3D Active Sensing Notes

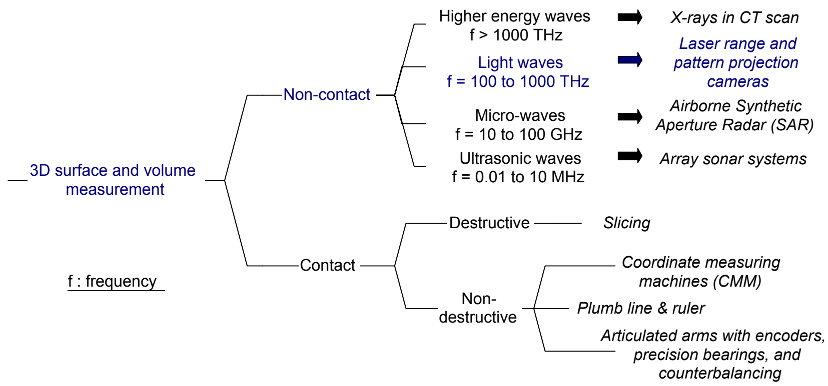
Adapted from the following sources:

François Blais, Terrestrial Laser Scanning
International Summer School Digital Recording and 3D Modeling
24-29 April 2006, Aghios Nikolaos, Crete, Greece

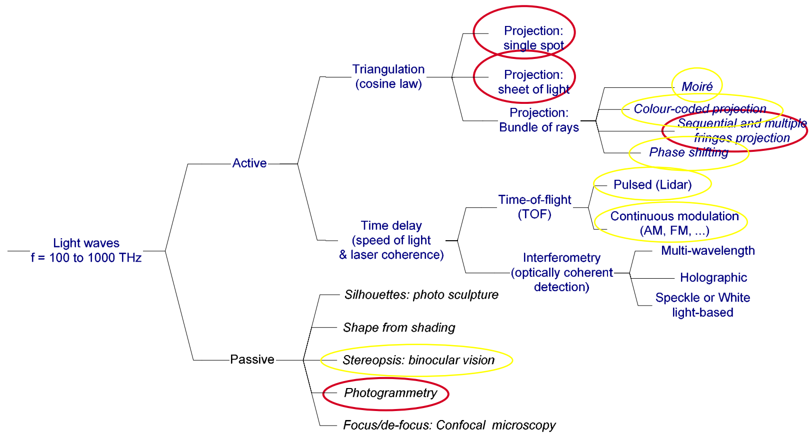
Siggraph 2000 Active Sensing notes by Brian Curless

P. Allen, 3D Photography class notes

Measuring 3D Shape: General



Measuring 3D Shape: Light waves



3D Sensing

- Sonar - Acoustic waves (10 kHz - 10 MHz)
  - "Nature's active 3D sensor": bats, dolphins
  - Accuracy ? Resolution ?
  - Specularity
    - example 1, f=50 kHz -> λ = 340 m/s / 50 kHz, λ = 6.8 mm compared with typical surface roughness $\approx$ 0.05 mm
    - example 2, f=1 MHz -> λ = 340 m/s / 1 MHz, λ = 0.34 mm compared with typical surface roughness $\approx$ 0.05 mm
- 3D Sensing: Radio to Light Waves - Microwaves 1 - 100 GHz
  - Radar: 3 mm to 300 mm
- Optical - 0.3 μm to 2 μm (150 THz)
  - With ambient light: stereo vision
  - Structured light : active systems

Theodolite, Range, Digital Cameras

Active 3D Sensing: Time-based

- Time of flight - incoherent detection
  - Speed of light: c=299 792 458 m/s (vacuum)
  - Pulse
  - Amplitude, phase, or frequency modulation $\lambda = c / f$
  - c/n: n is the refraction index (in air 1.00025)
- Interferometry - coherent detection
  - Phase of optical wave is measured : self-mixing interference patterns

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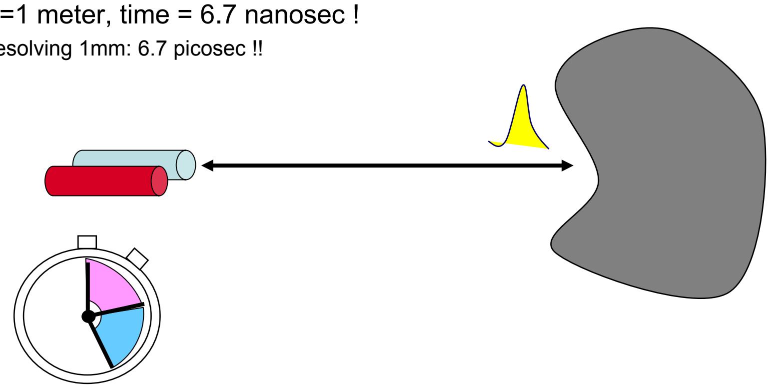
Laser Radar (LIDAR)

- Distance = Speed of light × Time / 2
- For d=1 meter, time = 6.7 nanosec !
  - Resolving 1mm: 6.7 picosec !!



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Features

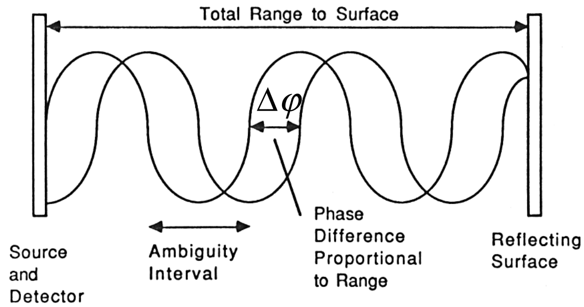
- Usable at very long ranges (km!)
- Error almost independent of distance
- Allows coaxial detection: no shadow
- Pulse detection:
  - rise time
  - multiple reflections
- Requires fast electronics
- High laser power
- Using phase instead of time: ambiguity interval
  - More accurate
- Using Frequency modulation and optical interference
  - Very accurate but very expensive

Imaging radar: Amplitude Modulation

The current to a laser diode is driven at frequency:

$$f_{AM} = \frac{c}{\lambda_{AM}}$$

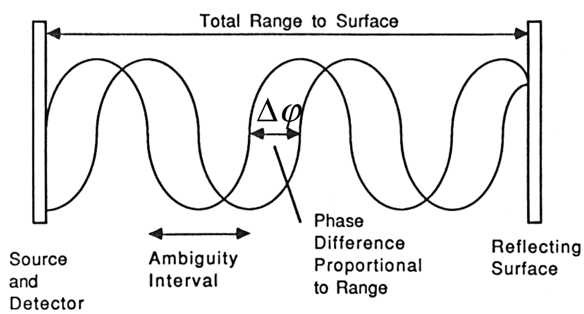
The phase difference between incoming and outgoing signals gives the range.



Imaging radar: Amplitude Modulation

Solving for the range:

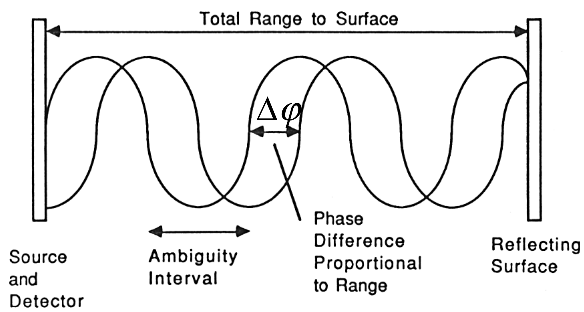
$$2r = \frac{\Delta\varphi}{2\pi}\lambda_{AM} + n\lambda_{AM}$$



Imaging radar: Amplitude Modulation

Solving for the range:

$$r = \frac{\Delta\varphi}{4\pi}\lambda_{AM} + \frac{n\lambda_{AM}}{2}$$



Imaging radar: Amplitude Modulation

Note the range ambiguity:

$$r_{ambig} = \frac{n\lambda_{AM}}{2}$$

The ambiguity can be overcome with sweeps of increasingly finer wavelengths.

Active 3D Sensing: Triangulation-Based

- Single point
- Sheet of light
- Focusing techniques
- Combined focusing and plane of light
- Coded light approach
  - Moiré techniques
  - Pattern projection
  - Gray-code and other coding techniques
  - Colour coding
- …

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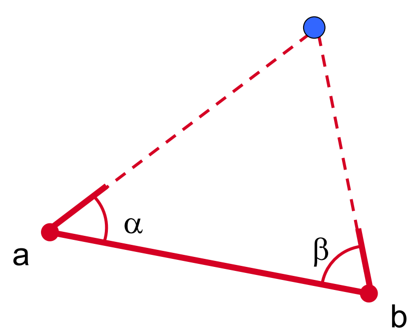
Active 3D Sensing: Triangulation-Based

- One side + 2 adjacent angles completely determine a triangle:
- Several Methods
  - Single point
  - Sheet of light
  - Focusing techniques
  - Combined focusing and plane of light
  - Coded light approach
    - Moiré techniques
    - Pattern projection
    - Gray-code and other coding techniques
    - Colour coding



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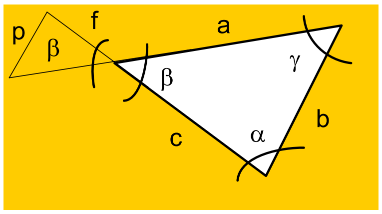
Triangulation

- Trigonometry: Greek Philosopher Thales 6th century BC



$$\frac{p}{b} = \frac{f}{c}$$

$$\frac{a}{\sin(\alpha)} = \frac{b}{\sin(\beta)} = \frac{c}{\sin(\gamma)}$$

$$a^2 = b^2 + c^2 - 2\,bc\,\cos(\alpha)$$

$$c = a\cos(\beta) + b\cos(\alpha)$$

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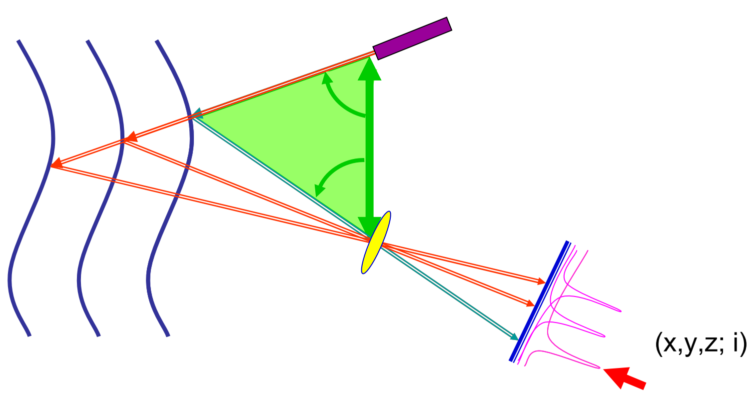
Active Optical Triangulation

- Single point probe



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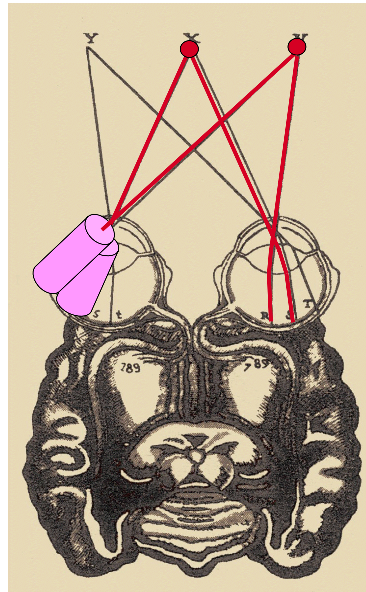
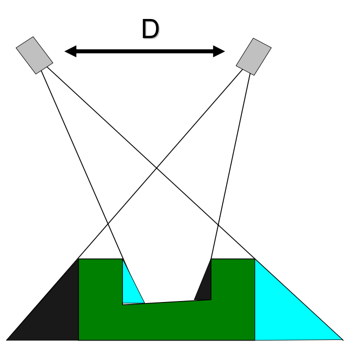
Connection to Stereopsis



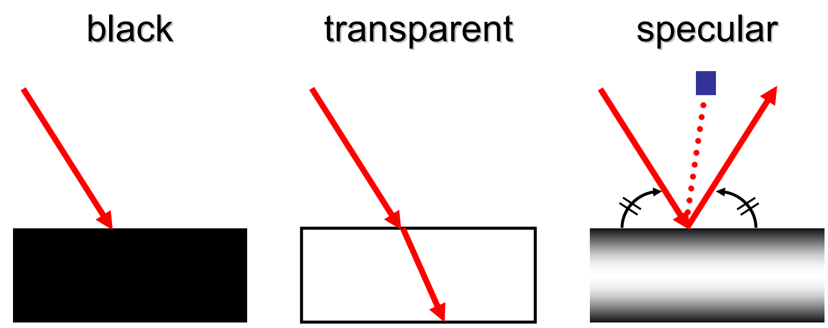
Shadow Effects

- Shadow effects are inherent to optical triangulation, active AND passive (e.g. stereo)
  - Some regions of the object cannot be measured because of the separation between the light source and the detector
  - Magnitude of the shadow effect increases with the triangulation baseline D

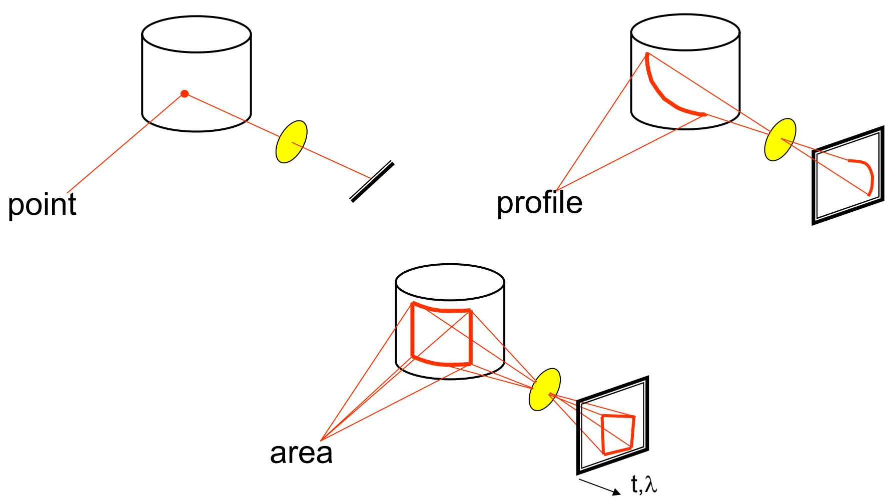


Limit Surface Conditions

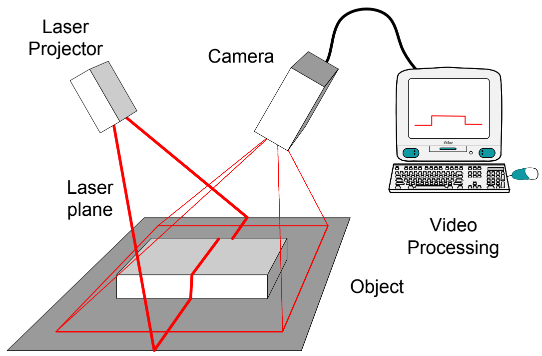
- Measurement requires that “some” light be reflected towards sensor
- Detection impossible if surface is PERFECTLY:



Triangulation Configurations



Plane-of-Light Method



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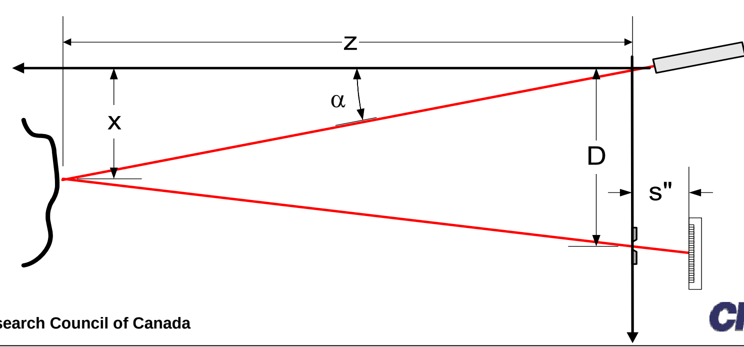
Basic Optical Triangulation

- Thales: 1 distance +2 angles
- Basic optical triangulation: pin-hole model
  - The light beam generated by the laser/light projector is deflected at an angle a (to scan the object)
  - The position p of the diffused image of the laser/light spot on the surface is measured by the imaging device



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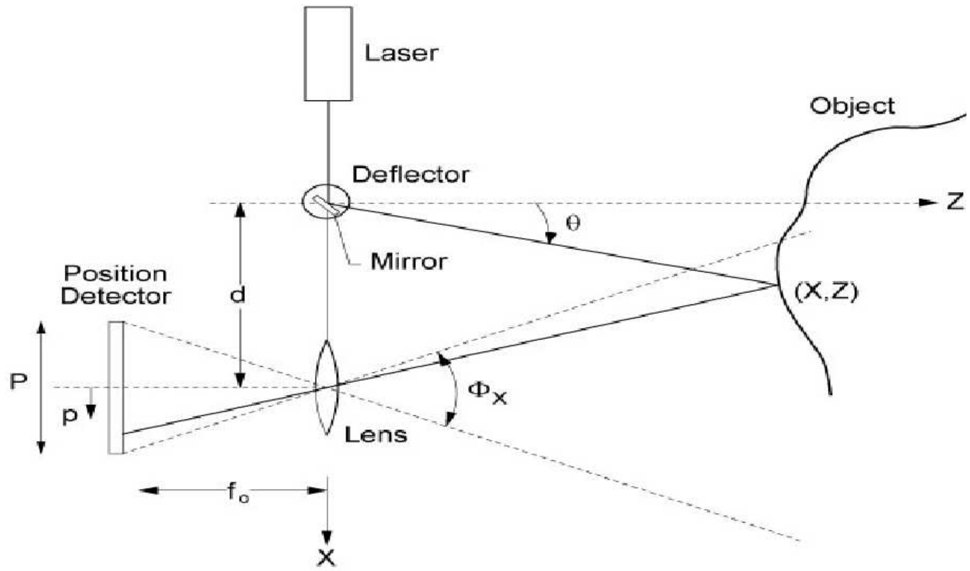


Figure 1: Geometry of laser rangefinder

- Fig. 1 shows the basic geometry of laser triangulation. If we know the direction of the laser source and the 3D ray emanating from the vision sensor that images the laser, we can intersect them in 3D to find the depth.
- To solve for depth (Z) and horizontal position (X), we can refer to figure 1:

$$\frac{p}{f_0} = \frac{d - X}{Z} \quad tan\,\theta = \frac{X}{Z}$$

$$\frac{p}{f_0} = \frac{d - Ztan\theta}{Z}$$

$$Z = \frac{f_0\,(d\, -\, Z\,tan\,\theta)}{p}$$

$$Z = \frac{f_0 d}{p} - \frac{f_0\,Z\,tan\,\theta}{p}$$

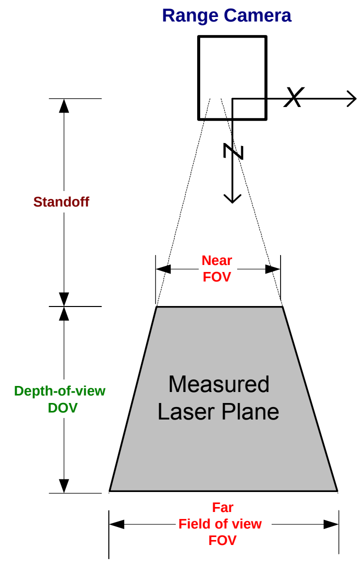
$$Z\, +\, \frac{f_0\,Z\,tan\,\theta}{p} = \frac{f_0\,d}{p}$$

$$Z\,(1\, +\, \frac{f_0\,tan\,\theta}{p}) = \frac{f_0\,d}{p}$$

$$Z = \frac{f_0\,d}{p\, +\, f_0\,tan\,\theta}\ ;\ X = Z\,\tan\,\theta$$

This says that if we know the focal length f_0 of the camera, the location of the imaged laser spot on the camera p, the separation of the camera and the laser d (the *baseline*), and the deflection angle of the laser source θ, we can find the 3D location of the surface where the laser hits.

Volume of Measurement



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Range Equation: Triangulation

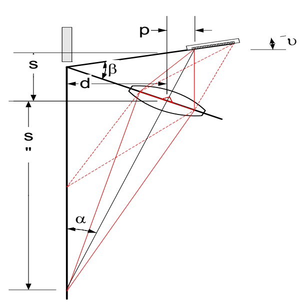
- Range: $$z = \frac{d \cdot f}{p + f \cdot \tan(\theta)}$$
- Depth of field: $$\frac{1}{z_{\min}} = \frac{1}{z_{\max}} + \frac{P}{f \cdot d}$$
- Field of view: $$\Phi = 2 \cdot \tan^{-1}\left(\frac{P}{2 \cdot f}\right)$$

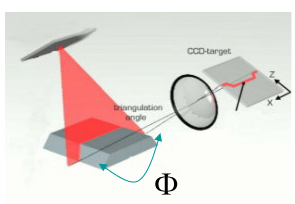
d = Triangulation base

f = lens focal length

P = detector size

p = peak position





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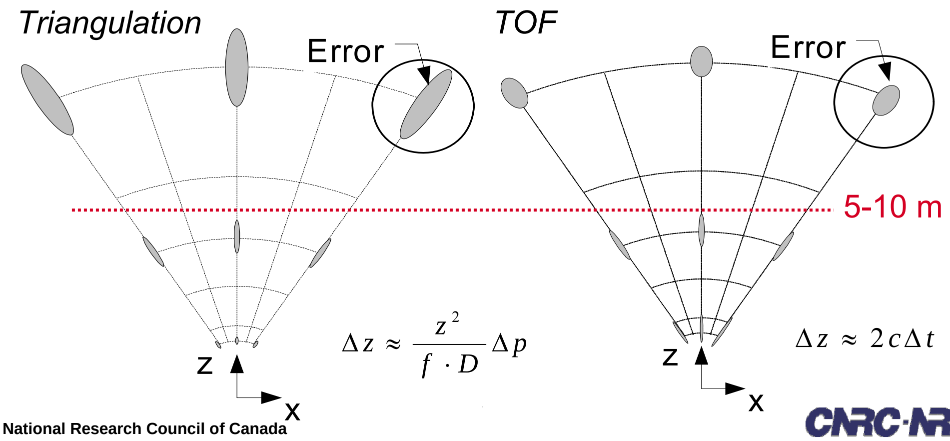
Uncertainty vs Field of View

- Z uncertainty: $$\sigma_z \approx \left(\frac{z^2}{f \cdot D} \right) \sigma_p$$
- Lateral Field of View X: $$\Phi_x = 2 \cdot \tan^{-1}\left(\frac{P}{2 \cdot f} \right)$$
- To decrease the uncertainty in z, we can
  - Decrease range Z : increases shadow effects
  - Increase the triangulation base D : increase shadow effects
  - Increase the lens focal length f : reduces field of view
  - Decrease the measurement uncertainty on σp
- To increase the field of view, we can increase
  - Lens focal length f: increases uncertainty
  - CCD dimensions

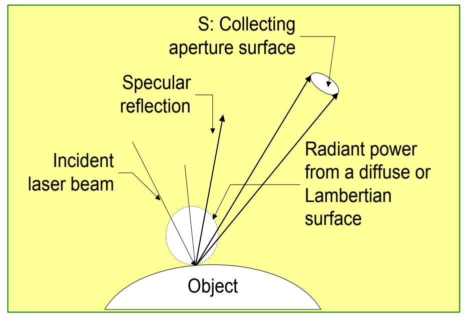
Error Distribution: Laser Spot Scanning

The measurement error distributions of a triangulation/TOF based laser scanner are ***inhomogeous*** and ***anisotropic*** in behavior.



Influence of Surface Reflectance

- Another factor on σp is introduced by
  - Amount of light returned to the CCD by the object
  - Distortion of the image of the laser spot = distortion of its centroid
    - Non-uniformity of the object reflectivity vs. spot size
    - Multiple reflections
    - For diffused reflection



$$P_{sensor} = P_{laser}\left[\frac{T_1 T_2 \rho_d S \cos(\alpha)}{\pi R^2}\right]$$

T_1, T_2 = Transmission coefficients of emission and collection optics

ρ_d = Diffuse reflectance coefficient

S, R = Collecting aperture and distance to object

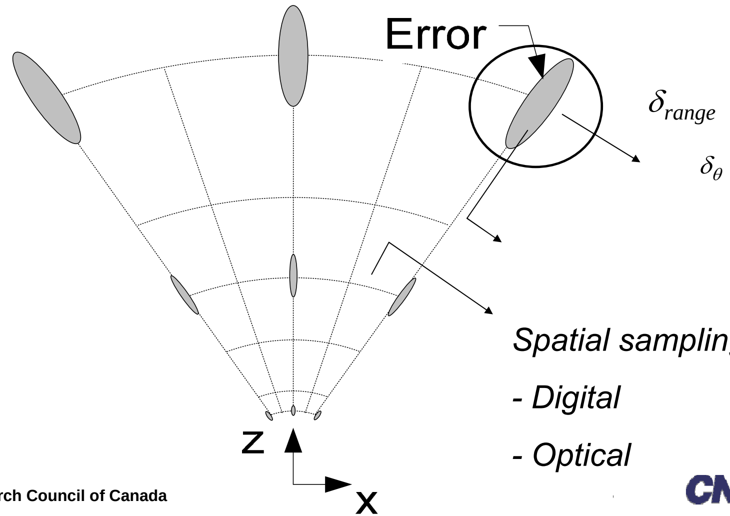
α = Angle between normal of the surface and solid angle

Applications: industrial vs. heritage

- There is no market (yet) for laser scanner in the field of heritage
- Must look at industry to find a suitable range sensor
- Development of 3D laser scanner is costly, even laboratories (e.g. NRC) have developed their 3D systems first for industrial applications
  - They can adapt their technology for specific research (e.g. heritage)

INDUSTRIAL SECTORS	FOV (m)	ACCURACY (mm)
Automobile 90% of car 10% of car	 1 × 1 0.2 × 0.2	 0.5 0.05
Naval	20 × 20	5
Aeronautics Space	10 × 10 100 × 100	1 10
Mechanical	0.25 × 0.25	0.025
Micro-electronics	0.05 × 0.05	0.0025

Uncertainty: laser scanning and imaging systems



Spatial sampling:

- Digital

- Optical

Aliasing

- In statistics, signal processing, and related disciplines, aliasing is an effect that causes different continuous signals to become indistinguishable (or aliased of one another) when sampled
  - When this happens, the original signal cannot be uniquely reconstructed from the sampled signal. High-frequency components will be aliased with genuine low-frequency ones.
  - In digital imaging and computer graphics, it may produce Moiré patterns
- Nyquist criterion
  - One way to avoid **aliasing** is to make sure that the signal does not contain any sinusoidal component with a frequency greater than *f/2*. More generally, it suffices to ensure that the signal is appropriately *band-limited*, namely that the difference between the frequencies of any two of its sinusoidal components must be strictly less than *f/2*.
  - This is rarely done with laser scanner

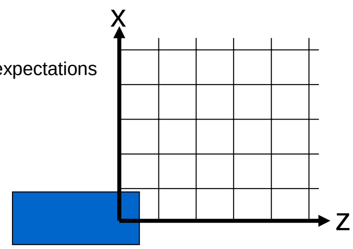
(from Wikipedia)

What will limit accuracy and resolution

- Optical (scanner)
  - Geometry – e.g. focusing, depth of focusing and <u>optical resolution</u> (not digital)
  - Diffraction limits (Raleigh criteria)
  - Gaussian beam propagation (laser beam)
  - Spot size vs. depth
  - Speckle, signal buried in noise
- Optical (surface)
  - Spot size or projected pixel size vs. depth of focus
  - Range shift and noise due to surface penetration
  - Range artefacts on edge and reflectance jumps
- Non-optical
  - Vibrations
  - Air turbulence
  - Mechanical errors
  - Human errors
  - Introduced by calibration

What is Calibration ?

- Establishing all the parameters/knowledge required for transforming the raw sensor measurements into dimensional quantities
  - e.g. for triangulation: (scanning angles + position on CCD/camera) = (x,y,z)
  - Coordinate system:
    - Sensor-centered
    - Usually Cartesian
- Why is it difficult ?
  - Each sensor design is unique
  - Each sensor is unique
  - Not an imaging device, but a measurement instrument: high expectations
  - Requires a "chain of accuracy"
  - Measurements affected by external factors
    - Temperature, atmosphere, vibration, …
  - Affected by measured surface properties
  - Not always easy to assess quality:
    - A nice image is not necessarily a good image !



"Black Box" Calibration

- Models everything as a transfer function from the measurements (angles,p) to (x,y,z)
- Built from sets of actual measurement of known geometry
  - How accurate is the "known geometry"

- Internal sensor parameters implicitly represented
- Can include additional parameters/measurements
- Applicable to very complex systems
- Typically requires A LOT of measurements !
- Still some implicit hypotheses, e.g. in choosing the sampling density and interpolation method

Terminology (1) – from VIM

- Accuracy: closeness of the agreement between the result of a measurement and a true value of the measurand. If one wishes to measure absolute quantities then this is important.
- Reproducibility: closeness of the agreement between the results of measurements of the same measurand carried out under changed conditions of measurement. One needs this feature if the same artefact has to be measured, let say, at different times or by a different user.
- Uncertainty characterizes the dispersion of the values that could reasonably be attributed to the measurand. The measurement uncertainty can be further decomposed in a systematic and a random part. (σ)

Terminology (2)

- Systematic errors: mean that would result from an infinite number of measurements of the same measurand carried out under repeatability conditions minus a true value of the measurand. This type of error can be due to poor calibration, range measurement artefact, ambient light conditions, reflectance properties of surface, etc. Can be reduced by modeling the errors.
- Random errors: this type of error originates from stochastic temporal and spatial variations of influence quantities. One has to lower this quantity to avoid resorting to excessive filtering.
- Resolution: smallest difference between indications that can be meaningfully distinguished. One needs this feature in order to avoid being limited by quantification noise, CCD resolution, spot size, etc.

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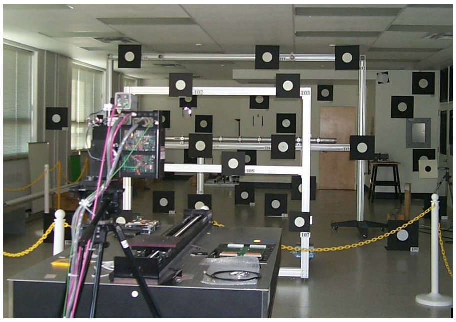
Calibration Set-up

- Structure used for calibration
  - Requires accurate survey of the targets
  - Complex
  - Costly
  - Can't be used for simultaneous calibration of small and large volumes
  - Small number of targets affect accuracy
  - Occlusions and obstructions
- Used for model based calibration



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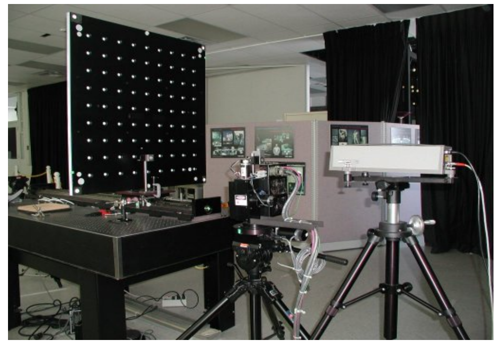
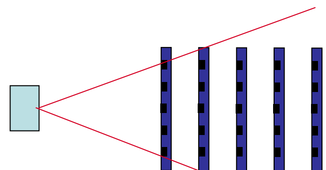
Calibration with a Target Array



- Known positions
- Accurately machined target array
- Range limited by the translation stage
- Does not cover the full FOV
- Used for model-based calibration, allows extrapolation
- Wobble, jitter, backlash, orthogonal motions, pitch-yaw
  - E.g. pitch-yaw 25 arc-sec = 0.12 mrad or 0.120 mm @ 1m
- A mechanical challenge



Calibration Toolbox

- Temperature controlled environment
- Anti-vibration tables
- Theodolites and photogrammetry equipment
- Optical measurement and alignment tools (e.g interferometers)
- High precision reference objects
- Optical quality reference surfaces
- Accurate linear and rotation stages
- Inspection software
- Access to high precision CMM and other measuring capabilities through other Institute and partners
- …

A final word on "calibrated" data

- Don't expect a zero mean Gaussian distributed noise
  - Even assuming a perfectly calibrated range sensor with "perfect" components and no residual distortion, the noise model is NOT Gaussian.
  - Gaussian noise is used only to simplify the mathematics
  - Local bias will always be present (even in the statistics sense)
- The source of bias in the calibrated data can be created by
  - Bias in the raw measurements (e.g. surface penetration, artefacts)
  - Bias in the calibration model; some internal parameters are not modeled (e.g. flat mirror surfaces, lens distortions, protective windows not 100% flat)
  - Bias in the measurements of the reference targets (ground truth)
- The model (inverse model) is not known
  - Therefore the real source of errors (bad calibration, bad measurements, or ???)
  - Small local bias are normal and the scanner will still be "calibrated" to nominal specs

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Laser Scanners: What to Look for…

- Certification from manufacturer
  - Clear specs
  - Methodology
  - Date of calibration
  - Beware of the single number spec !
  - On-site/user calibration check/recalibration capability
- Test for your specific material
  - Translucency, roughness, specularity
- A nice smooth image may be distorted !
  - problems when assembling multiple views
- Important Notes:
  - Calibrated data means: the specs under nominal conditions ("optimal" surfaces)
  - A Laser scanner is a measurement device and need to be recalibrated ($)
  - Current software tools assume data are "perfectly" calibrated
    - One 3D image always look nice, only when you put them together you will discover some interesting "aspects"; if you look carefully the 3D data will often still be within specs.

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Examples of Industrial Applications

- Providers of solutions – vertical integration
  - Improving the efficiency of existing operations
  - Developers and providers of solutions that use 3D
    - Automation of industrial processes
    - Specialized Process Control
    - Vertically integrated solutions
    - Services
  - Many companies are developing 3D systems but are not "advertising" themselves as 3D companies
- OEM and Camera Providers
  - Developers of 3D solutions for … providers of solutions
    - Inspection (e.g automotive)
    - Surveying
    - Anthropometry
    - Architecture
    - Heritage
    - OEM
  - Many potential solutions for one application
  - Several products with similar performances

Applications: heritage, anthropometry

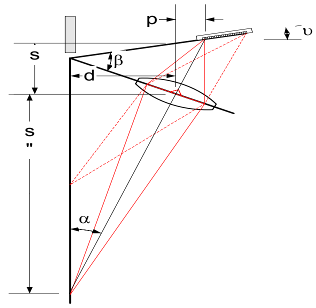
HERITAGE	FOV (m)	ACCURACY (mm)
Architecture		
80%	20 × 20	5
20%	1 × 1	0.25
Museum		
Sites	10 × 10	1
Object	0.1 × 0.1	0.05
ANTHROPOMETRY		
Body	2.0 × 0.5	0.2
Finger	0.05 × 0.025	0.01

NRC's Range Sensors

- Two classes of methods have been developed
  - Auto-synchronized and other scanning methods tries to optimize ranging by:
    - Eliminating the dependency between total field of view and instantaneous field of view
      - Dependence vs. f and D
    - The "best" elements and optical techniques for the measurement σp
      - Schleimpflug condition
  - Biris/BiView + plane of light method
    - Objectives: to preserve a good compromise between cost and performances
    - Reduce the dependency between field of view and f, using an anamorphic lens design

Examples of Single point probes

- Single point probe + Mechanical scanning
- Laser synchronization



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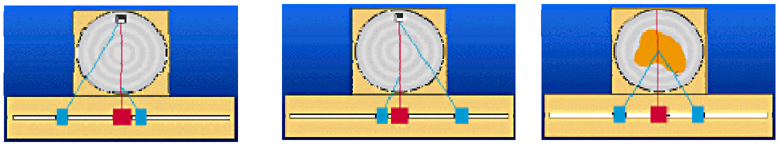
Digibotics System

- Single point probe
- Mechanically rotate/translate object
- Moves optical head(s) to measure rang
- 3 different configurations
- www.digibotics.com



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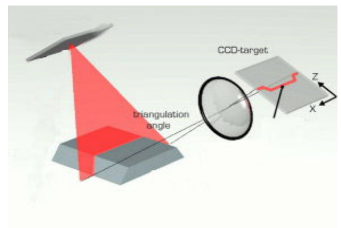
Laser stripe

- Line scanning
- Mechanical scanning
- With Positioning systems
  - Line Stripe + 6DOF Positioning system
    - Mechanical (CMM or …)
    - Magnetic
    - Optical (photogrammetry)



Minolta

- Laser stripe
- Galvanometer scan
- Interchangeable lens or zoom
- VI900 resolution
  - x = 0.17mm, y = 0.17mm, z = 0.047mm
- Volume
  - 111mm x 84mm to 1300mm x 1100mm
- Colour 640 x 480 pixel
- 40000 pts/sec
- www.minolta-3d.com

Faro Arm

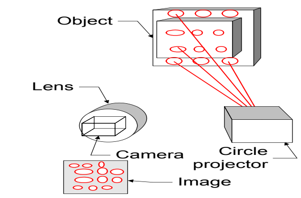
- Hand-held laser stripe camera mounted on mechanical arm
- Accuracy 2σ: 50μ
  Effective Scan Width: 64mm (2.5")
  Measurement Frequency: 30 images per second, 640 points per image = 19200 points per second
  Scan Distance: 89mm (3.5") to 184mm (7.25")

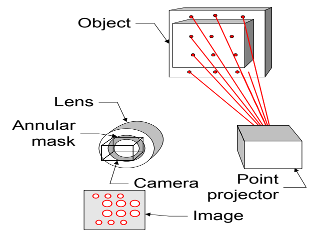
Polhemus

- FastScan
- Hand-held scanner
- Magnetic tracker (6 DOF)
  - Accuracy: 0.7 mm / 0.15 deg
- Designed to scan non-metallic objects
- Accuracy: 1 mm @ 200 mm
- 50 profiles/sec @
- www.polhemus.com

Example of pattern projection (cont.)

- Pattern projection
  - E.g. Circles: the diameter, eccentricity and orientation of the measured ellipse give range and surface orientation
- Annular mask
  - Diameter of the circle gives range
  - Rioux & Blais, 1984
- Laser speckle (random pattern)
  - Annular mask: diameter of the circles
  - Dual aperture mask, dual view: auto/inter-correlation of the image





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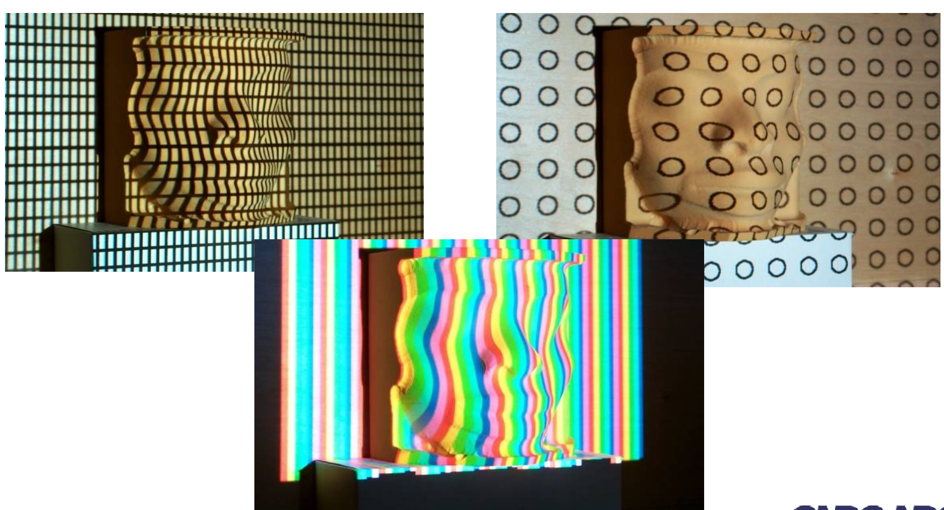
Pattern projection



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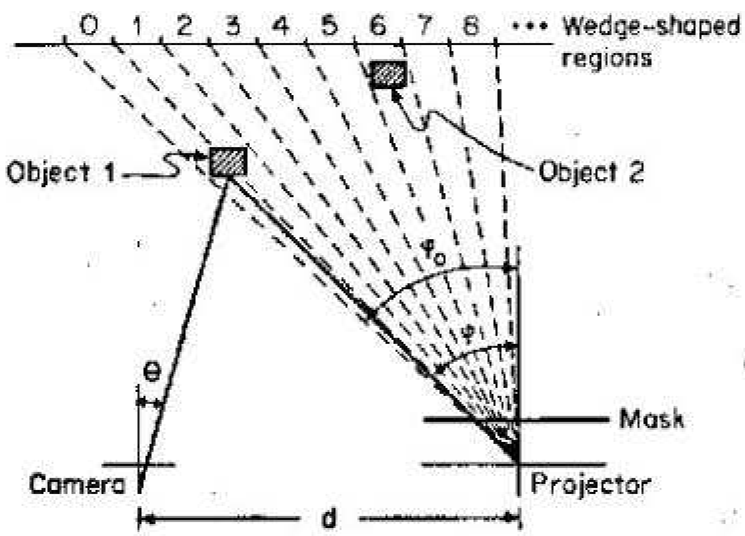
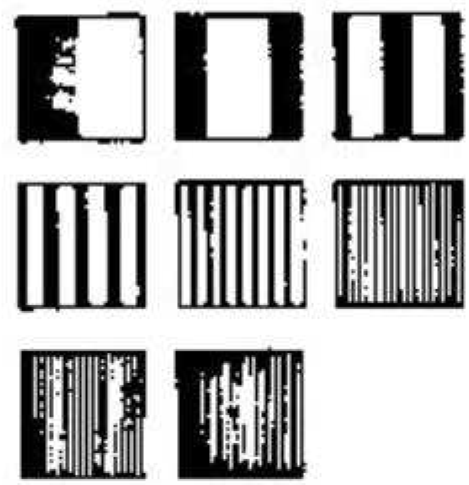
Structured Light Using Coded Light Striping



Geometry of Camera and Projector



Gray Code Projection Masks

Structured Light – Light Striping

= illuminated   = dark – not seen

Mask1								
Mask2								
Mask3								
Vis. 1	1	1	1	1	0	0	0	0
Vis. 2	1	1	0	0	1	1	0	0
Vis. 3	1	0	1	0	1	0	1	0
Region	A	B		C	D			
Bit Code	111	110	101	100	011	010	001	000

Use coded masks of light/dark to determine regions of space

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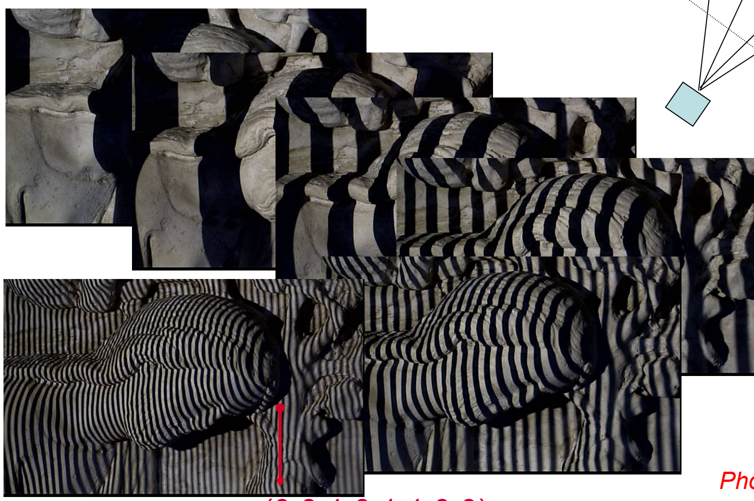
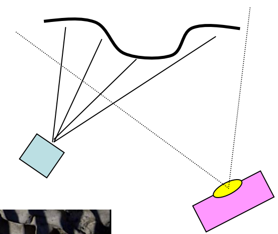
Fringe projection





(0,0,1,0,1,1,0,0)

- •Gray code = Phase shift
- •22 patterns in 2 sec
- •Flexible configuration

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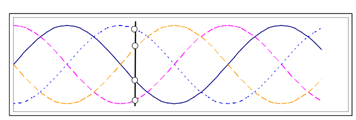
Integration of Gray Code and Phase shift

- Combined approach
  - Gray codes allow the measurement of 3D surfaces with sudden jumps in Z
  - Phase shift (spatial translation) allows the measurement of small features and is more accurate
  - Phase shift is more immune to defocusing from projector
  - Using stereo imaging reduces inaccuracies from projector (e.g. thermal stabilities)
  - From φ we can calculate range z
    - Needs 3 or more measurements *I* to find I_a, I_o and φ
    - *p is* given by the projector or from a second camera (stereo)



$$I_0 = I_a \cdot \sin\left(2\pi \cdot p_0 + \varphi\right) + I_o$$

$$I_1 = I_a \cdot \sin\left(2\pi \cdot p_1 + \varphi\right) + I_o$$

$$I_2 = I_a \cdot \sin\left(2\pi \cdot p_2 + \varphi\right) + I_o$$

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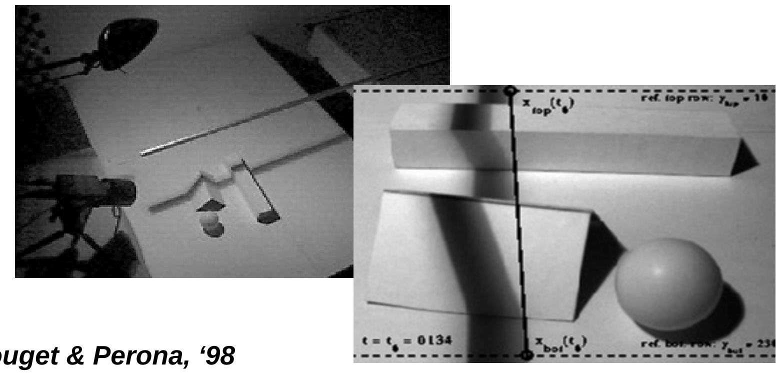
Triangulation: shadow scanning

- Optical arrangement: lamp, stick, photo-camera
- Shadow processing using space-time



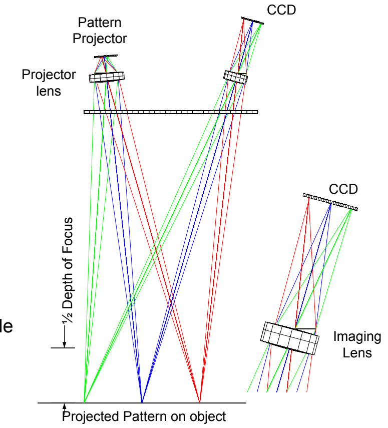
Bouget & Perona, '98

3D metrics

- Color coded grid pattern projection
  - Resolution 0.2 mm
  - 1/200th sec
  - Field of view: 210 mm x 320 mm
  - Depth of View: 100 mm
  - Lateral Resolution:
    - x axis: 2 mm
    - y axis: 1 mm
  - Depth Resolution: 0.2 mm
  - Color texture map
  - www.3dmetrics.com

Laser vs. Pattern Projection

- Lens: The pin-hole model (principal ray) is not sufficient at short range
  - Must consider the depth of field (defocusing)
- Laser
  - Point source and Gaussian beam propagation
  - XY resolution limited by size of laser beam only
  - Z resolution geometry + speckle Noise
- "White" light
  - Geometrical optics
    - Image of Pixel projected on object
    - Magnification of pixel + diffraction effects
    - Defocusing is important
  - XY resolution limited by Projector + imaging
  - Z resolution on *flat surfaces* is excellent - no speckle
  - Z accuracy similar
  - Smaller focus depth (Zmax – Zmin)

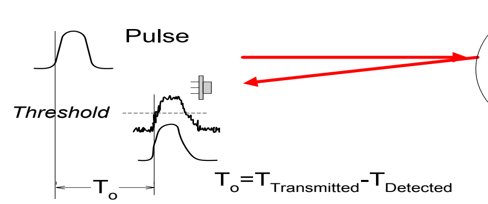


Laser Radar Techniques

- Ranging: Pulsed laser radar
  - Round trip delay: $R = c \frac{T_o}{2}$

    c = speed of light

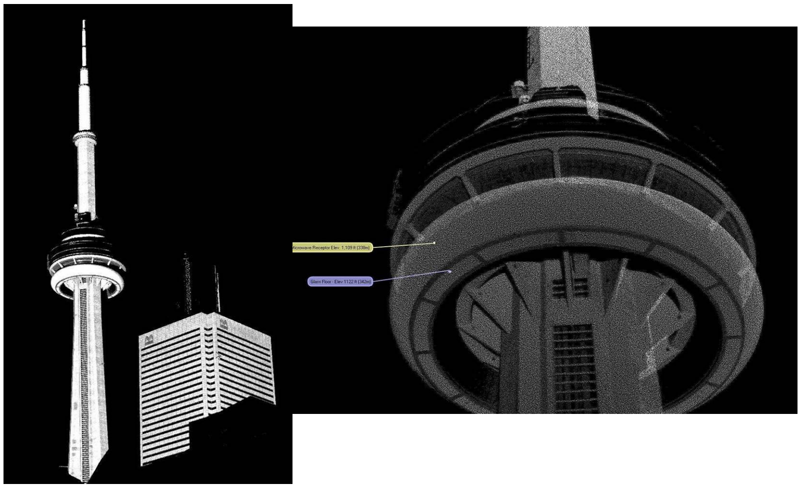
    $c = 3 \times 10^8 \; m/s$
  - Methods
    - Thresholding, multi-thresholding
    - Constant Fraction Discriminator (Time discrimination)
    - High-speed gating capability of laser diodes & micro-channel-plate
- With c=3 x 108 and ΔR=1 cm, ΔT=66 ps, BW = >50 GHz



$$\sigma_{To} = \frac{Tr}{\sqrt{(2 \; SNR)}}$$

Tr : rise time of pulse
SNR: signal-to-noise ratio

Time-of-flight: long range

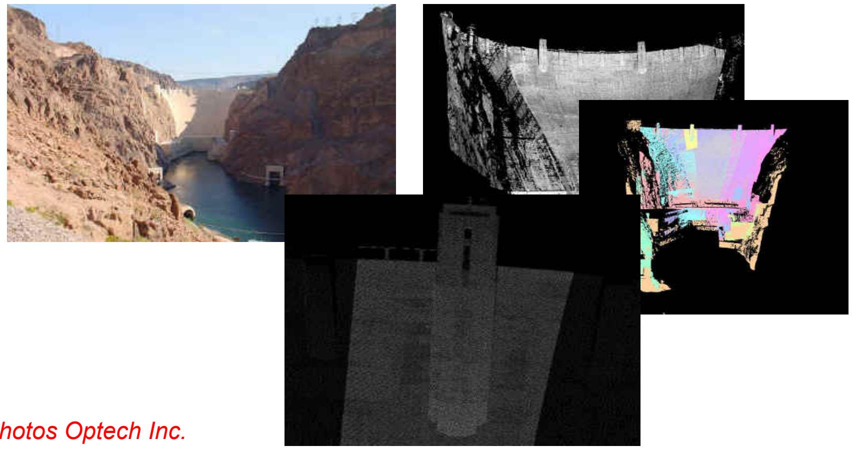


Optech

- ILRIS-3D
- Pulse Time-of-flight
- Range 350 m (up to 800 m)
- Accuracy 3-6 mm
- Spot size = 0.17R+12
  - 29 mm @ 100 m
- 2000 pts/sec
- FOV = 40 deg
- Controlled by PDA
- www.optech.on.ca

Time-of-flight: long range

- Applicable to long range



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Mensi

- Mensi – GS100
- Laser pulse
- Range 2 – 100 m
- Accuracy/resolution 6 mm
- 3500 pts/sec
- Controlled by PDA
- www.mensi.com

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Cyrax

- Pulse TOF
- Range 1.5 m – 50 m
- Accuracy 6 mm (1 sigma)
- Pointing +/- 60 urad
- Spot size < 6 mm
- FOV = 40 deg x 40 deg
- 1000 pts/sec

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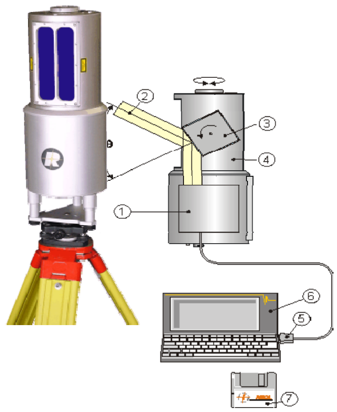
Riegl

- Different models
- E.g. LMS-Z360
- Accuracy 12 mm – (6 mm avg)
- Range 1 m – 200 m
- FOV = 90 deg x 360 deg
- Speed up to 8000 pts / sec
- Beam divergence 2 mrad
- www.riegl.co.at



Laser Radar: sources of error

- Considering the speed of light: $3x10^8$ m/s
  - Resolutions:
    - 1 psec = 0.3 mm 10 psec = 3 mm
    - 1 nsec = 0.3 m 10 nsec = 3 m
  - Phase variation-group delay of amplifiers (gain-bandwidth vs signal power)
  - Thermal drifts
  - Ambiguity for f = 10MHz -> 30 m, f = 1GHz -> 0.3 m
- Some sources of errors
  - Detection method, threshold, rise time
  - Opto-electronics and electronics:
    - thermal stability
    - non-constant group delay (Gain-Bandwidth) vs received signal power
  - Object surface condition
    - multiple reflection / diffusion

Summary

- Laser based systems
  - High dynamic range in intensity and good immunity to ambient light (e.g. using optical interference filters)
  - Noise limited by speckle
  - Simple laser plane of light methods
    - Cost effective, compact and rugged
    - Good immunity to ambient illumination
    - Require displacement of range profilometer to obtain a full 3-D image
  - Laser scanning systems
    - Field of view independent of range uncertainty
    - High density images 8000 × 8000 and large depth of view
    - Very high immunity to ambient illumination
    - Mechanically more complex (cost, ruggedness)

Summary (cont.)

- Pattern projection systems
  - High acquisition speed (small number of frames)
  - Cost effective (cost is in the projection system but is being driven down by other applications)
  - Limited range depth vs. image resolution
  - Poor immunity to ambient illumination (broad spectrum source)
- Time-of-flight system
  - Speed of propagation of light to compute range
  - Precision is quasi-independent of range (except for atmospheric perturbations)
  - Limited in absolute accuracy from 5mm to several cm
- Interferometric techniques – TOF/Interferometric
  - High precision measurement of range over limited volume of measurement
  - FM / interferometric system – excellent accuracy
  - High cost

Summary (cont.)

- There is no "winner"
  - Each technique has its advantages and inconvenience
  - Each method must be independently analyzed for a given application: accuracy, volume of measurement, speed, reliability, indoor-outdoor, cost, safety …
- In general
  - High accuracy = cost and slower system
    - Complexity of mechanical parts, electronics, etc
    - Engineering and support
- Always look for complementary techniques

Summary (cont.)

- Systems that use a Laser are characterized by
  - High dynamic range
  - Immunity to ambient light
  - Spatial resolution (X-Y) can be made independent from Z resolution
  - With a white laser a reflectance map can be extracted
  - Z uncertainty measurement is limited by speckle
- With non-coherent light
  - No safety hazard, Z resolution can be better that what is possible with laser over smaller depth of field
  - Depth of field is reduced vs a single wavelength laser
  - No speckle noise

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Conclusion

- Large number of 3D scanner companies and products
  - Still small market – costs are high and will remain high
- Many very interesting principles have been developed
  - Tailored for a given application or problem
  - Many unique and very interesting principles are not "cost attractive" even though technically better
  - We can see a consolidation of laser scanner companies
  - Market is focusing – many products will disappear (e.g. large triangulation Mensi)
- Software solutions still assume accurate range data = metrology
- R&D
  - A lot of R&D still to be done (both incremental et fundamental)
    - The "optimum/general/inexpensive" solution is not here … yet
    - 3D borrows from 2D technologies
    - Software solutions often assume "quasi-perfect data"
    - Time information is rarely used (static objects)
  - Danger of reinventing the "wheel"

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