Master in
Computer Vision
Barcelona

Module M4: 3D Vision

Lecture 4.9b: **3D Sensors and 3D data**

Lecturer: Josep R. Casas

Outlook

Session 9b: 3D Sensors and 3D data

- Motivation & Principles
  - Image vs Range sensing
- 3D Sensors
- 3D data

Session 10: 3D processing & applications

- Pointcloud processing:
  - PCL (2011) & Open 3D (2018)
  - Organized/Unorganized processing
  - Applications

Introduction to 3D Sensors, Data and Processing

3D vision has been introduced from the concepts of:

- **Projective transformations**
  perspective projection, *projectivities* (3D, plane-to-plane, ***n***-dimensional spaces, homography, invariants…)
- **Multiple-View geometry**
  reconstruct real world scenes from several images (projections) or from a moving camera (SfM)

Ok. That's the natural way into the field of 3D vision as, for visual perception, humans come equipped with:

- Two '**projective**' sensors
- Multi-view (**stereoscopic**) vision
- And 'Free Viewpoint View' (FVV or rather "Capture")

Motivation and fundamental questions

Motto:

Computer Vision = "Teaching computers to see"

Antonio Torralba *(MIT)*

Talk@CVC 20th Anniversary, Barcelona July 9th, 2015

Exciting time for CV: new architectures, DBs, productivization, future

Fundamental problems: ***reconstruct 3D world****, recognize…*

Questions around this:

*Q1: Is "**projective vision**" a natural way to capture the 3D world?*

*Q2: Do we need **photometry** to get **geometry**?*

*Q3: Does **3D vision** and **3D geometry** mean the same?*

Q4: Does 2D/3D matter for "Teaching computers to see"?

*Q1: Is "**projective vision**" a natural way to capture the 3D world?*

Projective vision ambiguities…

(c) 2018 jessicabackhaus.net

(c) 2011 Santiago Bañón

*Q1: Is "**projective vision**" a natural way to capture the 3D world?*

…used *smartly*

[not keen in bullfighting… at all!]

back

*A1: Is "**projective vision**" a natural way to capture the 3D world?*

2D vs 3D

- 2D vs 3D

  "2D imaging

  ...projects 3D scenes onto a planar surface (retina, sensor)...

  ...so that the depth (Z) dimension is lost"

  – *Can we **backproject** systematically?*
  – *Are there **imaging** sensors not projecting onto a plane?*
  – *How can depth (range) be perceived **directly**?*
  – *What would be the main **advantage** of capturing 3D directly?*

*Q2: Do we need to measure **photometry** to get **geometry**?*

back

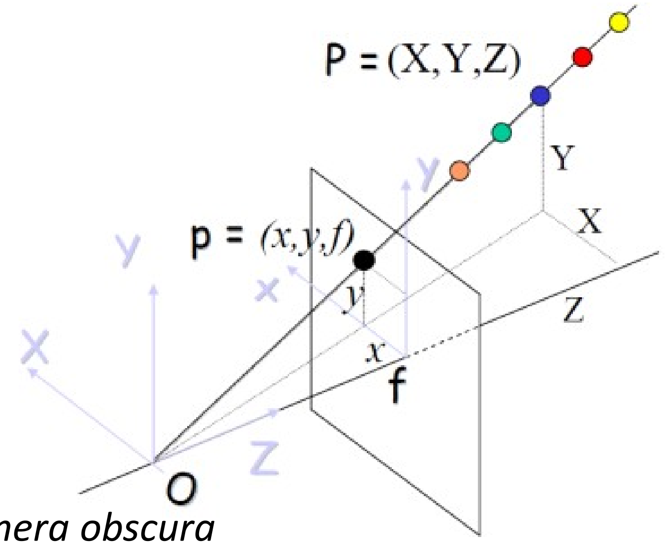
2D vs 3D

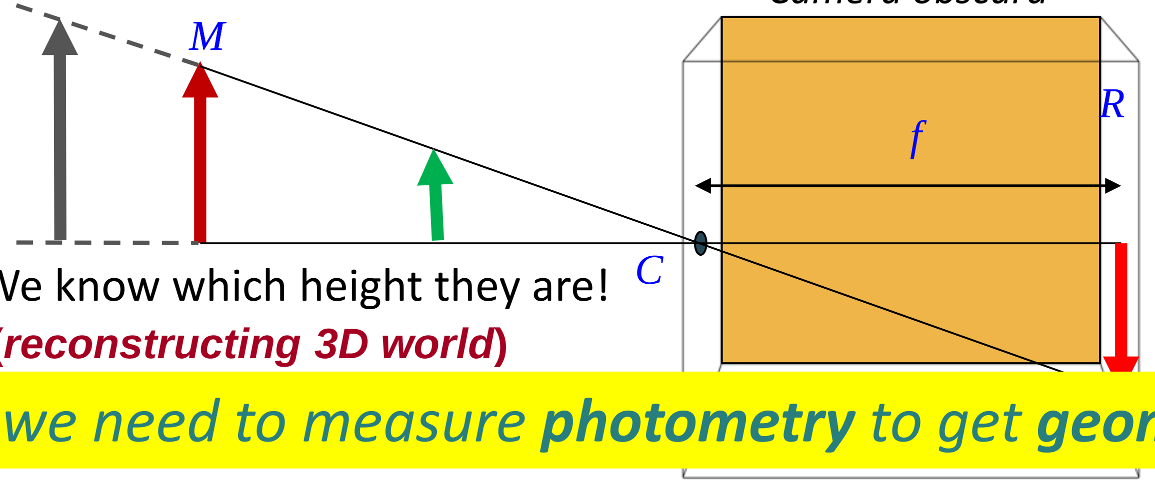
Yes! with distance measurement methods!

Range sensors (scanners!)

- 3D scanners and Lidar systems
- Light coding systems (e.g. Kinect™)
- TOF cameras (e.g. Kinect™ v2, Lidar)

*... as if we could **backproject!***





We know which height they are!

(reconstructing 3D world)

*A2: Do we need to measure **photometry** to get **geometry**?*

Example of 3D capture

back

… and then…

Will this result in a complete description of the scene?
…like a CAD design?
Will we have a whole view like Panoramic / Surround view?
…and Free viewpoint?

Q4: Does 2D/3D matter for "Teaching computers to see"?

What can we do with 3D vision?

Example I of 3D processing (AR)

AR magic mirror using Kinect (cf. T. Blum, N. Navab, TUM)

Q4: Does 2D/3D matter for "Teaching computers to see"?

Example II of 3D processing (AR)

A4: Does 2D/3D matter for "Teaching computers to see"?

What if…

… we could always backproject to 3D our 2D images?

- Geometry of objects and scenes in the 3D world can greatly help analysis and recognition
- 3D geometry has the potential to avoid the large variability in appearance and missing information due to projection, occlusions, motion, shadows...
- Yes, 3D geometry may definitely **help computers to see** and "understand" complex visual scenes, reasoning about events that evolve in space and time…

3D/range/scan sensors vs Multiple View

Advantages 3D/range/scan

- …

- Direct measure of 3D geometry
- Independent of photometry (active)
  - does not hold for reflectivity
- From scan to CAD blueprints (illusion!)

Disadvantages

- …

- 2,5D!

  Surface vs 3D (interface air-matter vs volumetric 3D scanner, i.e. PET)
- Single viewpoint

  Neither panoramic, nor surround view

  → still need MultiView!!!
- Accuracy?

  vs MPix cams!

Symmetric paradigm of 3D Data

Double nature of 3D data

- Geometric information

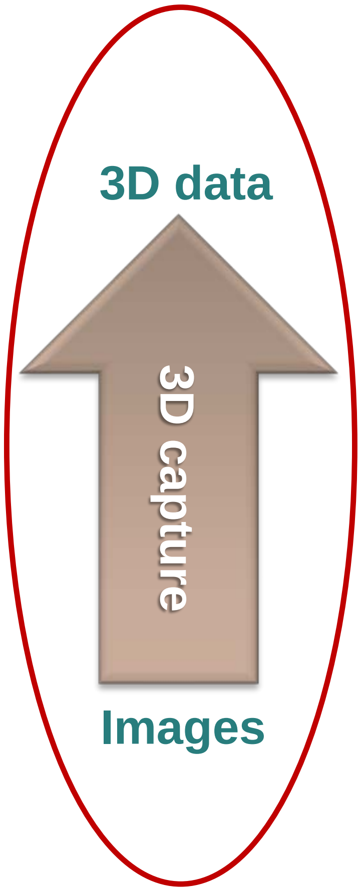
  Pure data, measures.
  Numerical representation of objects
  → calculation, simulation, measurements

  … + reflectivity

- Photometric information (images)

  Can be rendered, displayed and presented visually, by exploiting our perception capabilities

  → exploration, analysis and understanding
  (same than looking at the physical world)



Reconstruct the world with range sensors?

Illusion!

- Occlusions
  - → incomplete view
- Multiple viewpoints
  - → need multiple range sensors (or moving around on static scenes)
- Only air-opaque interfaces (not the interior of objects)
  - → Range is not X-Ray ....fortunately! ☺

…but better than stereo/multi-view!

- *Back-projection* with a single sensor
- Independent on scene illumination and surface texturing

Photogrammetry

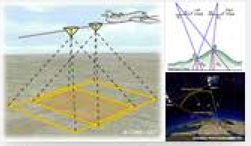
Photogrammetry refers to the practice of deriving 3D measurements from photographs.

- Advances in digital cameras, processors, and computation, yield **extremely dense and accurate 3D surface data** from a limited number of photos with standard digital photography
- Structure from Motion (SfM) and sub-pixel image matching yield **3D-dimensional structure by analyzing projected 2D motion fields** created by a sequential change of position of the camera sensor relative to the object. Photographic sequences are captured to maximize information available from the change in viewpoint
- Resulting **data sets are software platform-independent** and can be reused

Disadvantage: ***computation time…***

Photogrammetry examples

Aerial

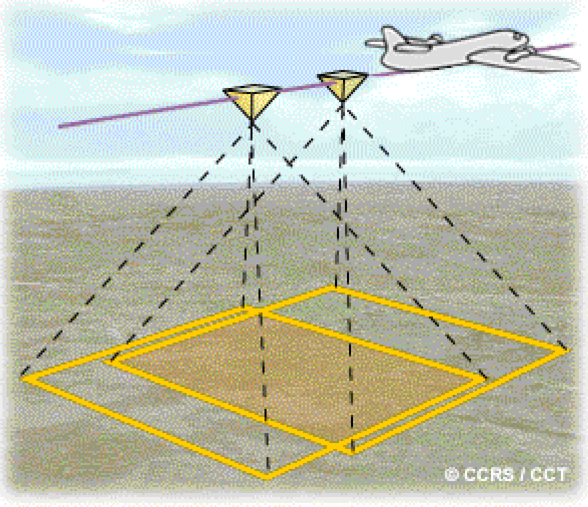


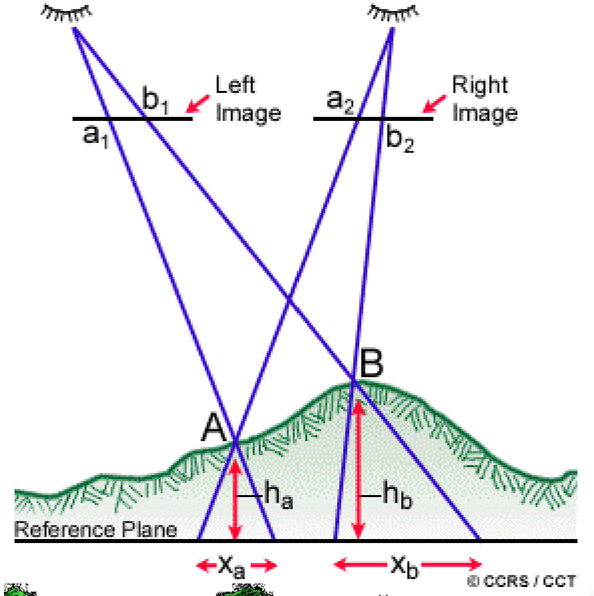
Stereoscopic

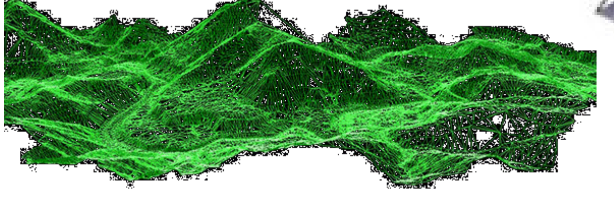
Architecture

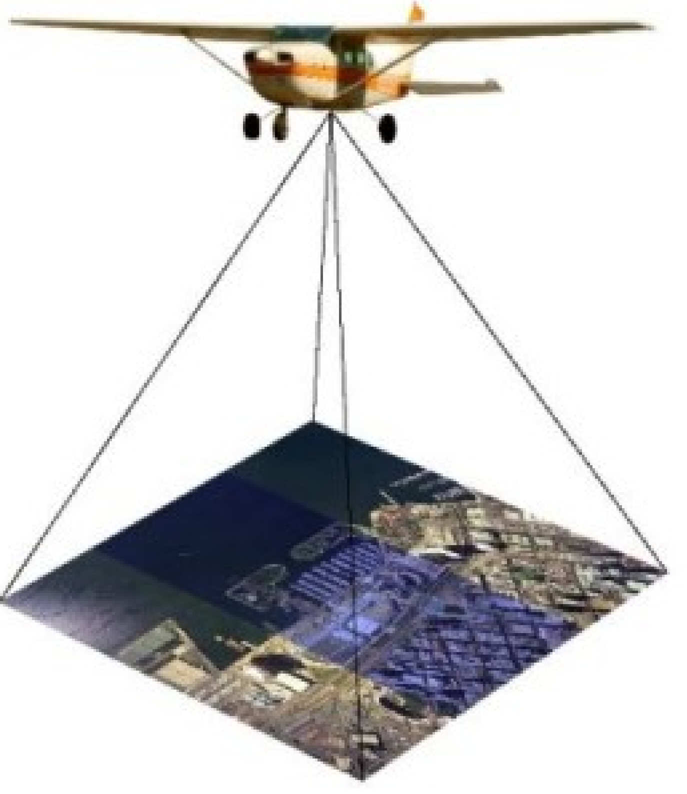
Close Range

Surveying





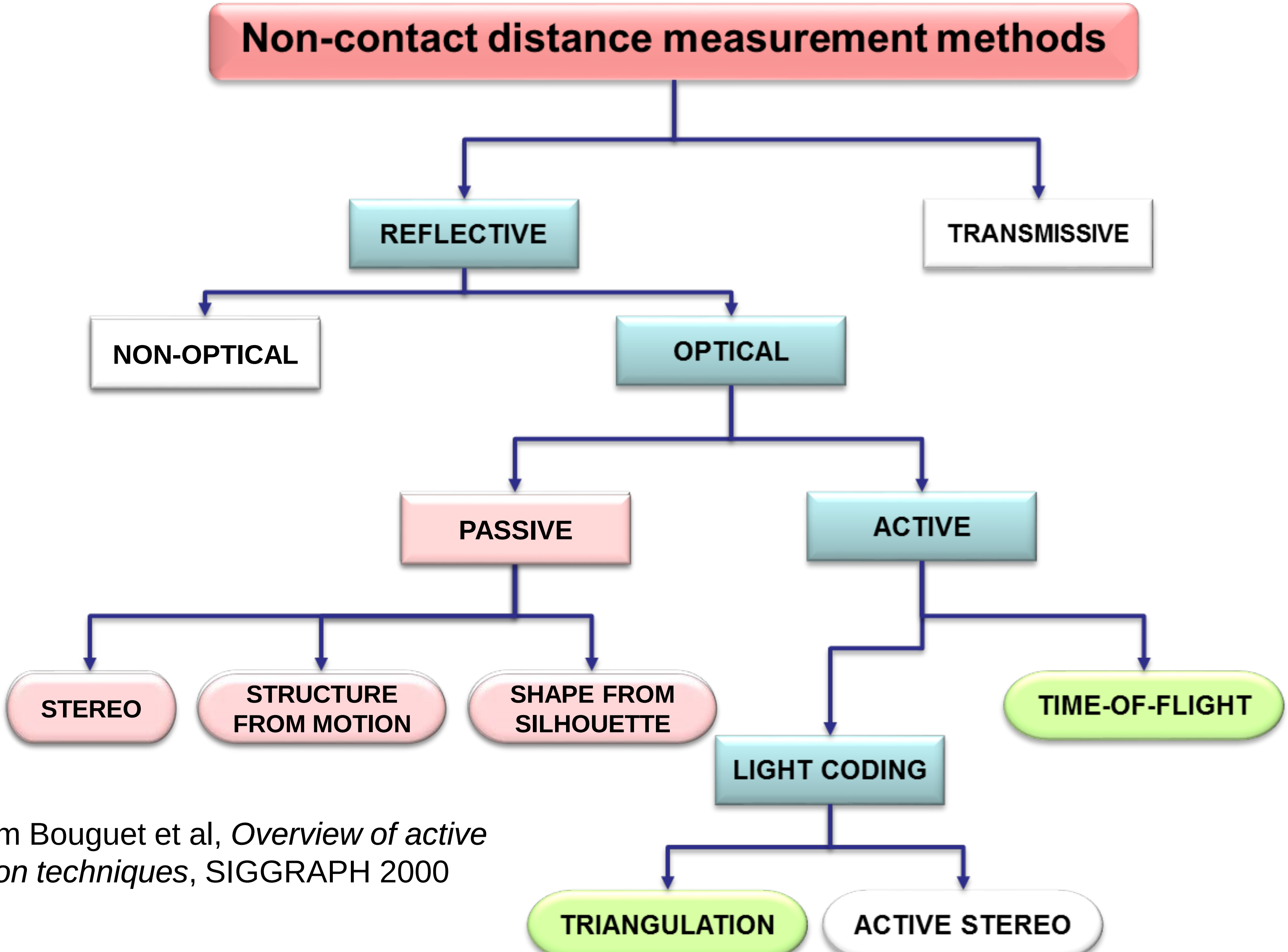




3D sensors

Depth, range, scan...

“Non-contact” – distance measurement methods



From Bouguet et al, *Overview of active vision techniques*, SIGGRAPH 2000

Depth or Range sensing Methods

Reflective optical methods:

- Passive range sensing

  3D distance measurement by the way of radiation already present in the scene. Not necessarily in the visible spectrum

  – E.g. stereo, multi-camera (triangulation, SfS…)
    Off-the-shelf light field cams have demonstrated improved depth estimation using multiview stereo configs [Bishop 2012]

- Active range sensing

  3D distance measurement obtained by projecting in the scene some form of radiation

  – ToF (IR/laser) → high frame rate, low res, noise [Foix 2011]

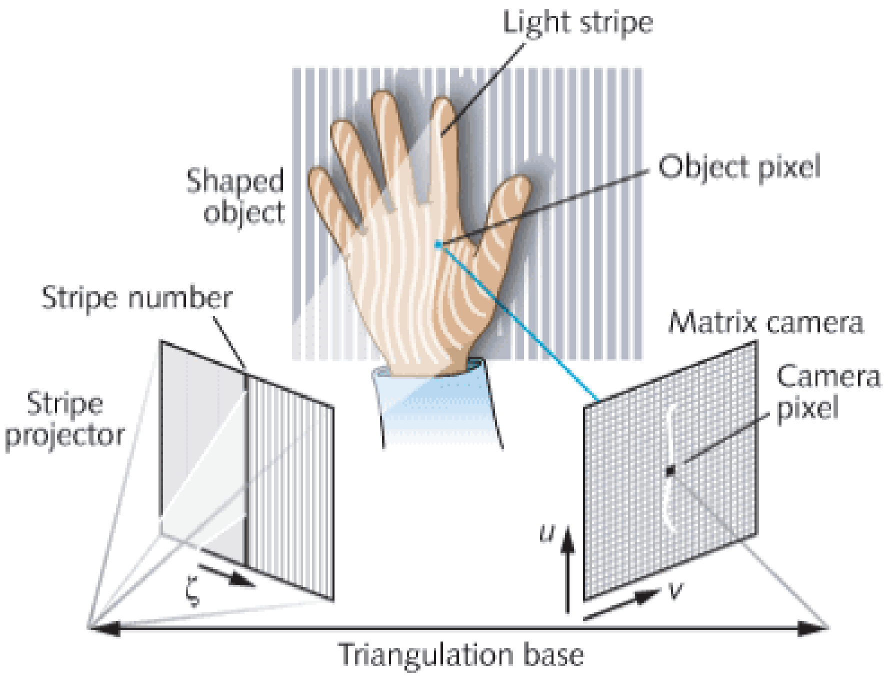
  – Lidar (UV/visible/IR) → sequential (low frame rate)

  – Structured Light (IR/visible) → artifacts, noise, indoor [Salvi 2010]

Structured Light methods

Structured light methods

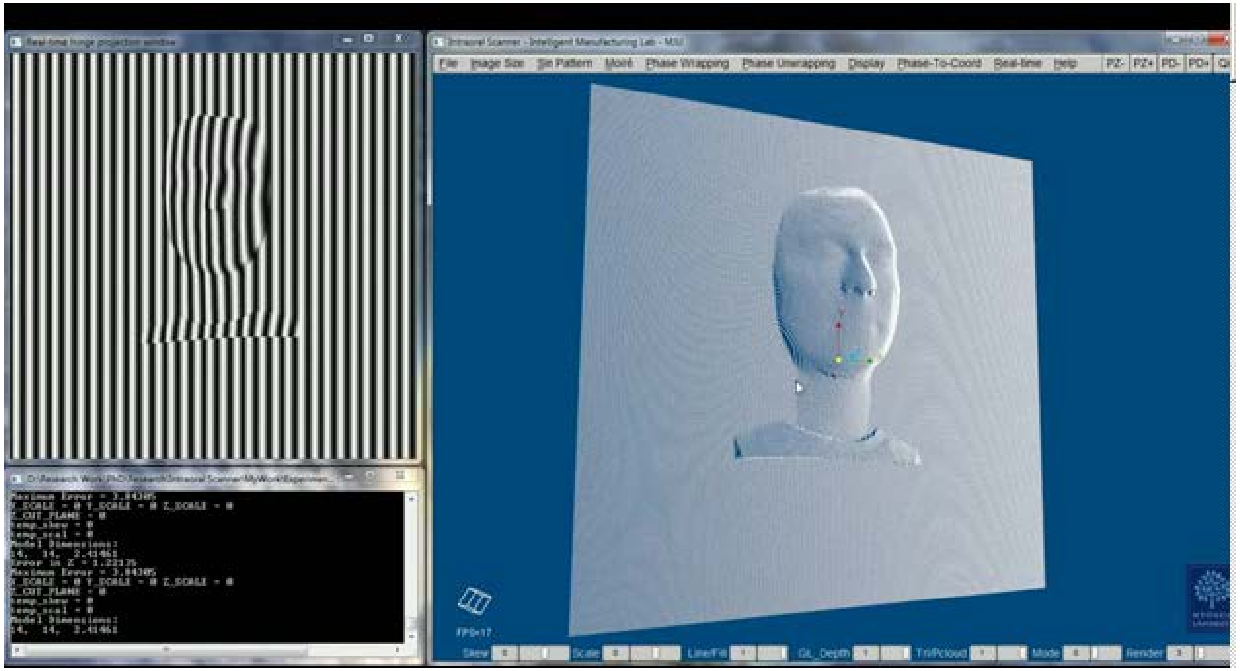
- Calculate the shape by how the strip is distorted.



http://www.laserfocusworld.com/articles/2011/01/lasers-bring-gesture-recognition-to-the-home.html

Real time Virtual 3D Scanner - Structured Light Technology

- Demo

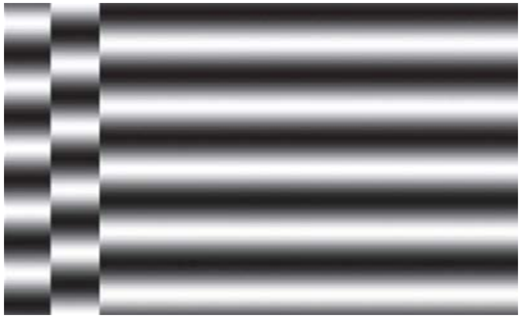


http://www.youtube.com/watch?v=a6pgzNUjh_s

Computational Depth Sensing

- Depth cameras do not sense depth information directly, rather, through either the space deformation or the time delay of light signals
- Computation needed!

  Computational Depth Sensing: image sensors with onboard advanced signal processing algorithms (Redesign [Xiong 2017])



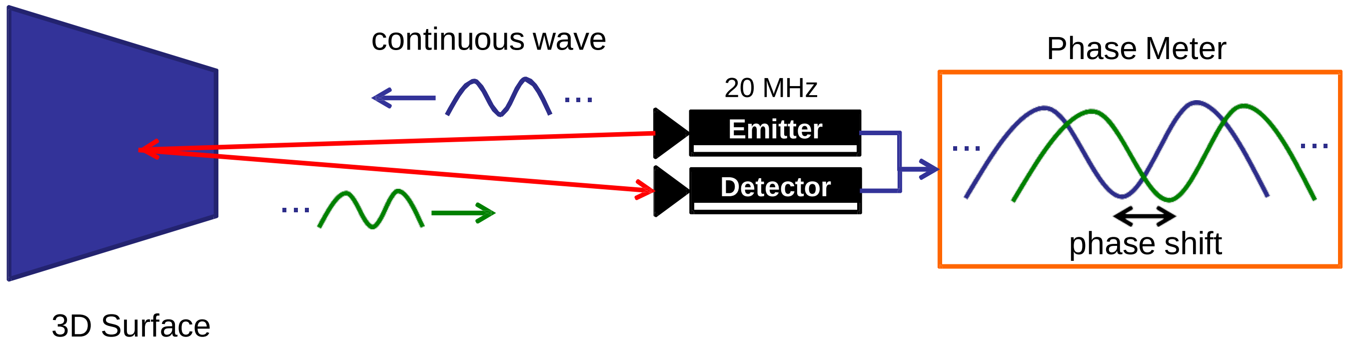
Example of phase shifting (Xiong et al, 2017)

TOF Imaging

Principles of ToF sensors

Continuous Wave Modulation

- Continuous light waves instead of short light pulses
- Modulation in terms of frequency of sinusoidal waves
- Detected wave after reflection has shifted phase
- Phase shift proportional to distance from reflecting surface



Principles of ToF sensors

Continuous Wave Modulation

Advantages:

- Variety of light sources available as no short/strong pulses required
- Applicable to different modulation techniques (other than frequency)
- Simultaneous range and amplitude images

Disadvantages:

- In practice, integration over time required to reduce noise
- Frame rates limited by integration time
- Motion blur caused by long integration time

TOF *Imaging*

Swissranger™ SR4000
Mesa Imaging

Matricial Time-Of-Flight Cameras

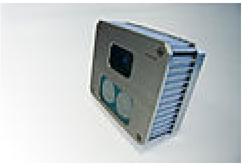
- Active sensors
- Acquire 3D geometry at video rate (up to 50fps)
- E.g. MESA Imaging
  PMD Technologies
  Optrima SoftKinectic
  CANESTA (*acquired by Microsoft in 2010*)
  ...

Kinect for Xbox One by Microsoft

D-IMager
Panasonic

pmd[vision] CamCube
PMD Technologies

FOTONIC-B70
Fotonic



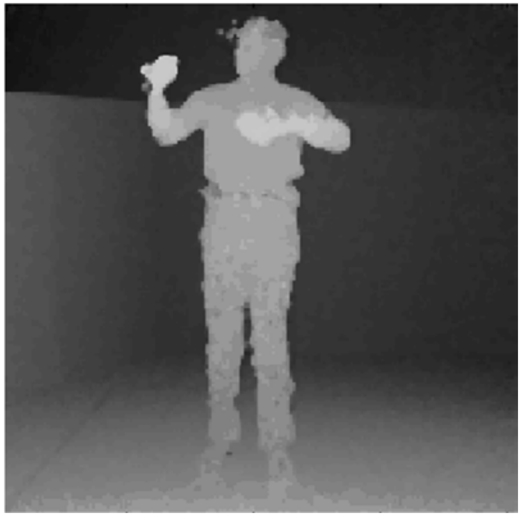
3D MLI Sensor
IEE S.A.

pmd[vision] CamBoard
PMD Technologies

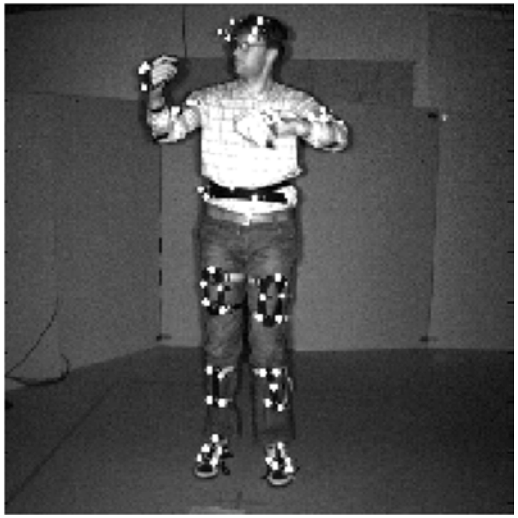
Principles of ToF Imaging

Continuous Wave Modulation

- Simultaneous availability of (co-registered) range and amplitude images



Depth Image



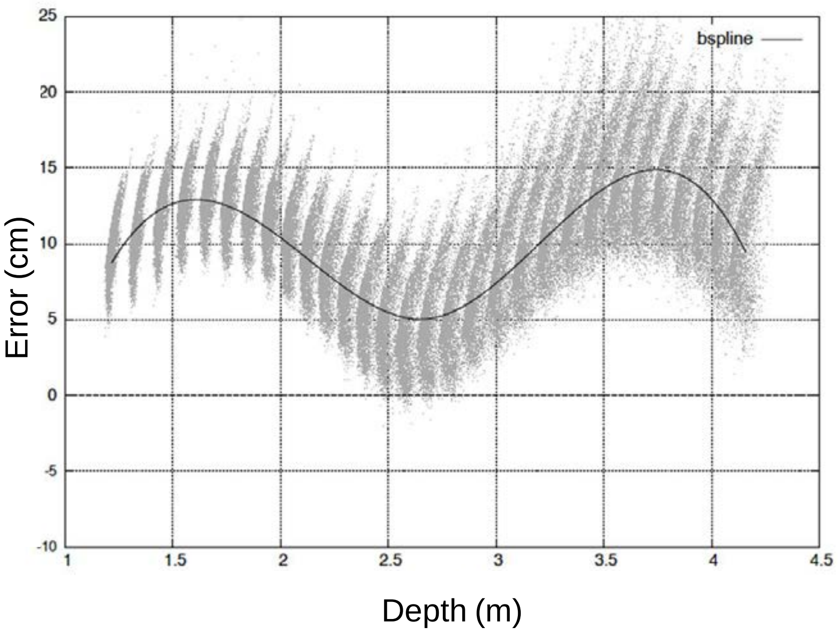
Amplitude Image

Computer Vision with ToF Cameras

Measurement Errors and Noise

Systematic distance error

- Perfect sinusoidal signals hard to achive in practice
- Depth reconstructed from imperfect signals is erroneous
- Solution 1: camera-specific calibration to know distance error
- Solution 2: alternative demodulation techniques not assuming perfect sinusoidal signals

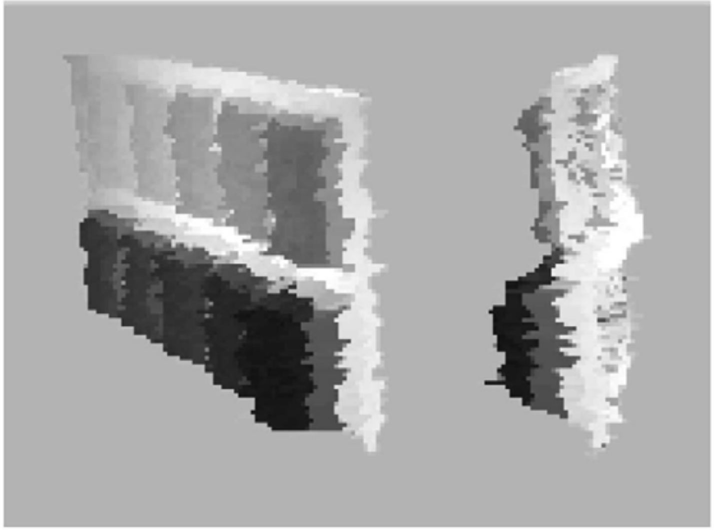


Computer Vision with ToF Cameras

Measurement Errors and Noise

Intensity-related distance error

- Computed distance depending on amount of incident light
- Inconsistencies at surfaces with low infrared-light reflectivity
- Correction by means of corresponding amplitude image



Depth images of planar object
with patches of different reflectivity

Computer Vision with ToF Cameras

Measurement Errors and Noise

Depth inhomogeneity

- Current ToF cameras have low pixel resolution
- Individual pixels get different depth measurements
- Inhomogeneous
- "Flying pixels", especially at object bondaries
- Correction: discard pixels along rays parallel to viewing direction

Red circles: „flying pixels“

Kinect

- RGB, Depth Sensor, and Multi-mic Array
- Works with structured light (dots rather than strips) to determine distance for each pixel

Kinect

Kinect For Windows 1

Kinect For Windows 2

Image via http://blogs.msdn.com

Some Commercial Depth Sensors: Specs



	MS Kinect	MS Kinect2	Asus Xtion Pro Live	Occipital Structure
Color	640x480 (2x!) @30fps	1920x1080 @30fps	1280x1024 @30fps	(iPad cam)
Depth	320x240 16bit	512x424	640x480 (320x240@60)	640x480 (320x240@60)
Range (m)	(0.4)0.8-3,5	0.5-4,5	0.8-3,5	0.4-3,5
FoV (VxH)	43º x 57º	60º x 70º	58º x 45º	58º x 45º
Tilt motor Accelerom.	±27º (V) 2G(1º)/4G/8G	–	–	–
Audio	16bit PCM @16kHz 4 mics	16bit PCM @16kHz 4 mics	2 mics	(iPad mic)
USB	2.0	3.0	2.0	2.0 (hack)
Tracker	20 joints (2x)	26 joints (6x)	–	–

Others: e.g. Carmine from *PrimeSense*, Orbbec sensors, VicoVR or Stereolabs ZED

Some depth cameras currently in the market

gestoos.com/developer-center

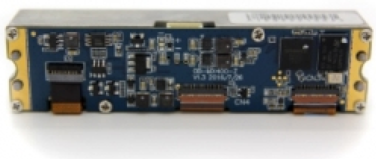

Asus XtionIntel


RealSense depth camera D415


Intel RealSense depth camera D435


iSense


Occipital Structure


Orbbec Astra Mini


Orbbec Astra Series


PMD Flexx

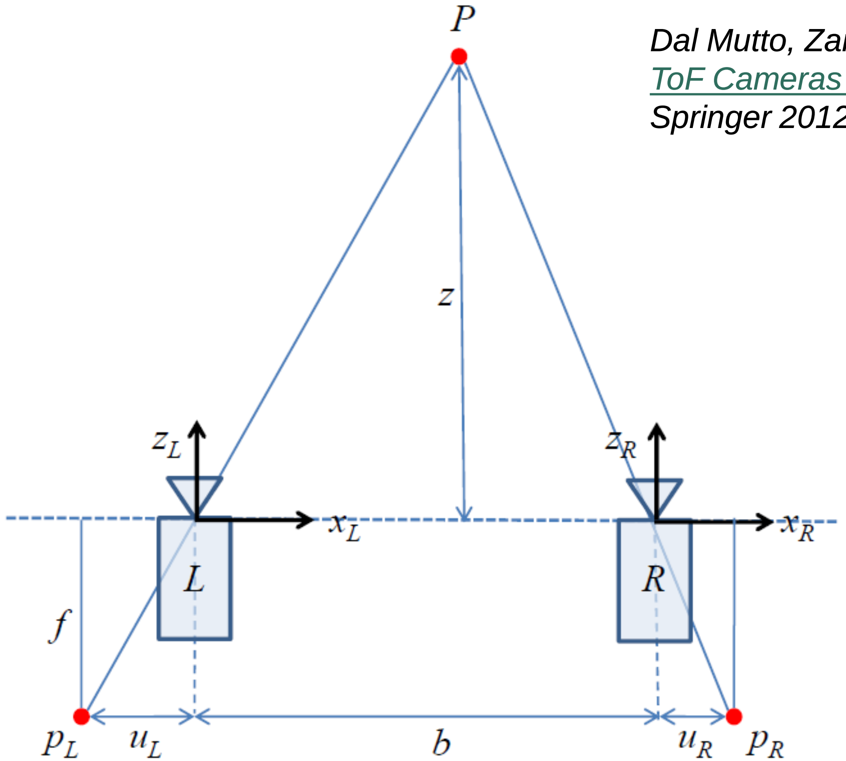

PMD Monstar

Kinect: depth imaging principles

- Active triangulation
- Matricial arrangement
- Structured light coding
  - Correspondence solving: codewords
- Artifacts
- Light coding strategies
  - Kinect pattern
- Practical issues
  - Calibration, artifacts
  - Comparison to other 3D scanning methods
- Demo

Active Triangulation

Stereo Triangulation



Conjugate pixels: p_L, p_R

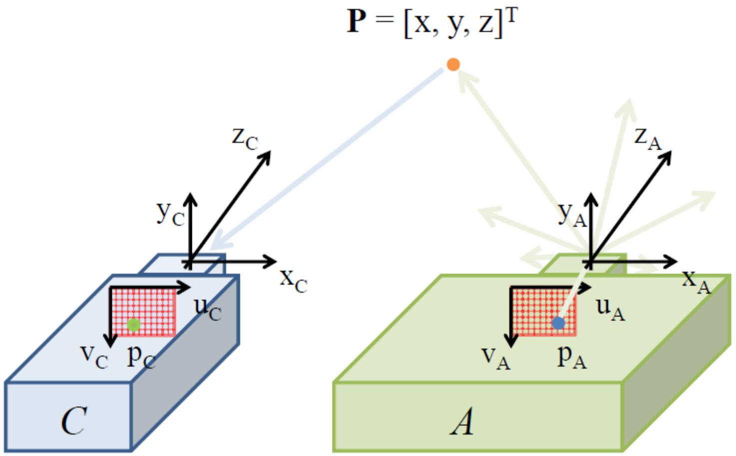
Disparity: $d = u_L - u_R$

Depth: $z = bf/d$

(calibrated and rectified)

Dal Mutto, Zanuttigh, Cortelazzo
[ToF Cameras and MS Kinect]
Springer 2012

Active Triangulation



Same geometry:

camera (R) replaced by projector (A)

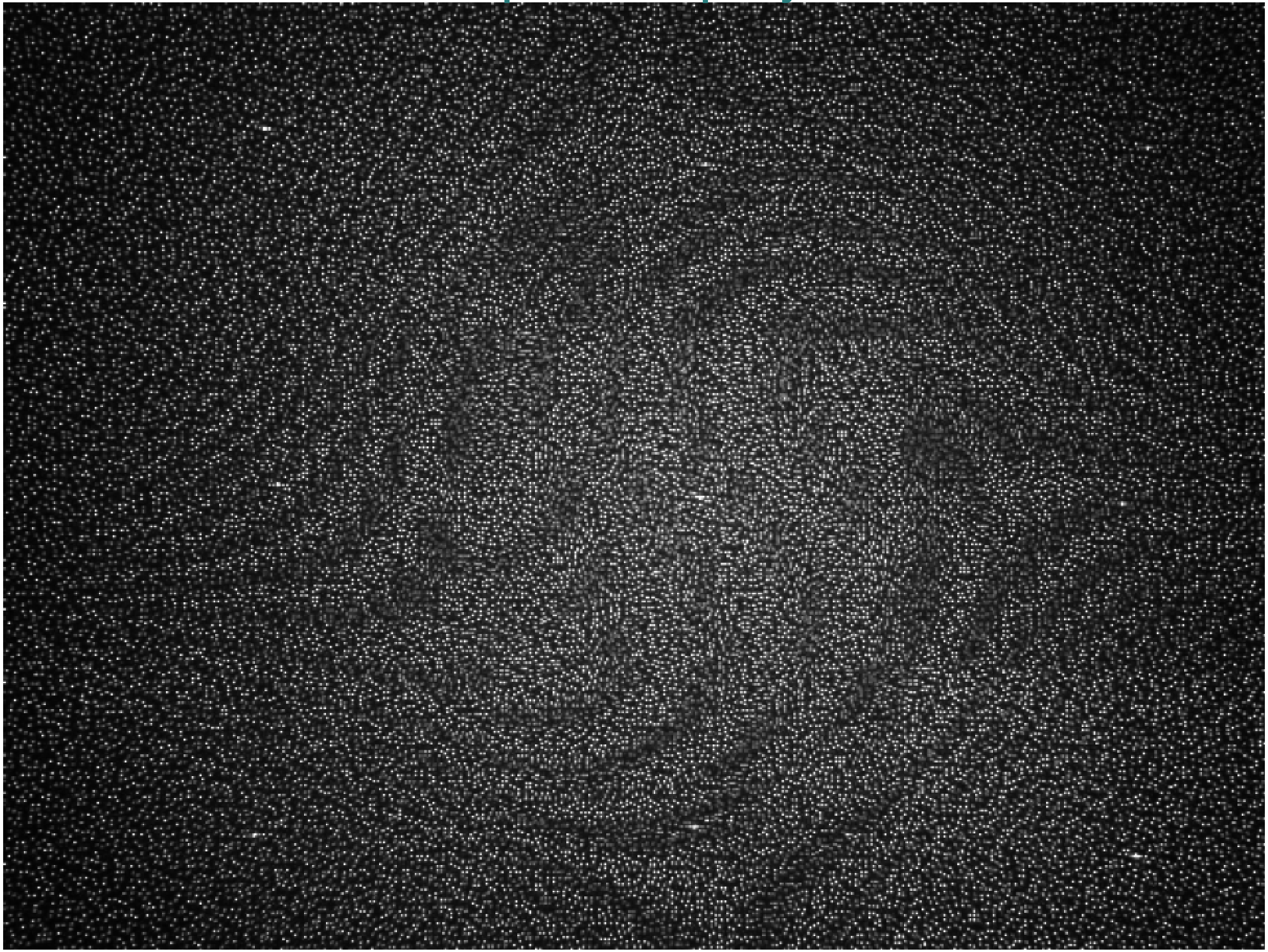
p_A pattern pixel, p_C camera pixel

p_A, p_C are conjugate → disparity d

Depth of scene point P: $z = bf/d$

(calibrated and rectified)

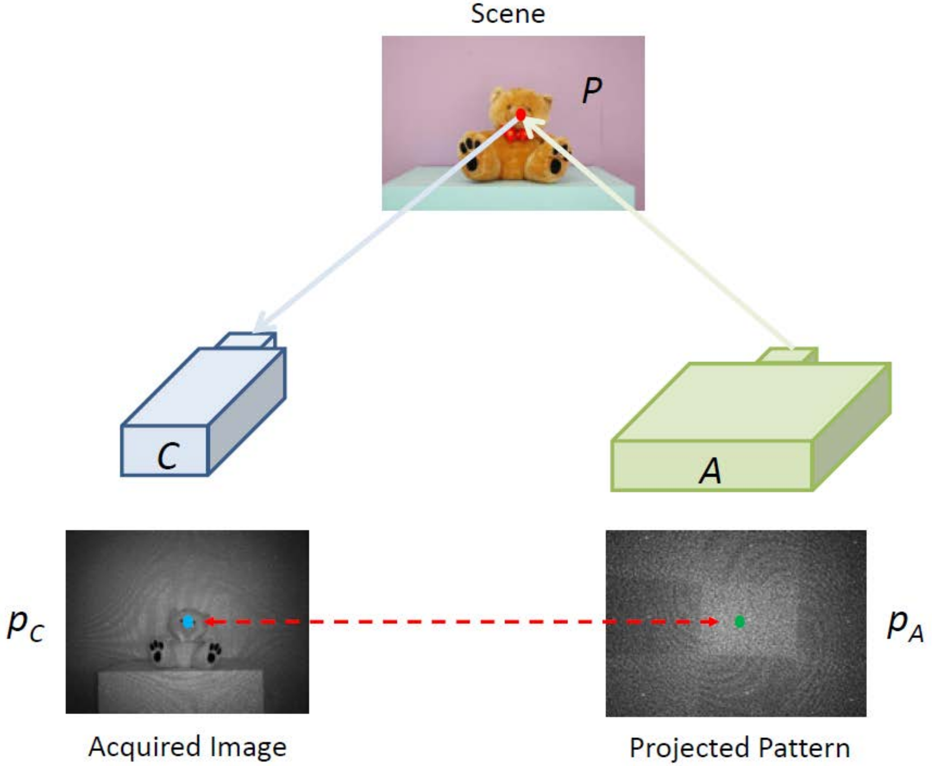
Kinect pattern projected

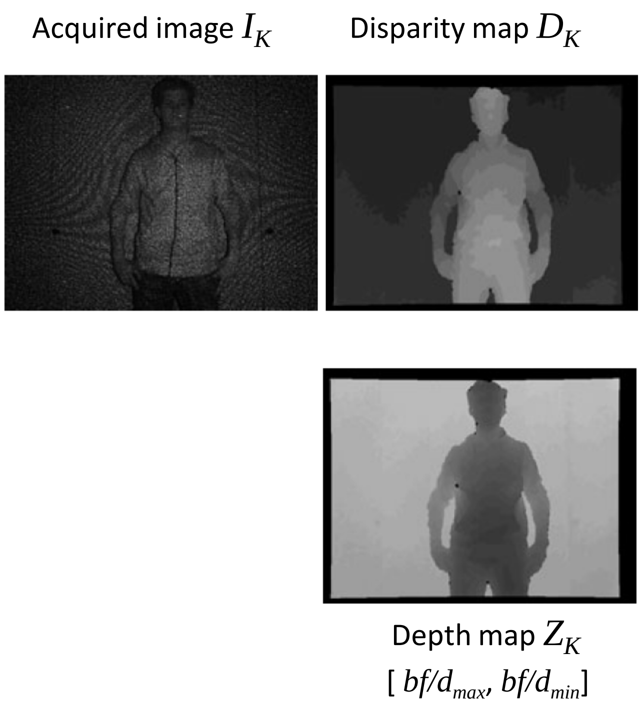


(from Dal Mutto, el al 2012)

Matricial Active Triangulation

IR Projector and camera (invisible)

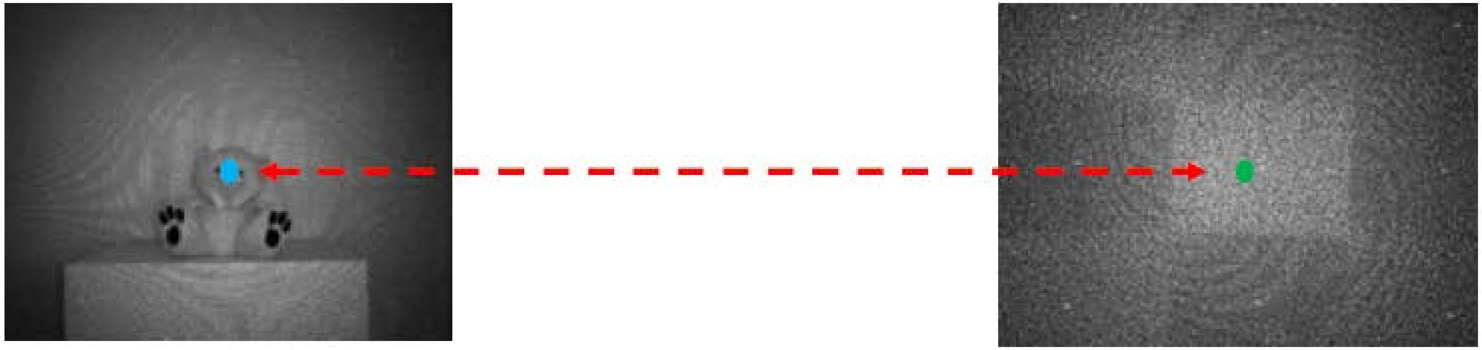




(from Dal Mutto, el al 2012)

Structured light coding

p_C



p_A

Acquired Image | Projected Pattern

- Solves the correspondence problem
  - Each pixel of the pattern is associated to a *codeword* (specific local configuration of the projected pattern)
  - The pattern is projected (A), reflected in scene and captured (R)
  - A correspondence estimation algorithm analyzes the received codewords in the acquired image (I_K) in order to compute the conjugate of each projected pattern
  - Pattern design adopts codewords *effectively decodable* in presence of non-idealities of the projection/acquisition process

Decodable codewords

The projection/acquisition process introduces an horizontal shift d (disparity) proportional to the inverse of the depth z of scene point P for each pixel p_A which is associated to a codeword (window centered at p_A).
Codewords should be:

- Different enough: low cardinality!
- Row-separable

  In calibrated & rectified setups conjugate points lie in horizontal lines

  - The more the local pattern distribution of a single pixel differs from the local pattern distribution of other pixels of the same row, the more **robust** will be the coding
  - Local distribution of the pattern for pixel p_A given by the illumination values of the pixels in a window around p_A
  - For windows n_W pixels, there are $n_P^{n_W}$ possible pattern configurations
    $n_P = 2^8$ for an 8-bit grayscale projector

Codeword artifacts

Artifacts in the projection acquisition process:

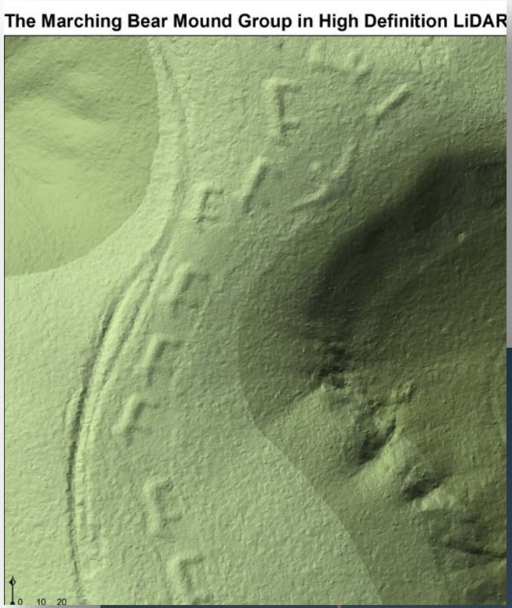
- Perspective distortion, due to varying depths in scene
- Color (gray level) distortion, due to reflectivity properties of objects
- External illumination, due to other light sources in the scene (IR noise)
- Occlusions, not all pixels projected will be seen by the camera
- Projector and camera non-idealities (non-linear characteristics)
- Projector and camera noise (Gaussian, additive)

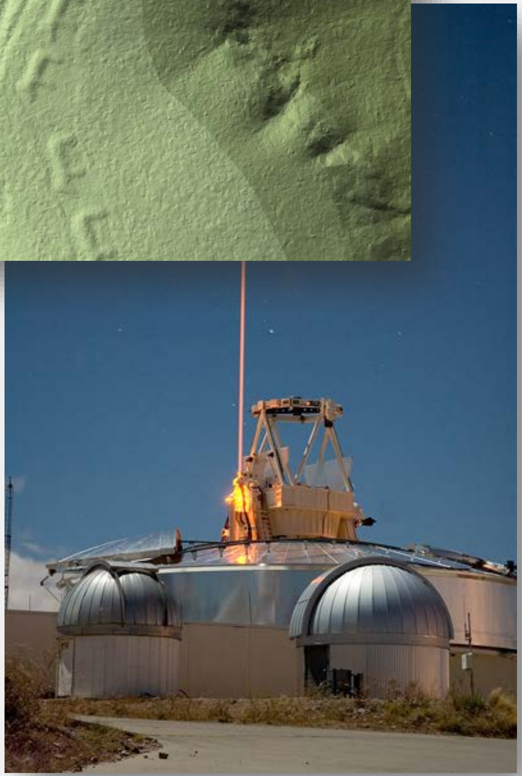
Lidar

LIght Detection And Ranging

(also called LIDAR, LiDAR, and LADAR)

Lidar





Surveying method/Measurement technique:

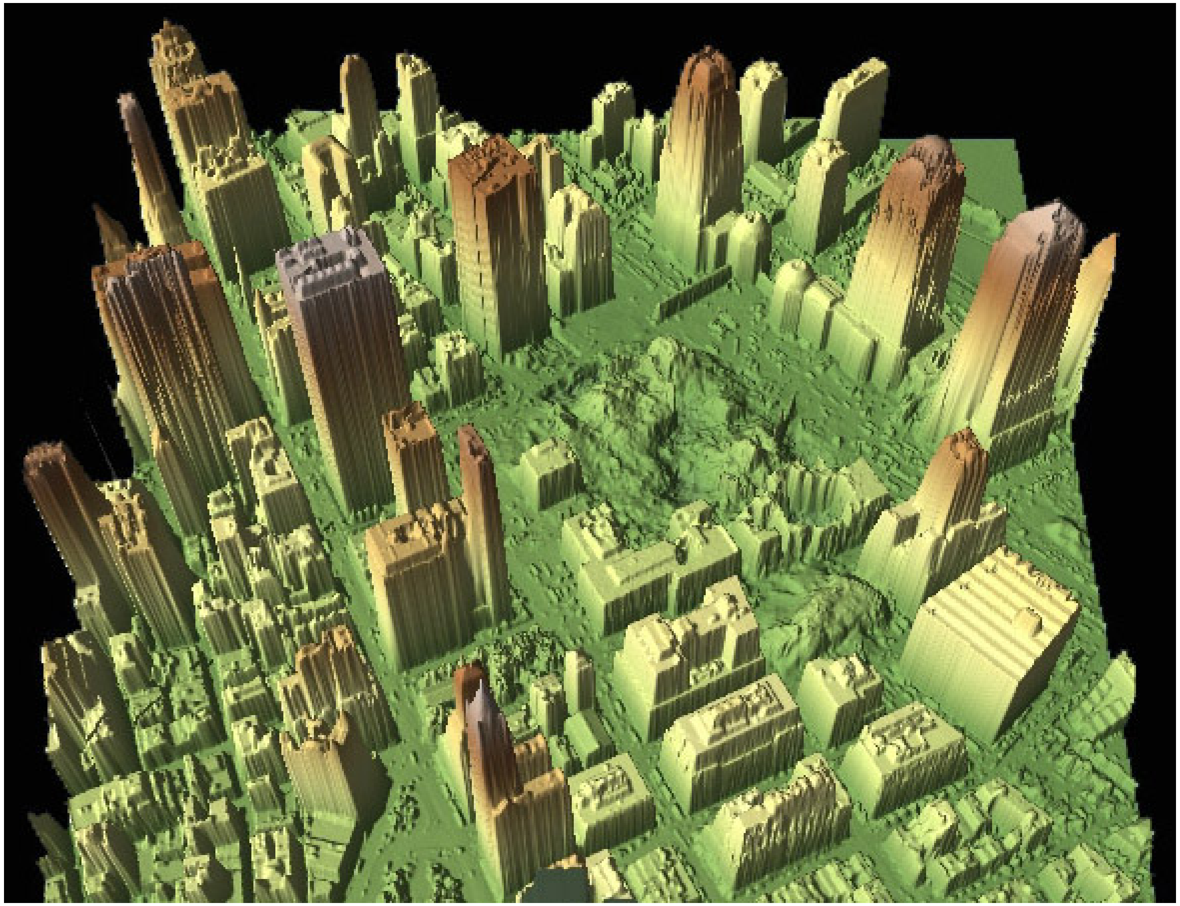
- Pulsed laser light illuminates an object, the reflected pulses are recovered and measured with a solid-state sensor
- Time elapsed provides an automated measurement of distance to target (concept also referred to as ladar or ToF imaging)

Popular applications:

- Earth resources exploration, landing aids, object recognition, self-guided vehicles and safety and security applications in transport

LIDAR light detection and ranging scanner

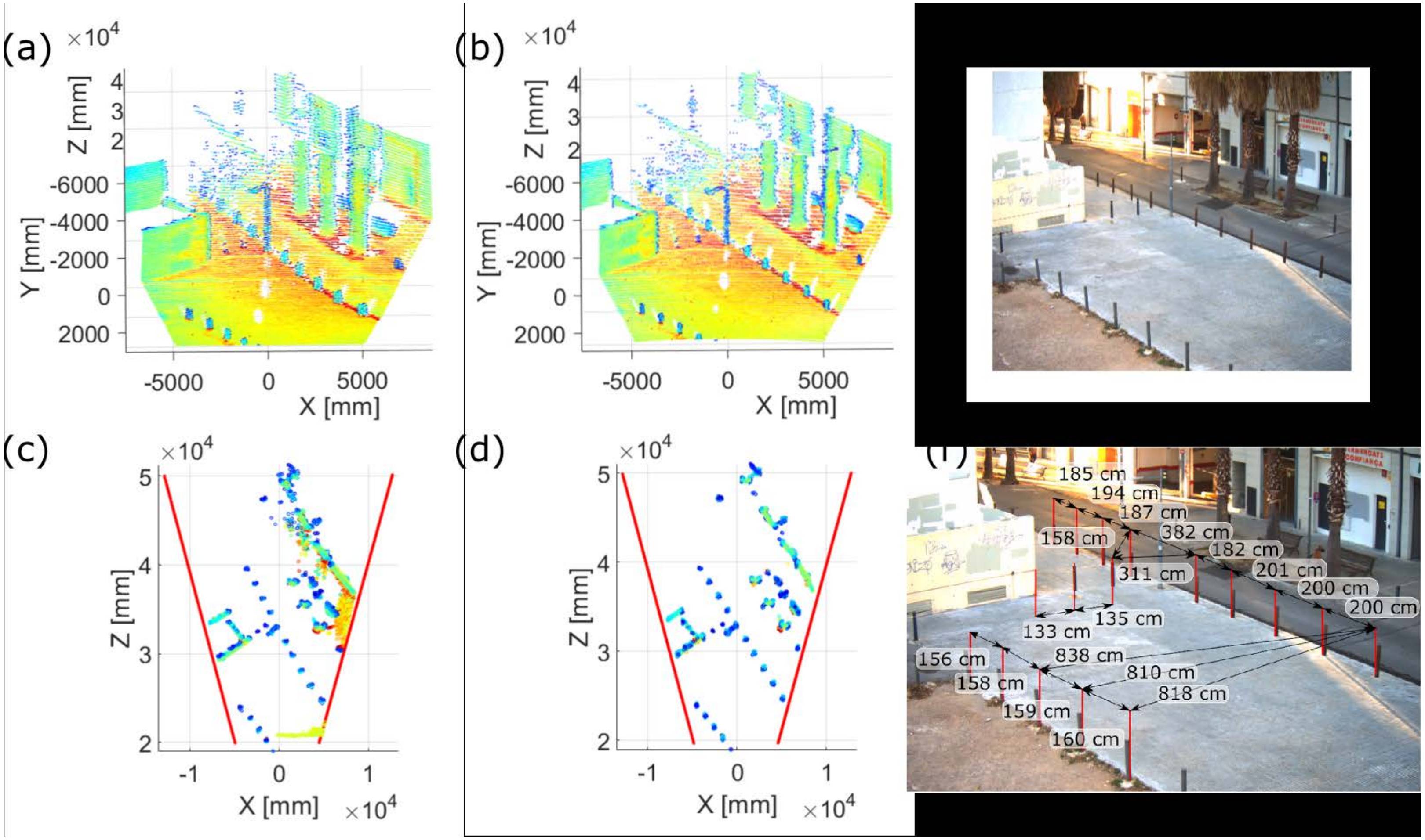
- http://www.youtube.com/watch?v=MuwQTc8KK44



Leica lidar

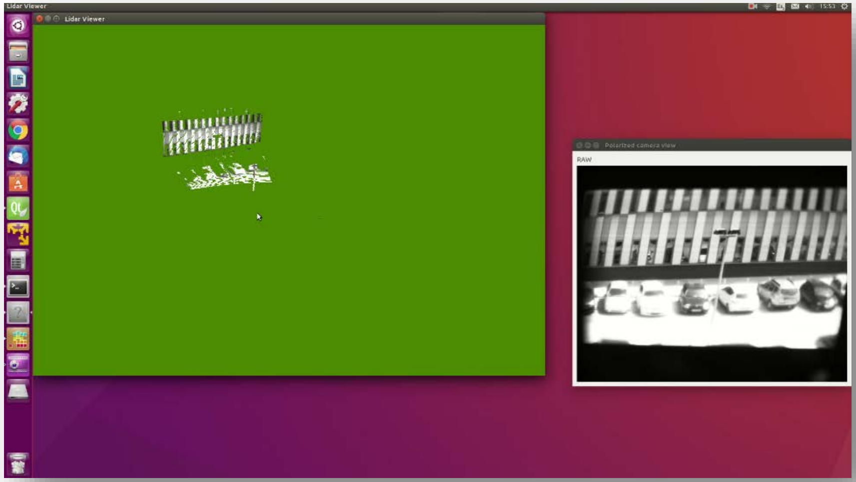
http://hodcivil.edublogs.org/2011/11/06/lidar-%E2%80%93-light-detection-and-ranging/
http://commons.wikimedia.org/wiki/File:Lidar_P1270901.jpg

Data fusion: RGB-Lidar

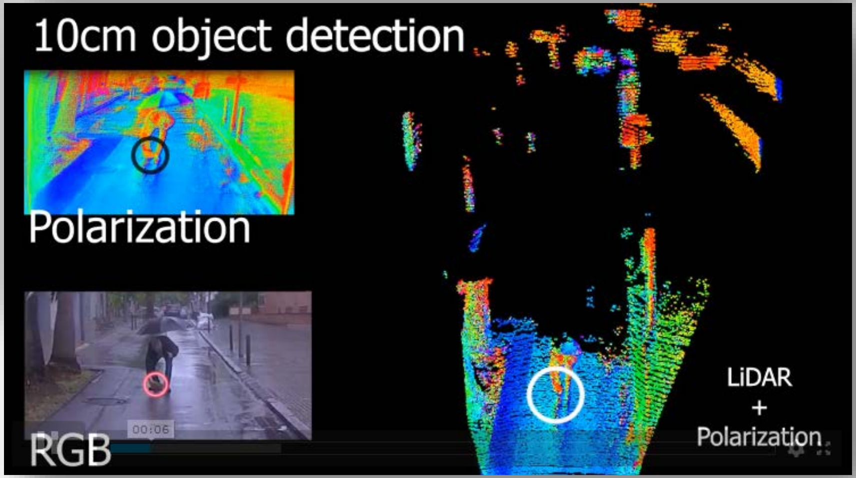


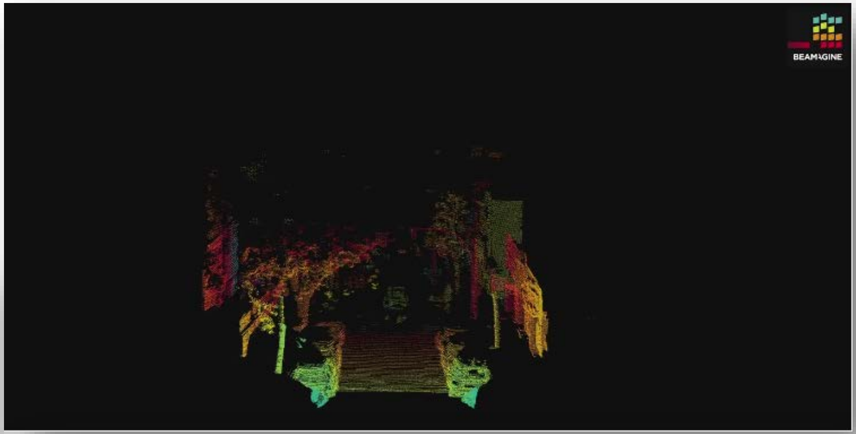
P. García-Gómez, et al, Geometric Model and Calibration Method for a Solid-State LiDAR, Sensors 20(10) 2020

Examples



Dense Lidar (P. García-Gómez, et al)





beamagine.com (applications)

Comparison chart

Technology	Outdoor	Detection range [m]	Accuracy [cm]	FOV	Angular resolution	Obst Det. Terr Mapp.
HD-LIDAR	✓	120	4	27°V 360°H	0.4°V 0.09°H	Not included
Multi-Plane LIDAR	✓	120	10	3°V 85°H	0.8°V 0.125°H	OD, external unit
Kinect	✗	4-5	Up to 0.2	43°V 57°H	0.09°V 0.09°H	Not included
3DV	✓	**Up to 40**	**Variable**	**32-50°V 40-65°H**	**0.06°V 0.06°H**	**OD+TM, plugins**

3DV VisLab.it (video)

3D data

Depth, cloud, mesh...

3D data representation

- Depth map
  - **2.5D** (concept: RGBD = 2D + depth)

- Point cloud
  - **organized**: keeps relationships in sensor neighborhood
  - **unorganized**: one can ***just*** compute nearest neighbors in 3D

- Mesh
  - nice scanned/reconstructed surfaces: watertight / convex...

Point cloud data

- Organized point-cloud

  Resemble an organized image (or matrix-like) structure, with data split into rows and columns (data from stereo, depth or TOF sensors)

  → **projectable** point cloud: has a correlation according to a pinhole camera model between the (u, v) index of a point in the organized point cloud and the actual 3D values (x, y, z).
  This correlation can be expressed as: u = f*x/z and v = f*y/z

  → knowing the relationship between adjacent points (e.g. pixels), **nearest neighbor operations** are much more efficient, thus speeding up the computation and lowering the costs of certain algorithms in **PCL**

- Unorganized point-cloud

  Non-regular sampling of 3D space
  Neighborhood operations require ***KD tree*** search!

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My answers

*Q1: Is "**projective vision**" a natural way to capture the 3D world?*

Natural? Yes!
Some living beings are equipped with a pair of projective (passive) sensors (eyes) performing stereoscopic vision to compute distance…

Practical? Nope!
Capturing 3D geometry can be better done with active sensors probing the actual distance to scene surfaces

*Q2: Do we need **photometry** to get **geometry**?*

Yes!
In 2D projective imaging we do need photometry, and then we compute correspondence disparities from stereoscopic vision or SfM to get scene geometry.
But **Not!** for Lidar or TOF sensors, which can compute scene geometry by radar principles, and without resorting to disparity in photometric data…

My answers

*Q3: Does **3D vision** mean the same than **3D geometry**?*

Absolutely not!

3D vision usually assumes one (or several) points of view from which 3D geometry is computed, leaving part of the scene geometry unavailable due to occlusions!

On the contrary 3D geometry in Graphics or CAD design is a complete representation of the scene (even rendering occlusions and transparencies if needed)

*Q4: Does 2D/3D matter for "**Teaching computers to see**"?*

Geometry of objects and scenes in 3D world helps analysis and recognition. It has the **potential to avoid the large variability in appearance** and missing information due to projection, occlusions, motion, shadows...

Yes, 3D geometry may definitely help computers to see and "understand" complex visual scenes, reasoning about events that evolve in space and time