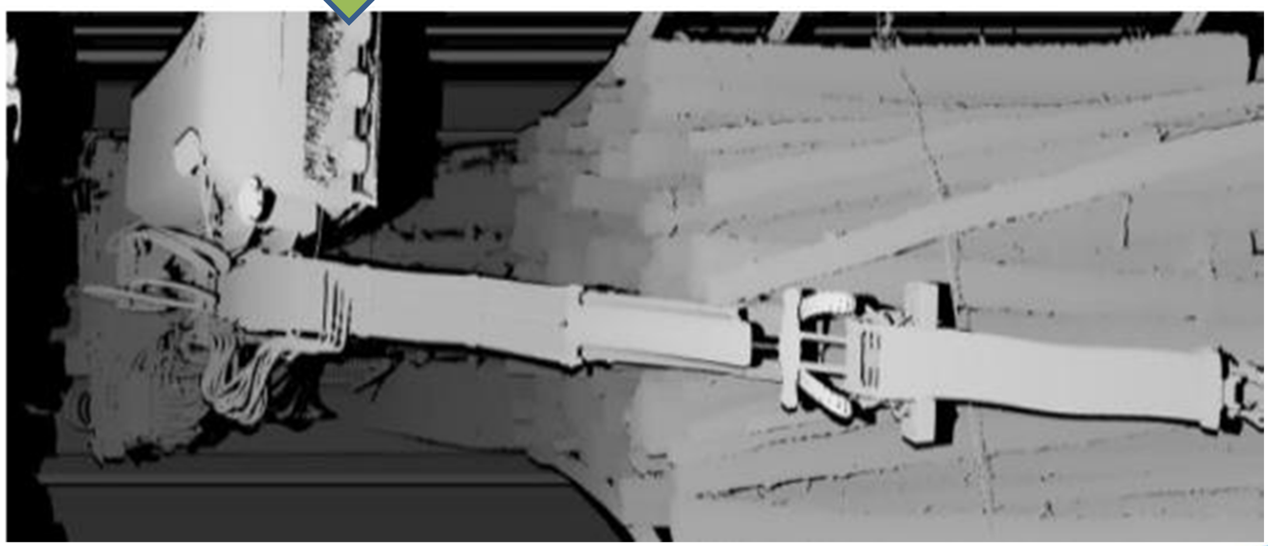
- VIN number stamped into car chassis
- Tire codes



"Backwards" Examples

Small FOV TOF 3D
- Milking Robot (LMI)

Large FOV laser triangulation
- Timber truck load volume (SICK Ranger)

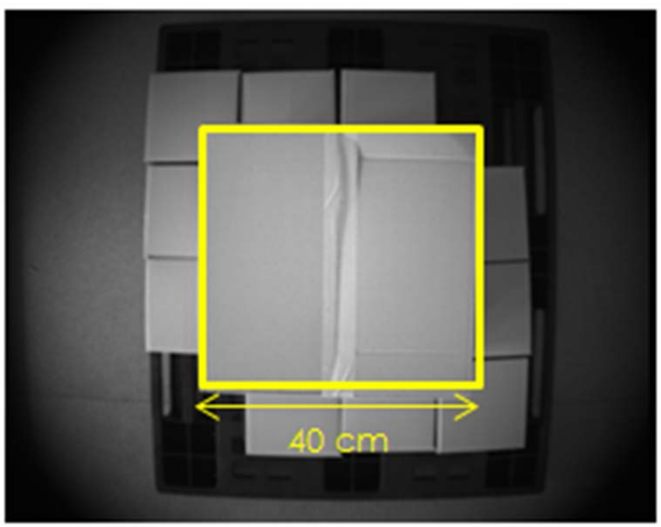


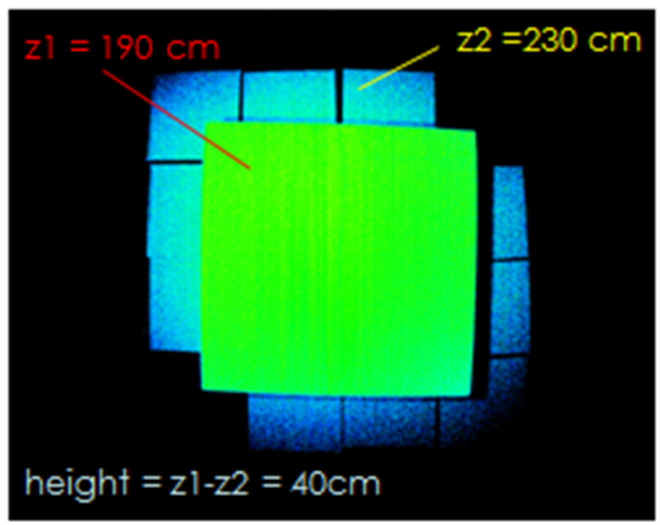
Road/Rail Inspection

- 3D laser line triangulation + line scan intensity/color

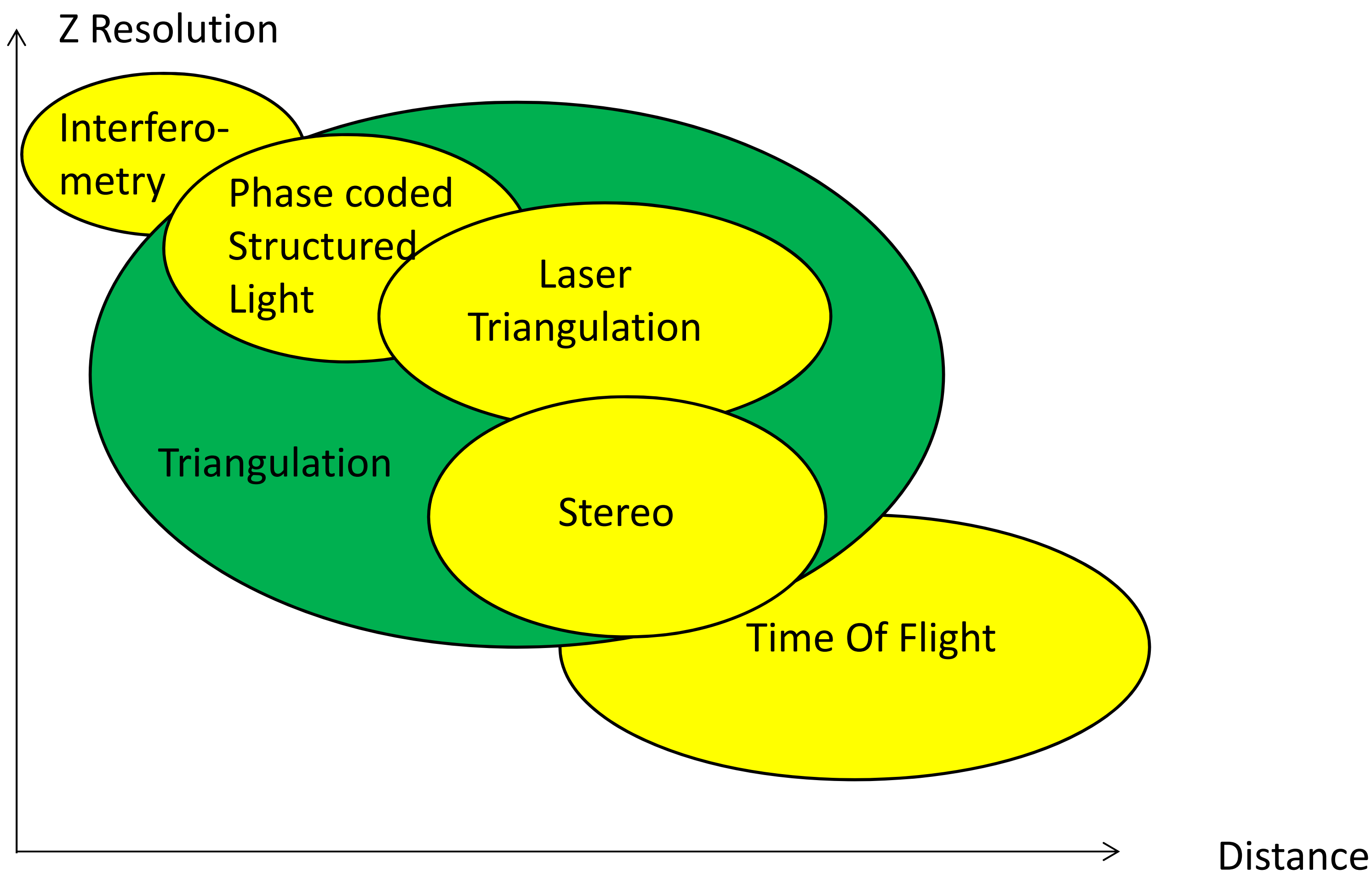
Logistics with TOF

- Measure volume and position on pallet or conveyor





3D Technology Overview



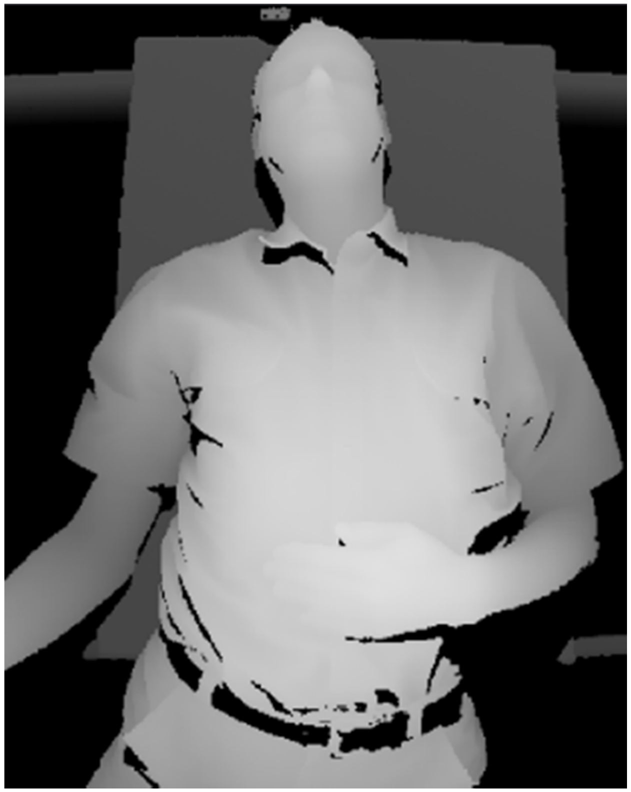
Application Discussion

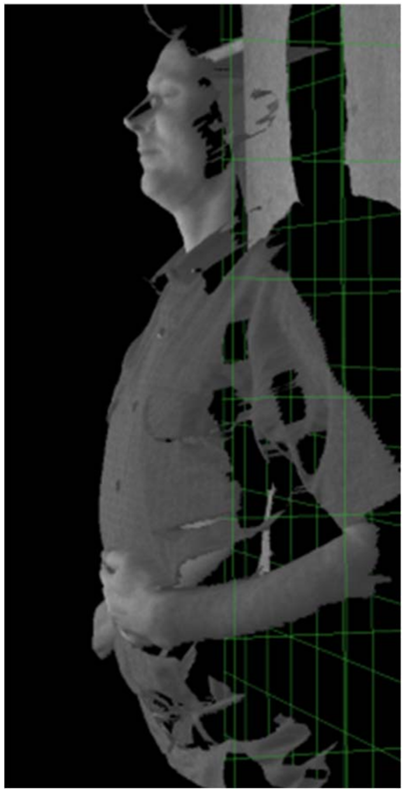
- Application requirements complex
  - What are the requirements for example, for a “good cookie”?
  - Iterative requirement work and testing a good way forward
- Basic requirements
  - Cost!
  - FOV size
  - Resolution X-Y-Z and accuracy requirements
    - Sampling theorem : at least (defect size) / 2 pixel size
  - Acquisition speed / object movement
  - Error tolerance : False Positives / False Negatives?
  - Environment – ambient and size limitations, laser class limitations
- Technology selection
  - Which technology would fit best?
    - Will the technology I have in my toolbox work?
- Early test
  - Try to get 3D data to prove/disprove visually the basic requirements
    - Can the defect be seen?
    - Can I see all aspects without occlusion?
    - Do I have enough signal without eye safety/cost issues?

Finally

- Any questions ??

Mattias Johannesson
Expert 3D Vision, Core Design
Identification and Measuring





3D data from scanning ruler – laser triangulation

Sensor Intelligence.

Mattias Johannesson

Expert 3D Vision, Core Design
Identification and Measuring

SICK IVP AB
Wallenbergs Gata 4
583 30 Linköping
Sweden

Phone: +46 13 362142
Email: mattias.johannesson@sick.com

www.sick.com

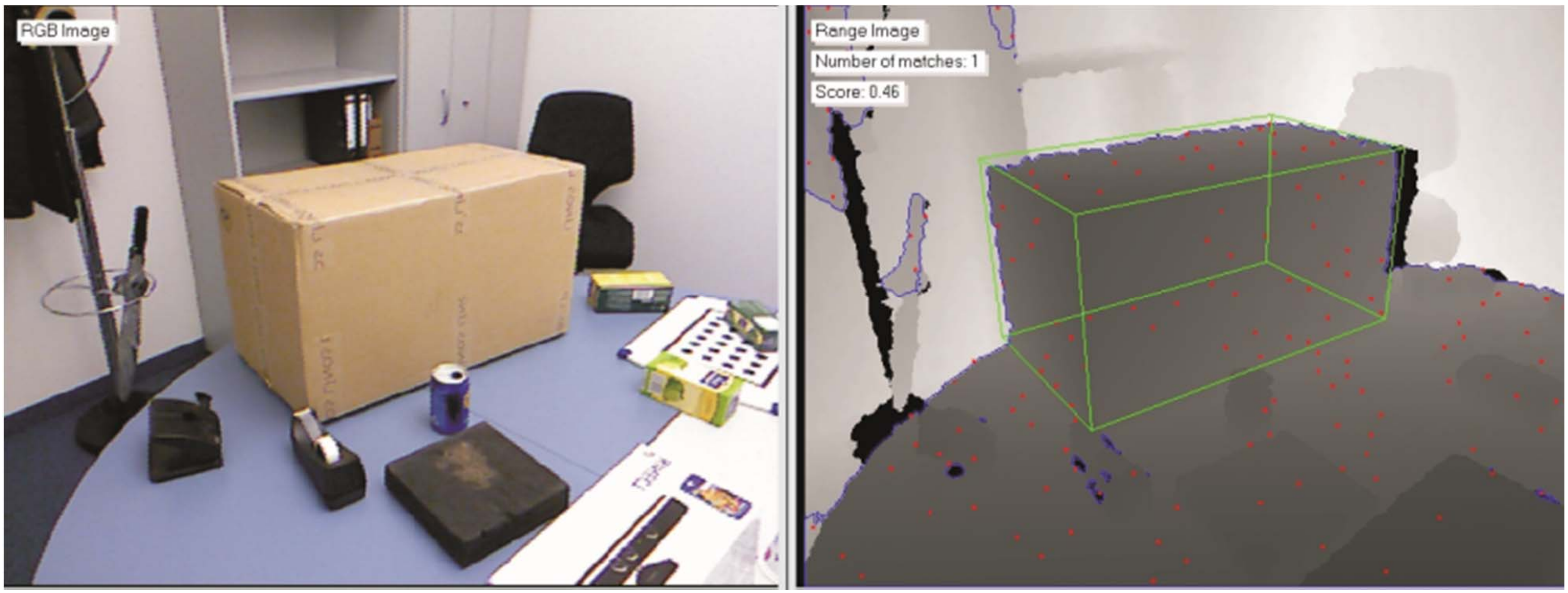
Bonus slides

- Collected here to show if time allows
- Printed also ”in logical place” in the handouts

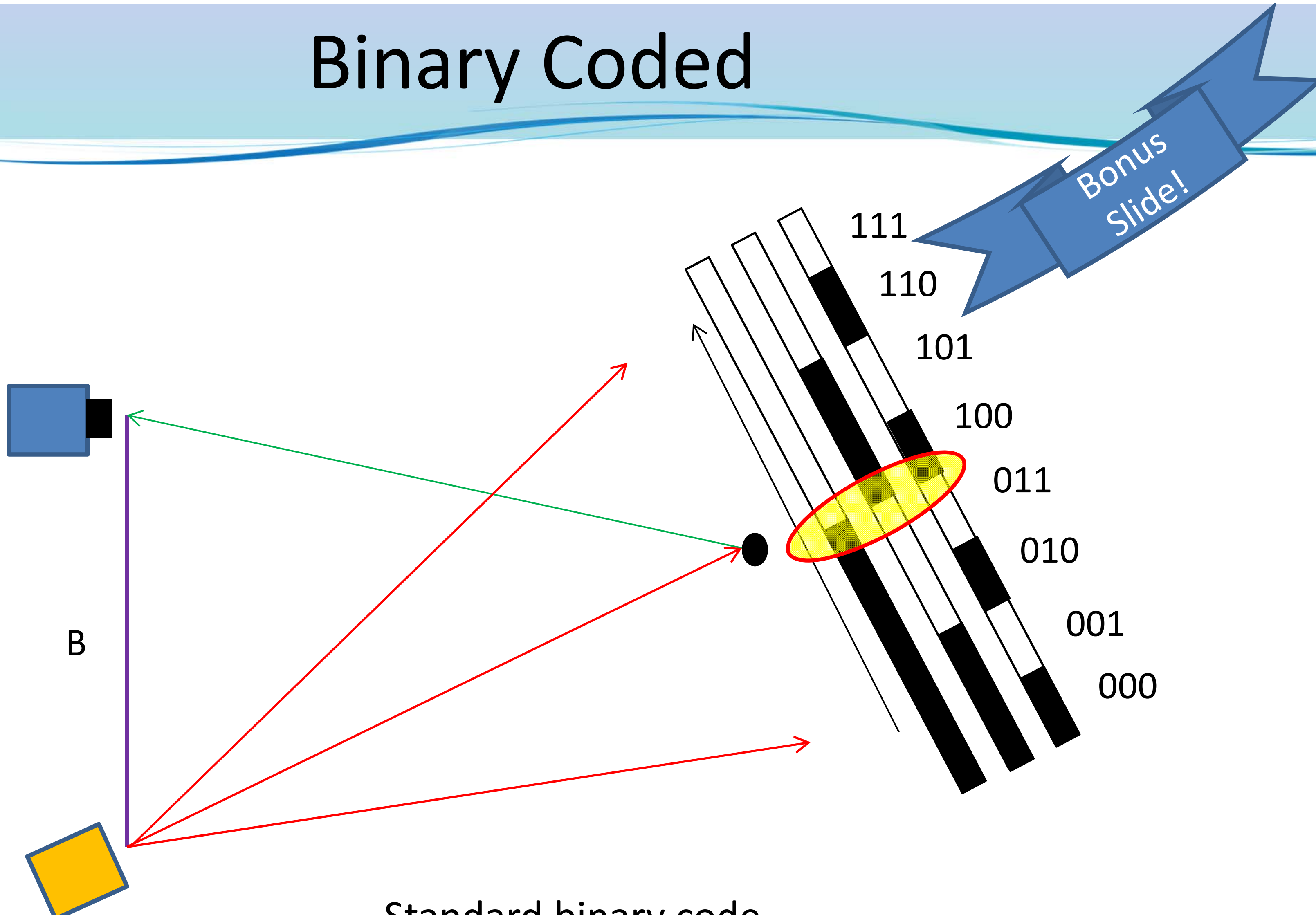
Kinect Application Sample

Bonus Slide!

- MvTec Halcon Image Processing SW example – Finding Box



Binary Coded

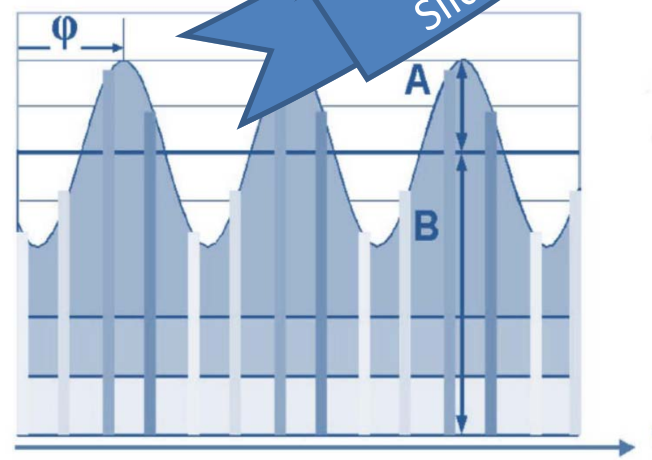


Standard binary code
- Many bits switch at same position

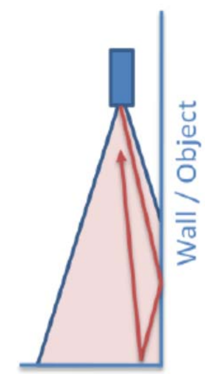
TOF With CW Modulated Light Source

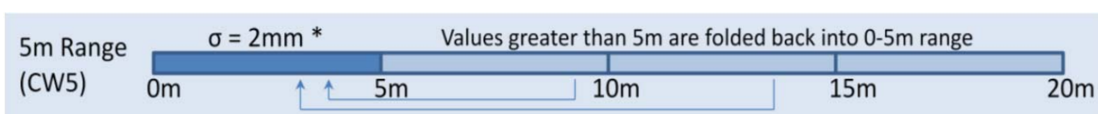
Bonus Slide!

- Modulate the light source
  - e.g. f = 30 MHz => 5 m range ambiguity limit
- 4 capacitors per pixel
  - Integrating one 90° phase interval each
- Integrate for many cycles
  - e.g. 20 ms => 5 ms/capacitor
- Find phase φ from the 4 values
  - φ_0 from pixel with direct optical feedback
- Wrapping problem for distances larger than 5 m
- Problems with ambient, reflections, saturation, motion …



$$d = c\frac{\varphi - \varphi_0}{4\pi f}$$





Misc. 3D Methods

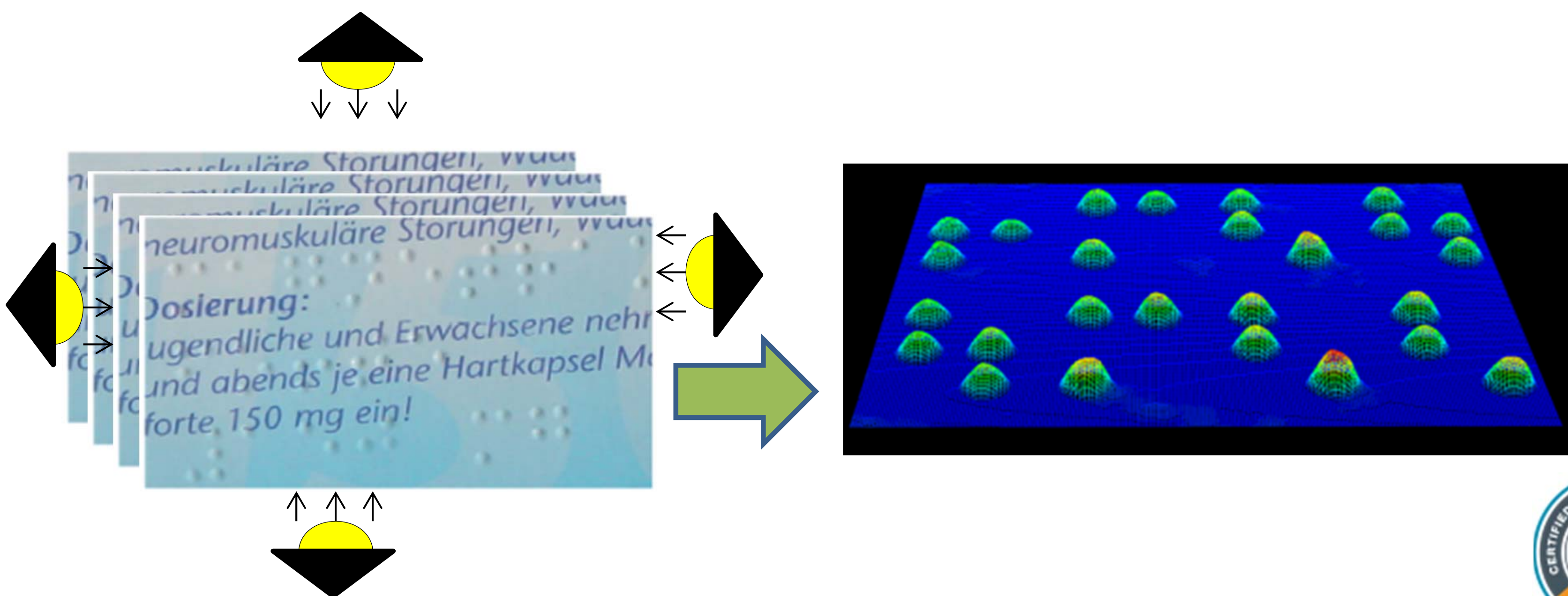
- Less common
  - Interesting theory
  - Special cases
  - On Bonus Slides !

Bonus Slide!

Shape from Shading

Bonus Slide!

- Gives shape information, but not real distance
  - Shade from different directions of illumination gives surface orientation information
  - Integrating the orientation gives depth variations
- Limitations
  - Only surface orientation, no actual depth
  - No discontinuities allowed



Light-Field 3D 1

- Micro lens array used to create "4D" light-field image on standard image sensor
  - 2D direction "subpixels" in each 2D "pixel"

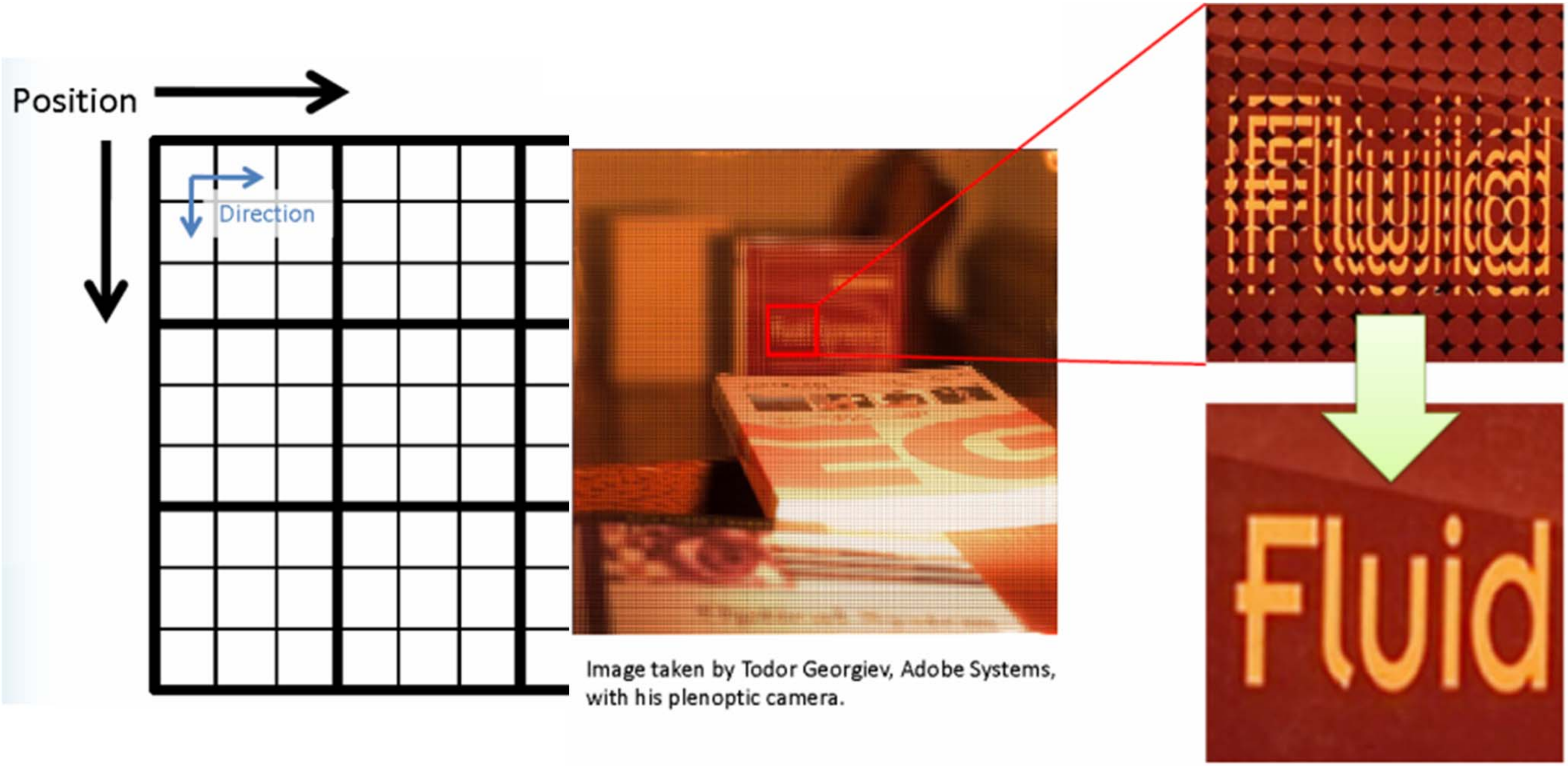
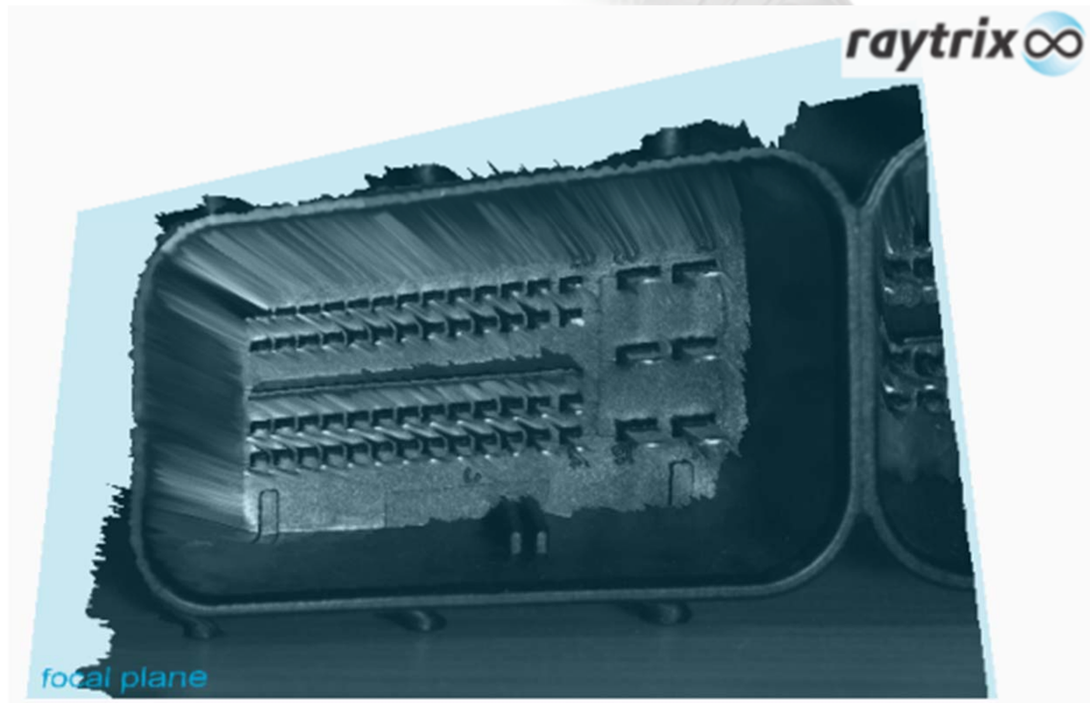


Image taken by Todor Georgiev, Adobe Systems, with his plenoptic camera.

Light-Field 3D 2

Bonus Slide!

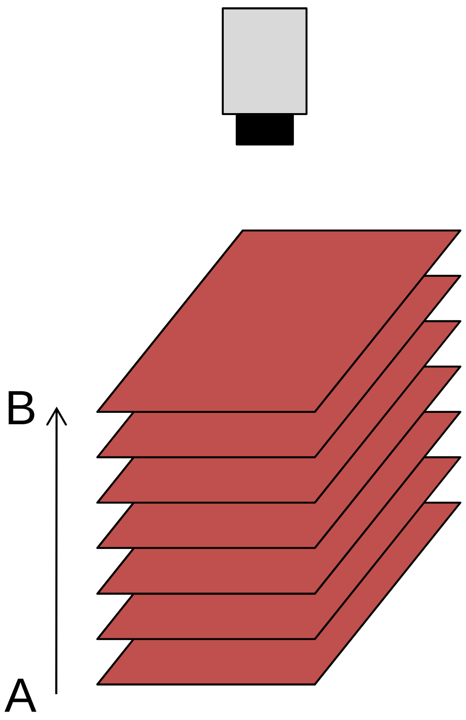
- Processing of light-field image
    - Refocussing
    - 3D calculation
- Cameras – Raytrix (Lytro)
- Features
    - "No occlusion"
- Limitations
    - Depth accuracy "lens aperture triangulation"
    - Special cameras
    - Complex processing
    - Lytro : no 3D, not industrial



Depth from Focus

Bonus Slide!

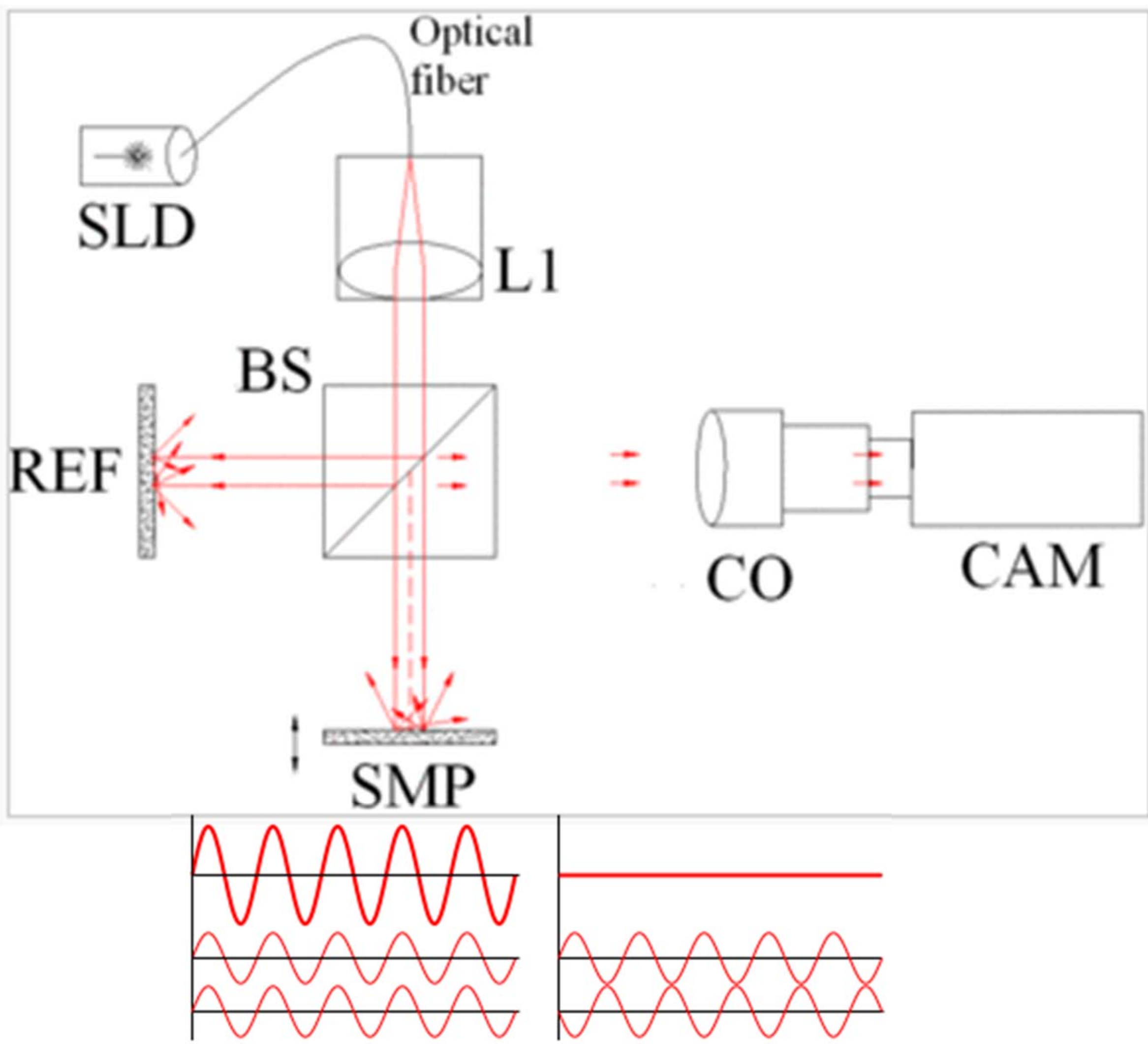
- Grab a sequence of images focused from A to B
- Scan through the stack and find where local focus is maximized
  - That gives the range



- Features
  - No occlusion
  - No structured illumination needed
- Limitations
  - Slow
  - Needs structure to estimate focus
  - Pixel regions needed to estimate focus
  - Poor accuracy
    - “Triangulation using lens aperture”

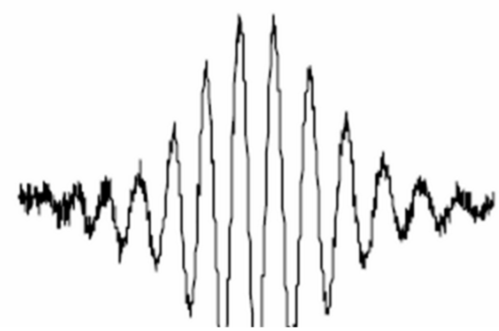
Interferometry 1

Bonus Slide!



Coherent (Laser) Light
- Periodic Interference
-> Flatness measurements

Incoherent (White) Light
- Interference @ same distance
-> Shape measurements



Interferometry 2

Bonus Slide!

- Features
  - Sub-micron accuracy
- Limitations
  - Complicated scanning mechanics
  - Static scene needed during scan