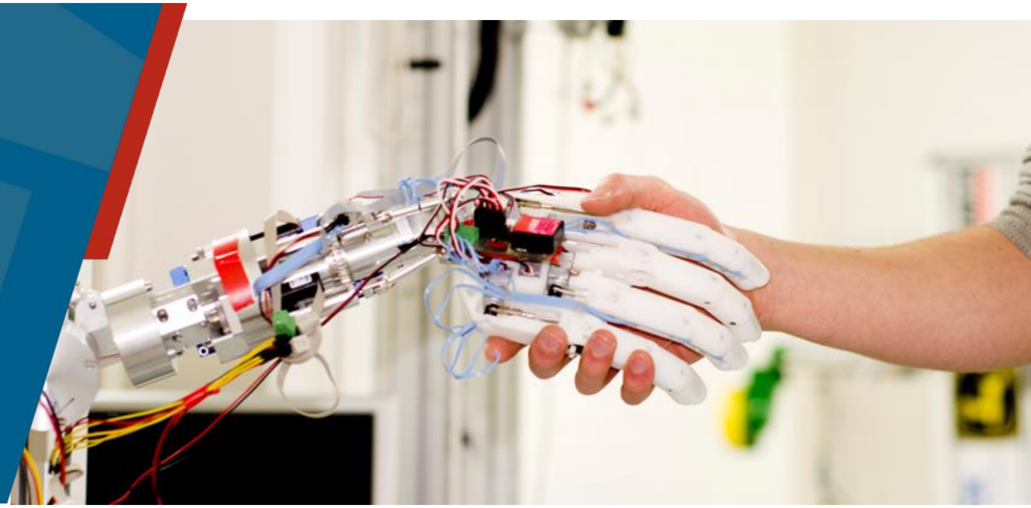
Autonomous Mobile Robots (AMR)

3. Sensor Systems



Prof. Dr. Karsten Berns
Robotics Research Lab
Department of Computer Science
University of Kaiserslautern, Germany

Contents

Overview of Sensors in AMRs

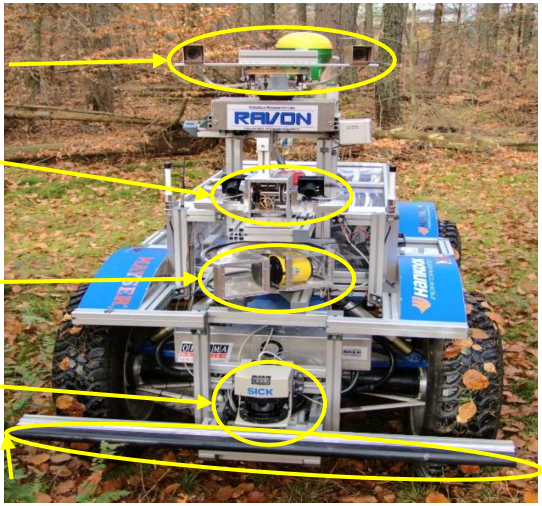
Stereo System
Long range

Stereo System
Obstacle Detection

3D Laser Scanner
Short term memory

2D Laser Scanner
Safety System

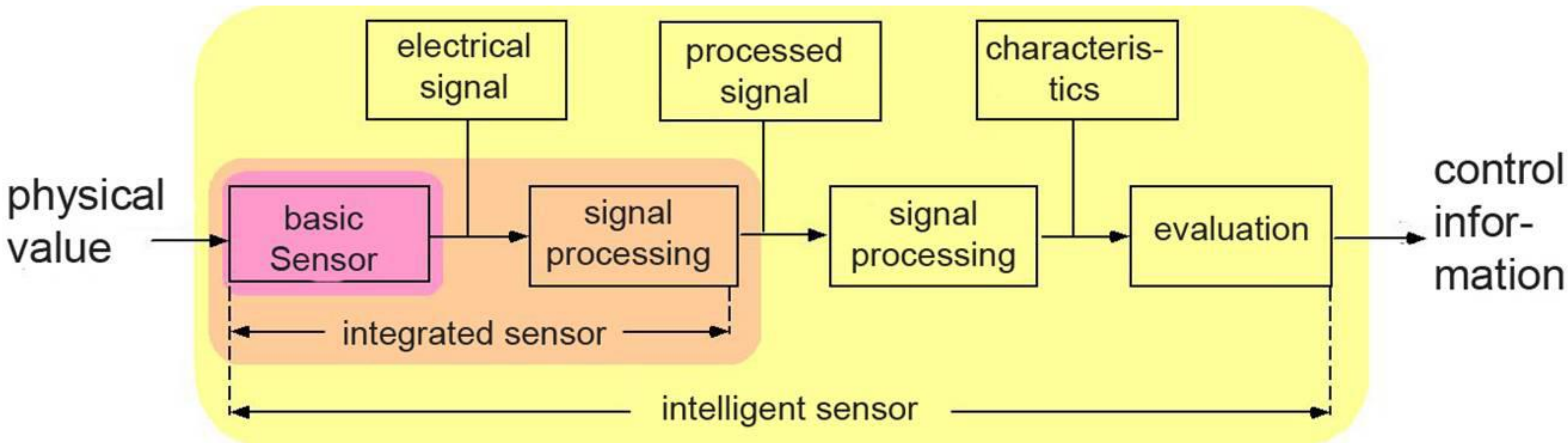
ring-Mounted Bumper



Definition

- Sensor (lat.: sensus = sense): System to transform different kinds of physical values (e. g. force etc.) into proper electrical signals
- Integration levels
  - Basic sensor: measurement and transformation of the signals
  - Integrated sensor: additional signal processing incl. amplification, filtering, linearization and normalization
  - Smart sensor: integrated sensor with computer-controlled analysis of the processed signal

Integration Level



Sensor Classification: Proprioceptive

Acquisition of internal states of a robot/machine e. g.: joint position, joint velocity, joint acceleration, orientation

- Position
  - Potentiometer
  - Optical encoder
  - Differential transformer transducer
  - Magnetic-inductive encoder
- Velocity
  - Tachogenerator
  - Optical encoder
- Acceleration
  - Si-sensor
  - Piezo-electric sensor
- Orientation
  - Gyroscope
  - Geomagnetic sensor

Sensor Classification: Exterceptive

Acquisition of external states (⇒ environment) e. g.:
obstacle distance, object identification, object position

- “Feel”
  - Artificial skin
  - Sliding sensors
  - Force-torque-sensors
- Approach
  - Inductive, capacitive sensors
  - Optical sensors
  - Acoustic sensors

Sensor Classification: Exterceptive

- Distance
  - Optical sensors
  - Radar sensors
  - Acoustic sensors
- Position
  - (Differential) GPS
  - Ground-based radio-systems
  - Natural/artificial landmarks
- Vision
  - Cathode ray tube cameras
  - CCD-cameras
  - CMOS-cameras

Classification Active/Passive

- Active sensors
  - Stimulation of the environment
  - Detection of response
  - Examples: ultrasound sensor, laser-scanner
- Passive sensors
  - Detection of already present signals
  - Examples: camera, microphone
- Task of sensor system
  - Detection of a time dependent environment

Classification of Sensors

Classification	Sensor System	PC or EC	A or P
Tactile sensors (detection of physical contact or closeness; security switches)	Contact switches, bumpers Optical barriers Noncontact proximity sensors	EC EC EC	P A A
Wheel/motor sensors (wheel/motor speed and positions)	Brush encoders Potentiometers Synchros, resolvers Optical encoders Magnetic encoders Inductive encoders Capacitive encoders	PC PC PC PC PC PC PC	P P A A A A A
Heading sensors (orientation of the robot in relation to a fixed reference frame)	Compass Gyroscopes Inclinometers	EC PC EC	P P A/P

A, active; P, passive; P/A, passive/active;
PC, proprioceptice; EC, exteroceptive – [Siegwart04]

Classification of Sensors

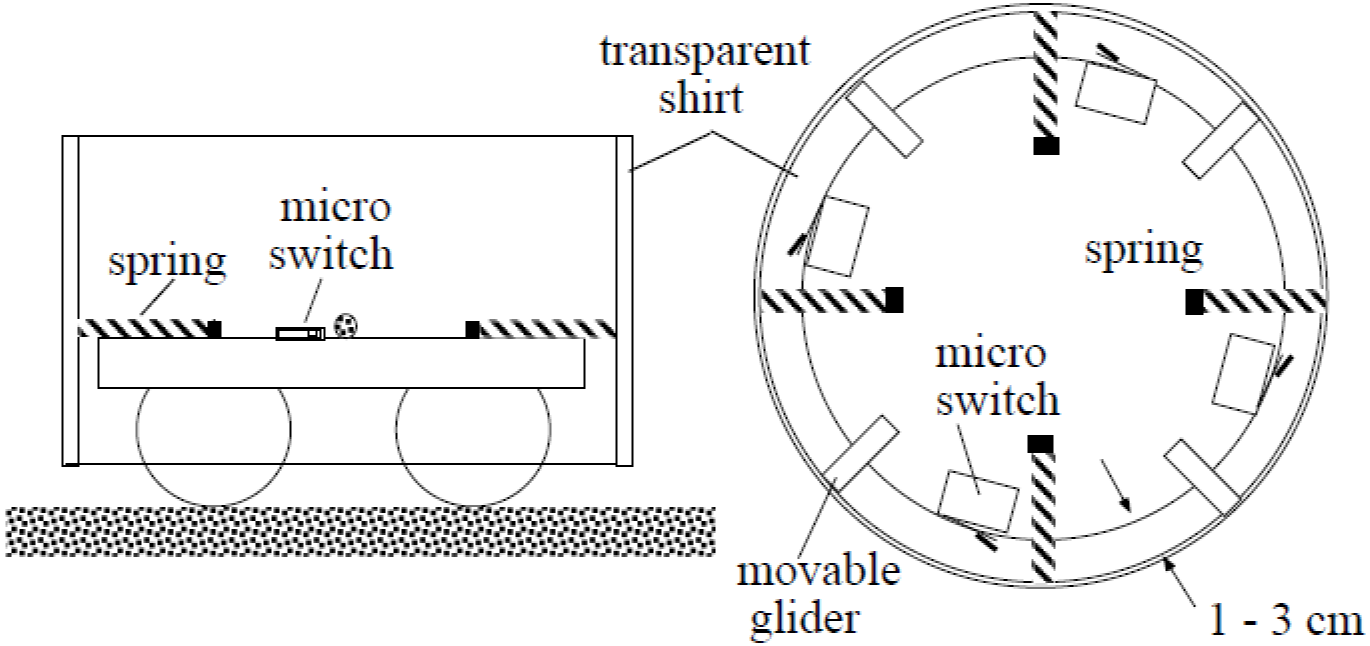
Classification	Sensor System	PC or EC	A or P
Ground-based beacons (localization in a fixed reference frame)	GPS Active optical or RF beacons Active ultrasonic beacons Reflective beacons	EC EC EC EC	A A A A
Active ranging (reflectivity, time-of-flight, and geometric triangulation)	Reflectivity sensors Ultrasonic sensor Laser rangefinder Optical triangulation (1D) Structured light (2D)	EC EC EC EC EC	A A A A A
Motion/speed sensors (speed relative to fixed or moving objects)	Doppler radar Doppler sound	EC EC	A A
Vision-based sensors (visual ranging, whole-image analysis, segmentation, object recognition)	CCD/CMOS camera(s) Visual ranging packages Object tracking packages	EC	P

Forces, Acceleration, Orientation

SENSOR SYSTEMS

Bumper

- Last resort before crashing
- Emergency break
- Consumes part of the impulse



Sketch of a simple bumper (sideview and bird's eye view)

Magnetic Wheel Encoders

Various measurement principles:

- Measurement of the number of magnetic pole changes of magnets at the perimeter of a disk
- Hall effect sensors
- Tacho generator: voltage produced by an electric generator turned by the wheel

Optical Wheel Encoders

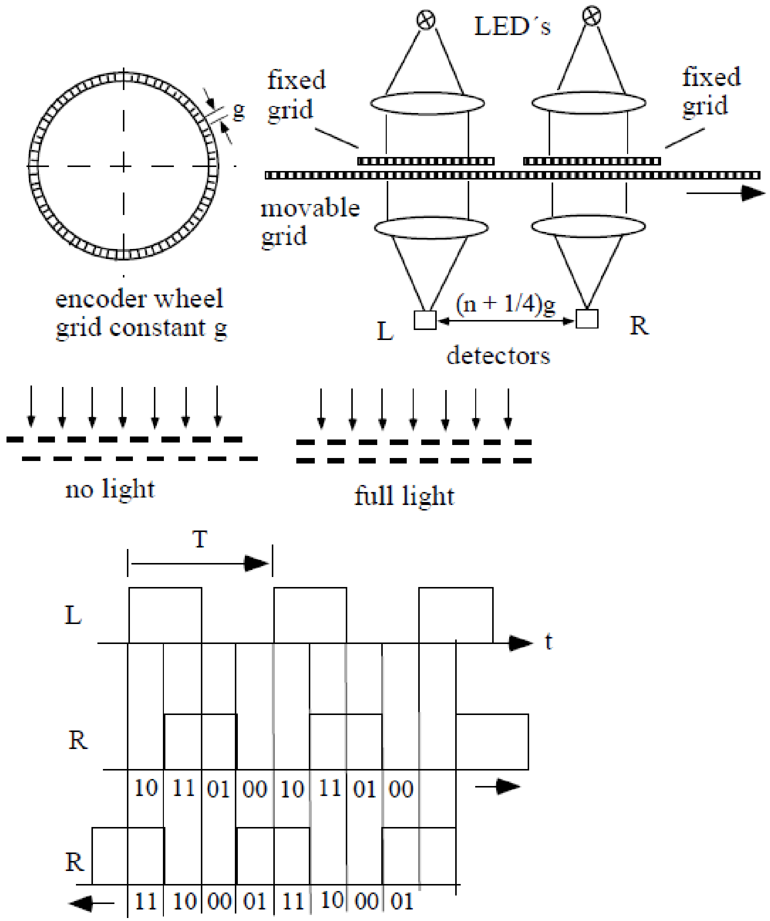
- Measurement principles
  - Distance measurement by number of ticks produced by a grid passing a light barrier
  - Two grids: one fixed to the vehicle chassis, the other one turning with the wheel
- Vehicle motion might be tracked simply by counting the number of ticks at the wheels resulting in the distance travelled s

$$s = 2\pi r \cdot \frac{n}{n_0}$$

  - n number of ticks measured
  - n_0 number of ticks for a full revolution of the wheel
  - r wheel radius

Optical Wheel Encoders: Direction Determination

- Two light barriers $(n + \frac{1}{4})$ grid constants apart
- Two signals, phase difference of $90°$ ⇒ determine direction
- Typical: grid of 4096 equidistant transparent and non transparent areas (resolution: $12\ \mathrm{Bit},\ 0.1°$)



Measurement principle of a wheel-encoder

Quadraturzähler, $4096\,\frac{\text{steps}}{\text{revolution}} \Rightarrow 12$ Bit, Resolution $< 0.1°$

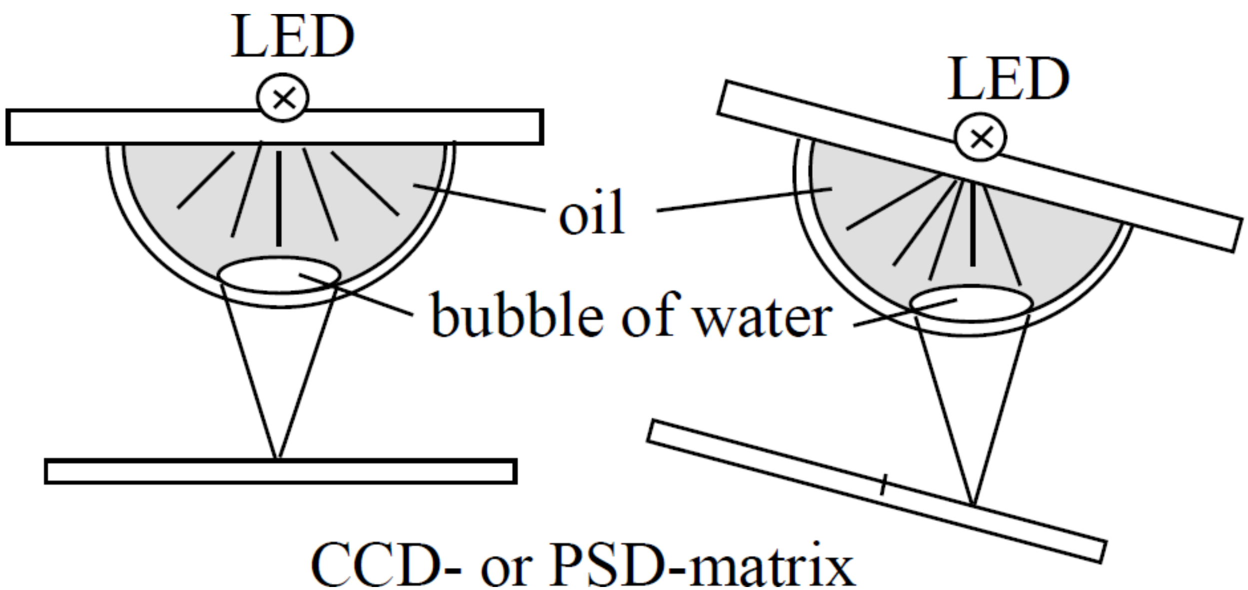
Inclinometers

- Application of inclinometers: measurement of upward/downward orientation, measurement of shifts to a side with the danger of toppling or falling to the side
- Measurement of inclination in two axes required
- Measurement principles
  - Optical inclinometers: liquid under the influence of gravity
  - Capacitive inclinometers: dielectric liquid in capacitor
  - Acceleration sensors: measure direction of gravity

Optical Inclinometers

- Usage of a droplet of liquid under the influence of gravity
- In a transparent half-sphere plastic bowl filled with oil a droplet of water forms a lens at the bottom, because water is more dense than oil
- The light of a LED is projected by that lens onto a CCD-matrix or PSD-matrix
- Any inclination shifts the droplet and so the picture of the LED at the CCD-matrix, indicating the amount of inclination
- An oil of suitable viscosity damps the movement of the water droplet to damp jitter from movements over uneven ground

Optical Inclinometers



Measuring principle of an optical inclinometer

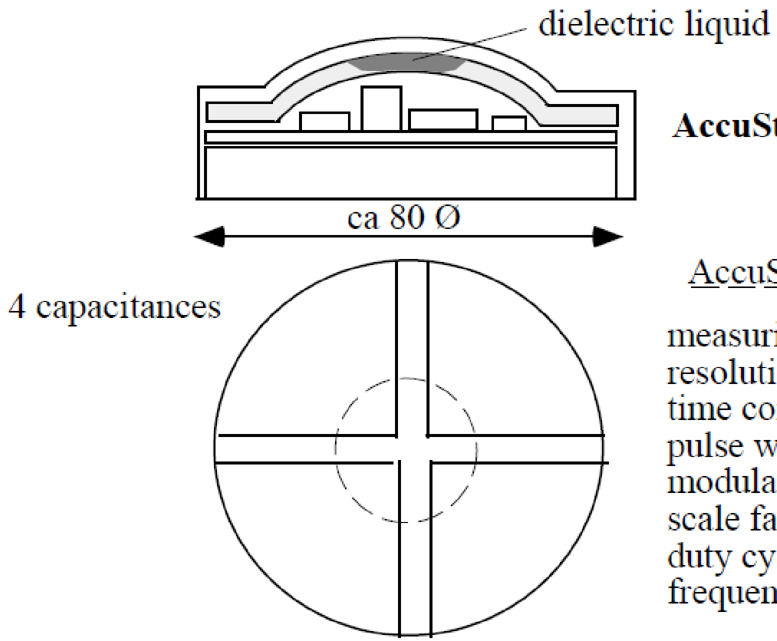
Capacitors

- Stores Charge
- Capacity $C = \varepsilon_0 \cdot \varepsilon_r \cdot \frac{A}{d}$
- $\varepsilon_0 = 8{,}8pFm^{-1}$ (Permittivity of a vacuum)
- ε_r (no unit): relative permittivity
- Unit of capacity: Farad (F) where $1F = 1AsV^{-1}$

Material	$\boldsymbol{\varepsilon_r}$
Air	1,000576
SiO_2	3,9
PVC	3,0 – 6,0
Si pure	11,7
Al_2O_3	6,0 – 9,0
Barium titanate	20000

Capacitive Inclinometers

- Dielectric liquid drop floats between the plates of a capacitance
- Any tilt shifts the drop to the side and changes the capacitances in a quad capacitance measuring device



AccuStar inclinometer

AccuStar II Mini

measuring range	±20 °
resolution	0.01 °
time constant	0.3 s
pulse width modulated output	0° -- 50 %
scale factor	0.7%/ Grad
duty cycle	T2/(T1 + T2)
frequency	1 kHz

Measurement principle of a capacitive inclinometer

MEMS

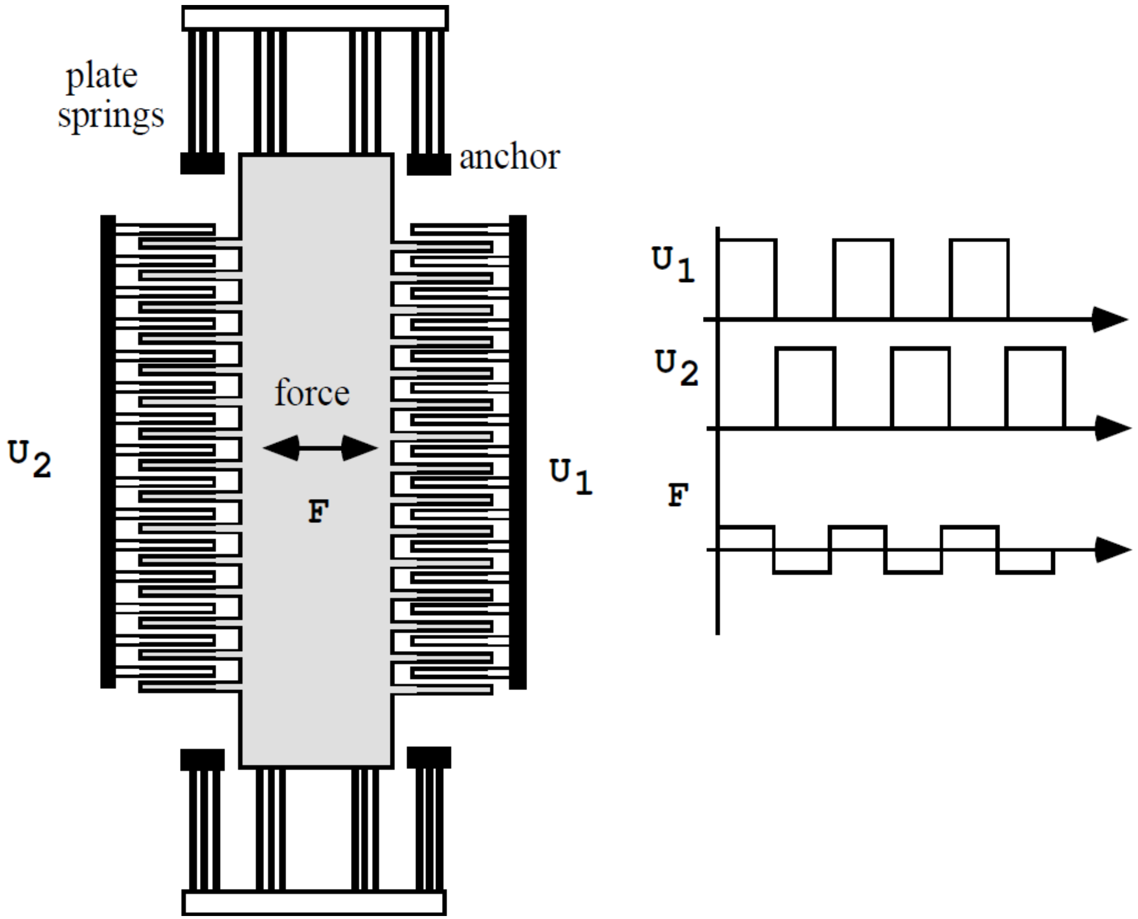
- Micro-Electro-Mechanical System
- Integration of complex electro mechanical systems into bulk silicon
- Silicon: material with good properties for this type of application, very well understood from decades of producing integrated circuits
- Same technique used for ICs is applied to etch out free swinging beams of silicon anchored to the bulk material at few points only
- Measurement principle: pair of capacitors, measure very small distance variations under acceleration
- Central difficulty: earth acceleration far larger than vehicle acceleration ⇒ orientation information required to remove unwanted gravity forces from the measurement results

MEMS: Measurement Principle

- A mass anchored to the bulk by plate springs is forced into oscillations by a comb of slabs acting as capacitors.
- Typical dimensions of the slabs
- $s = 125\ \mu\mathrm{m}$
- Thickness $b = 1\ \mu\mathrm{m}$
- Distance to the next slab $d = 1\ \mu\mathrm{m}$
- The force is multiplied by the number of combs gripping into each other
- One direction only, but activating two combs at each side of the mass alternatively switching the voltage driving the combs, one voltage may set the system into oscillations
- Typical frequencies: approx. $20\ \mathrm{kHz}$
- Typical voltage: $5\ \mathrm{V}$
- Small forces sufficient: damping of the system is low

MEMS

- Driving the capacitors by two voltages with 180° phase shift; resulting signal after synchronous demodulation is proportional to the difference in capacitances and measures the deviation Δd
- Measuring frequency is much larger than the oscillation driving frequency $\Rightarrow$ no interference

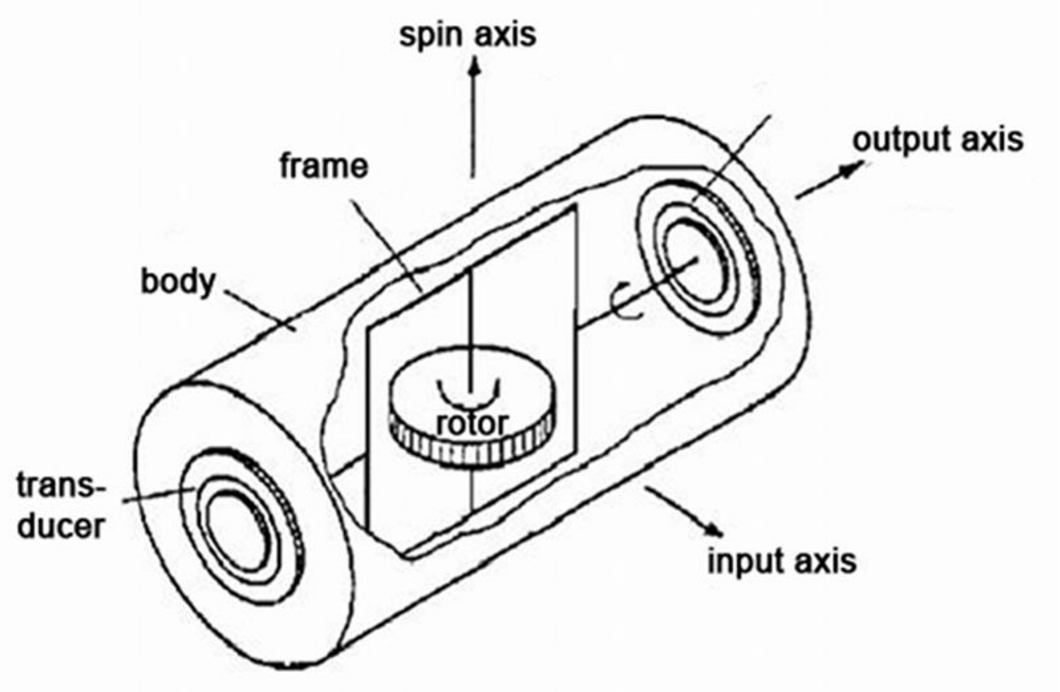


Forced Oscillations

Gyroscopes

- Torque applied to the input axis (cause)
- Gyro rotation around the spin axis (mediator)

=> rotation around the output axis (effect)

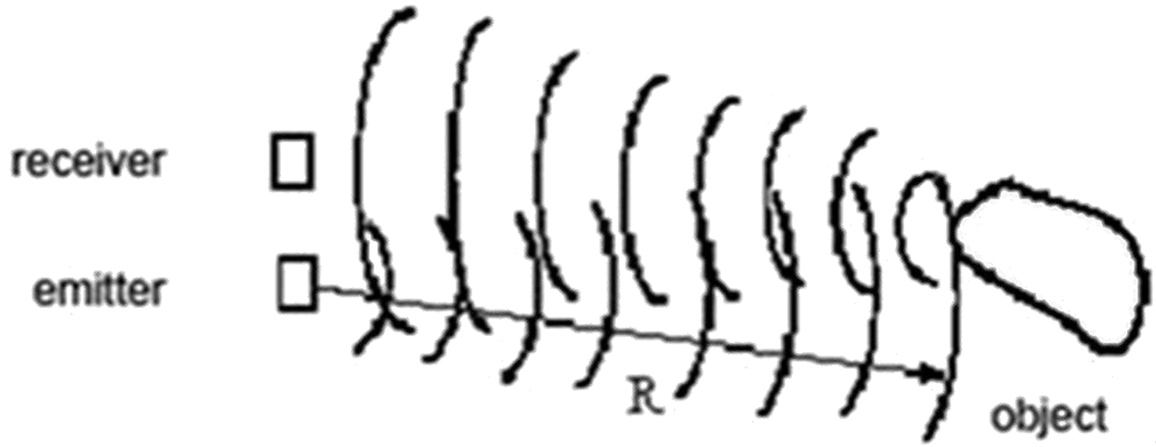


Distance Sensors

Active Distance Sensors

- Energy (sound, light, microwaves, etc.) is emitted
- Runtime/direction of the reflected energy is measured

- => Distance to objects by characteristic velocity and runtime



Principle of active distance detection

Energy at Object

- $f(R) = \begin{cases} a \cdot const \\ \frac{a}{R^2} \\ e^{-\frac{R}{\gamma}} \cdot \frac{a}{R^2} \end{cases}$

- Laser, tightly bundled beam
- Object absorbs energy portion a
- Absorbance of the medium
- (e. g. light in muddy water)

- I_0 Intensity of the emitted signal at emitter location
- $I_R = I_0 \cdot f(R)$ Signal intensity at object location (distance R)

Detector Intensity

- Reflected signal at the objects location: $I_1 = A \cdot \rho(\alpha) \cdot I(R)$

$$A = \begin{cases} \text{object surface area for normal source} \\ \text{area of laser beam (diameter } \emptyset\text{),} \\ \text{if surface area} > \frac{\pi}{4}\emptyset^2 \end{cases}$$

- $\rho(\alpha)$: Reflectivity $99\ \%$ with mirror-like surfaces and $\alpha \approx 0$, $0.01\ \%$ with highly absorbing surfaces
- Intensity at the detector

- $I(D) = I_1 \cdot f_2(R) \cdot B = A \cdot I_0 \cdot \rho(\alpha) \cdot f(R) \cdot f_2(R) \cdot B$

Detector Intensity

$$f_2(R) = \begin{cases} \dfrac{b}{R^2} \\ \dfrac{b}{R^2} \cdot e^{-\frac{R}{\gamma}} \end{cases}$$

- b: Ratio of energy absorbed by the detector
- B: Detector surface area
- $I(D) = A \cdot B \cdot \frac{1}{R^4} \cdot I_0 \cdot \rho(\alpha) \cdot a \cdot b$
- A: object surface area
- B: detector surface area
- I_0: emitter intensity
- $\rho(\alpha)$: object reflectivity
- a, b: opening coefficient of detector/object

Examples – Intensity at Detector

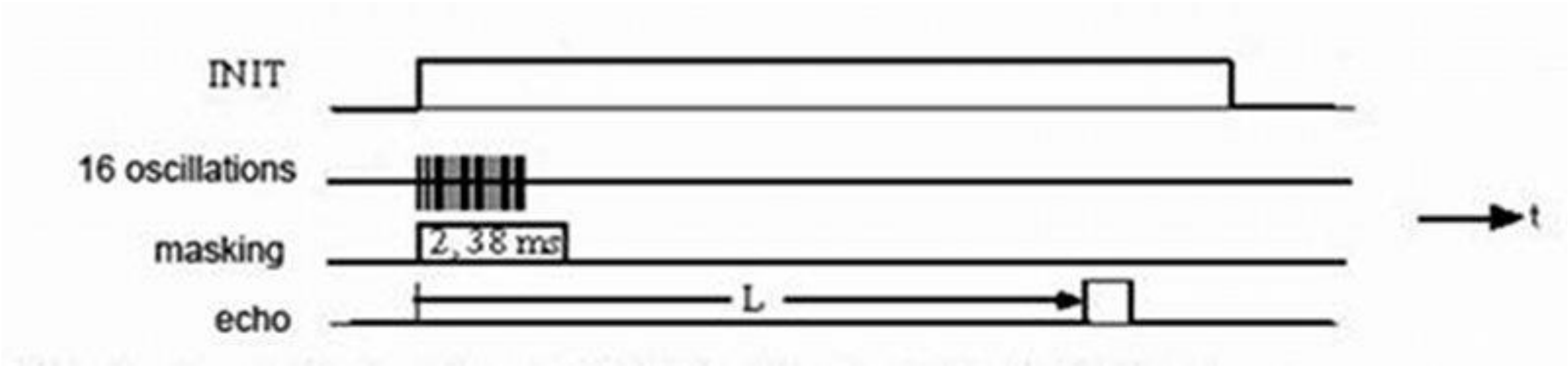
- Intensity at the detector if laser is used
- $I(D) = \frac{\pi}{4} \cdot \emptyset^2 \cdot B \cdot \frac{1}{R^2} \cdot I_0 \cdot \rho(\alpha) \cdot a \cdot b$
- Intensity at the detector with normal light and absorbance
- $I(D) = A \cdot B \cdot \frac{1}{R^4} \cdot I_0 \cdot \rho(\alpha) \cdot a \cdot b \cdot e^{-\frac{2R}{\gamma}}$

Ultrasonic Sensor

- Short sound impulses generated and emitted to object
- Time until first echo returns is measured
  (SONAR = SONic Automatic Ranging)
- Speed of sound: $c_{us} = 300\,\mathrm{m/s}$ (air), $c_{us} = 1500\,\mathrm{m/s}$ (water)
- Frequencies: usually 25, 50, $100\,\mathrm{kHz}$
  (wavelength in air 13, 6.6, $3.3\,\mathrm{mm}$)
- Range in air very limited due to strong absorbance ($\approx 10\,\mathrm{m}$)
- 50 wave trains emitted at one time at $50\,\mathrm{kHz}$ ($1\,\mathrm{ms}$)
- Distance d to object with runtime L

- $d = c_{us} \cdot \frac{L}{2}$

Ultrasonic sensor

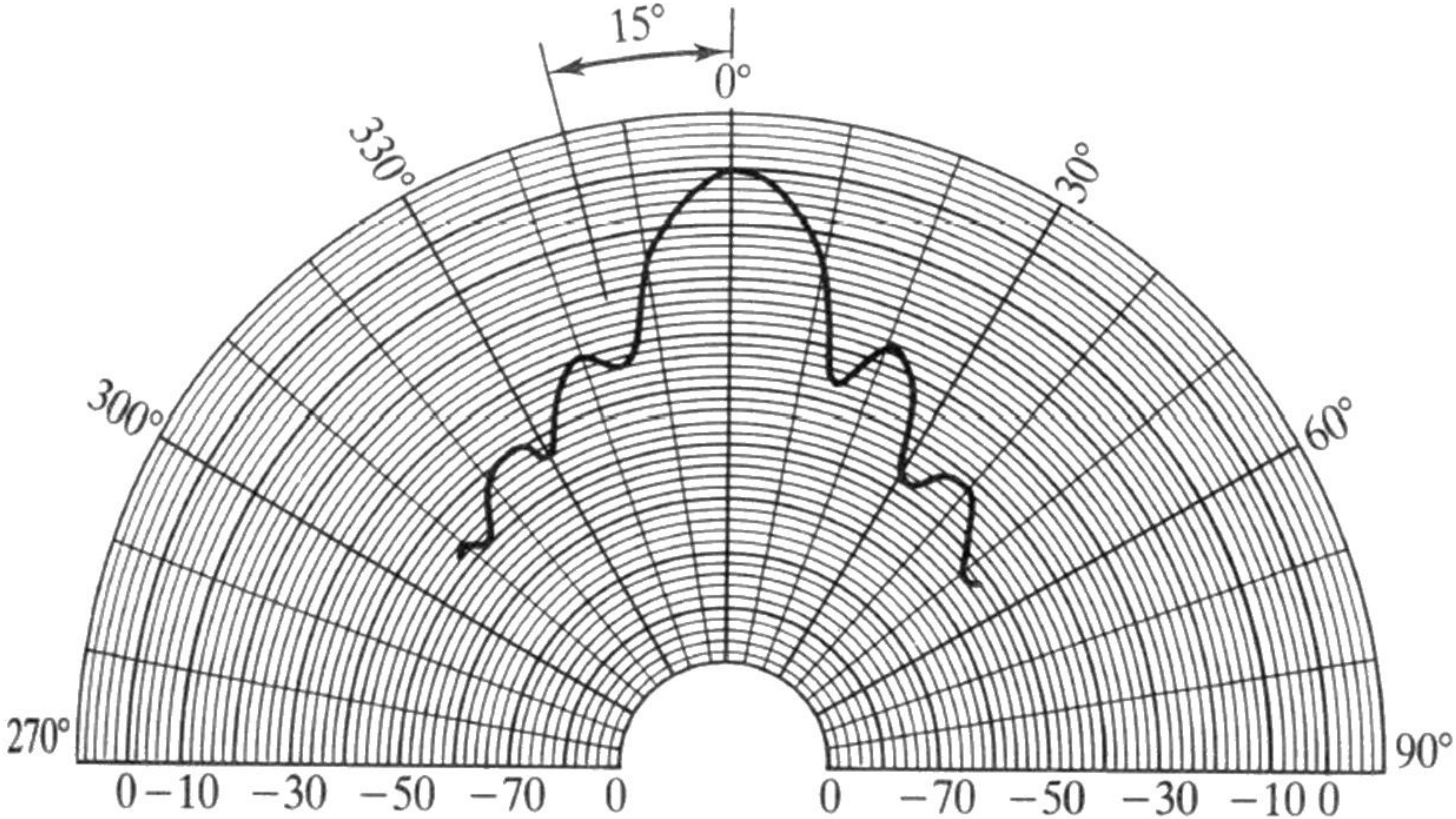


Principle of ultrasonic distance measurement

Ultrasound in Air

- Propagation with steady velocity
- Velocity is temperature dependent
- $330\,\mathrm{m/s}\ (0\,°C)$
- $343\,\mathrm{m/s}\ (20\,°C)$
- $355\,\mathrm{m/s}\ (40\,°C)$
- Sensors have to be adjusted to temperature
- Half of the elapsed time divided by the speed of sound results in the distance of the object

Propagation of the Ultrasonic Waves

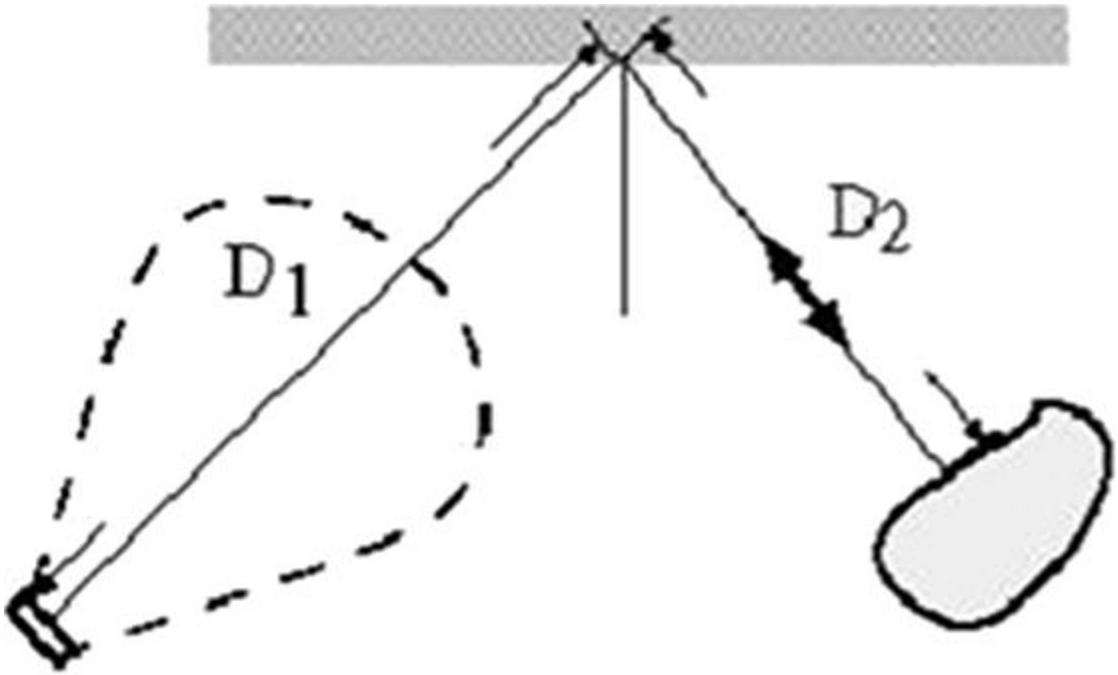


Propagation of the ultrasound waves

Properties of Ultrasonic Measurements

- Recognition improves with increasing surface area of the object facing the sensor
- Big objects with rough surfaces are best suited for recognition (Surface is considered rough, if roughness is bigger than the wavelength of the signal)
- Object transparency makes no difference to sensor (Advantage to optical systems)
- Small objects tend to reflect small amounts of the signal
- Wave distribution of smooth surfaces is too low (invisible at some angles)
- Smooth surfaces detection improves as wavelength declines

Problems: Reflexions



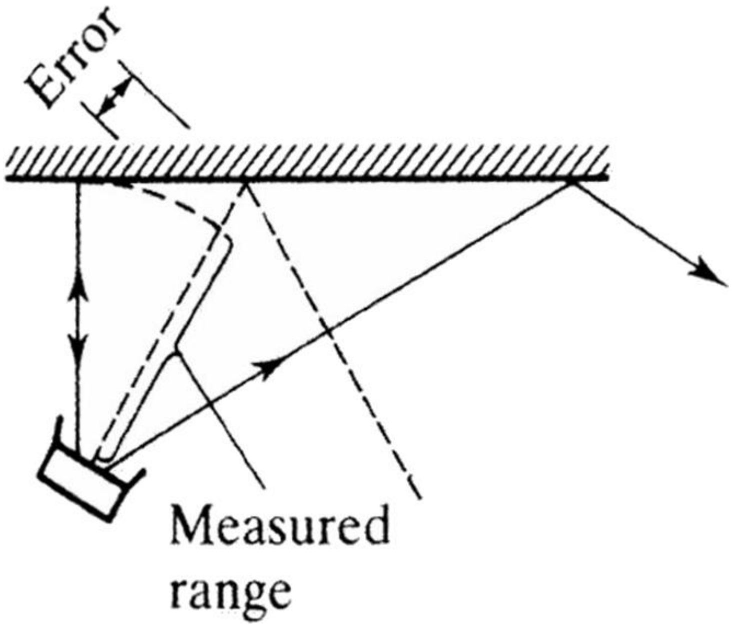
Pretended distance $D_1 + D_2$ due to reflexion at invisible surface

Problems: Reflexions

- Reflection on smooth walls: $f = 49\,\mathrm{kHz} \Rightarrow \lambda = 6.75\,\mathrm{mm}$
  $\Rightarrow$ all surfaces with roughness of less than $6\,\mathrm{mm}$ appear smooth to ultrasound sensor
- Heavily absorbing surfaces reflect a too weak echo
  $\Rightarrow$ only detection of very close objects
- Large opening angle ($30\,°$)
- Unable to detect precise direction
- Produces “crosstalk” with transducers close by

Problems: Myopia (Near-sightedness)

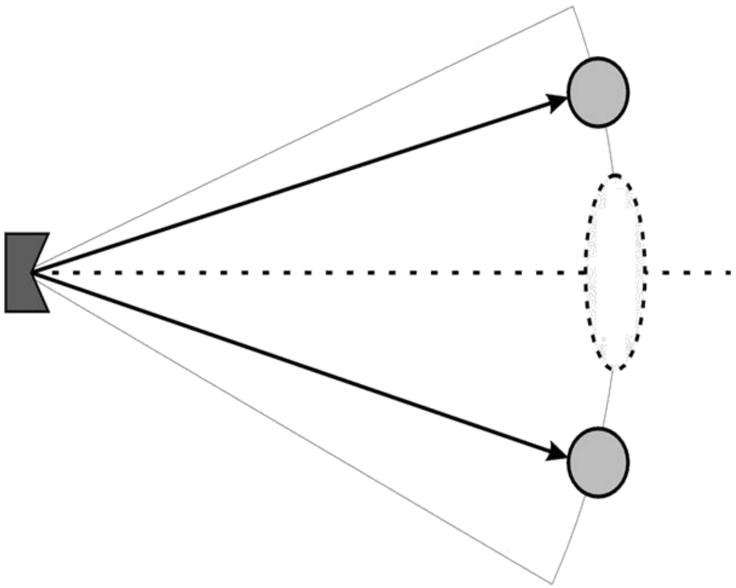
- On diagonal objects waves are reflected at different points in time
- The larger the opening angle, the worse the possible error
- Diagonal objects appear closer than they are



Myopia effect

Problems: Virtual Obstacles

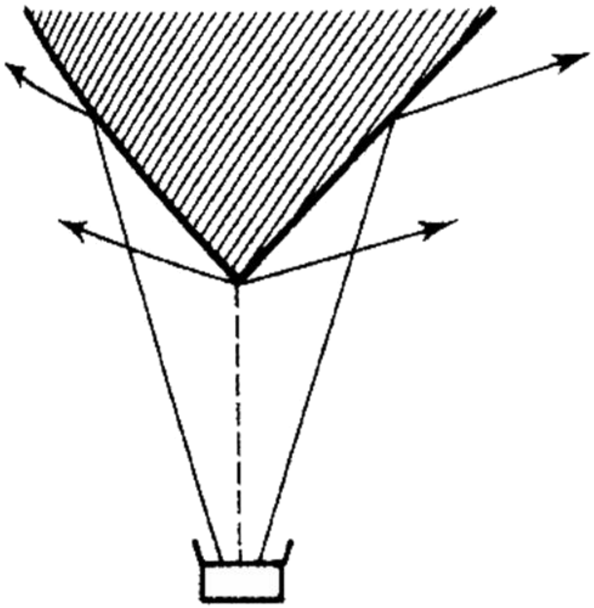
- Several obstacles at the same distance may be interpreted as a single object
- Can be avoided when more than one sensor is used
- The bigger the opening angle, the bigger the likeliness for a "virtual wall"

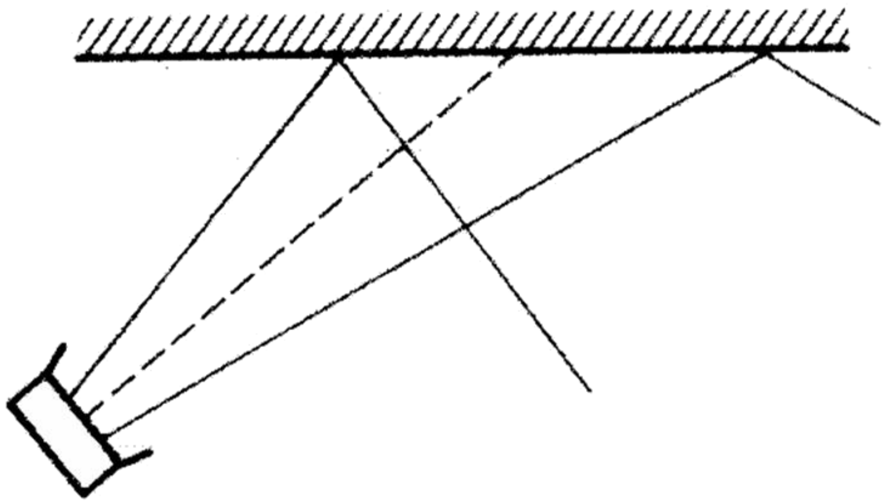


Virtual obstacle is indicated by the sensor

Problems: Total Reflexion

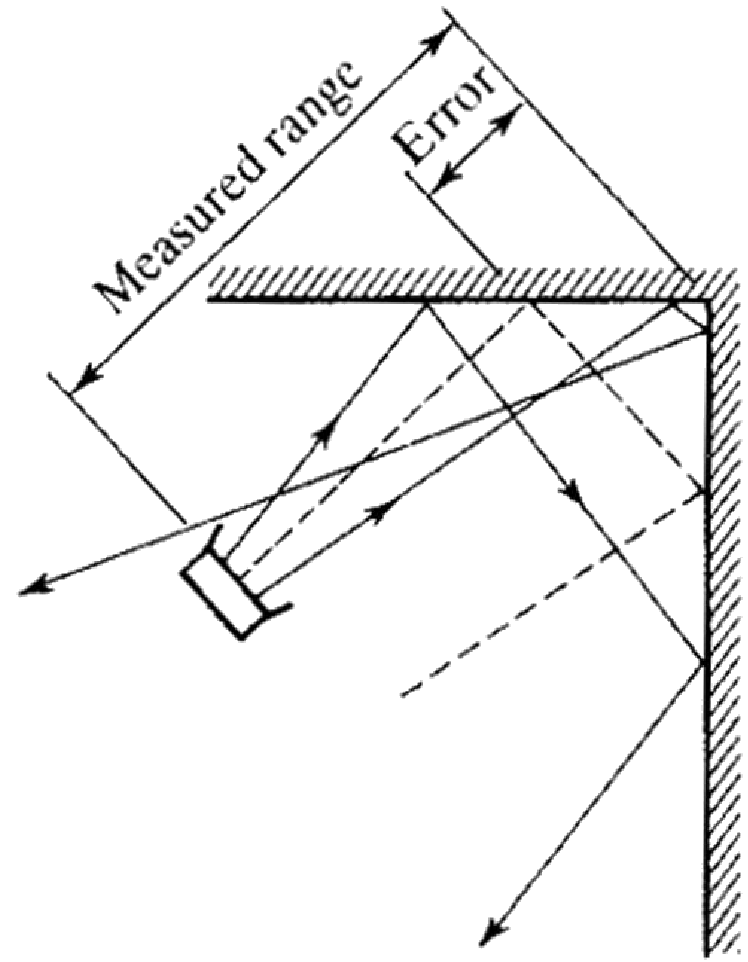
- At unfavorable angles the sound waves are completely reflected away
- In certain situations walls might not be detected





Problems: Multiple Reflexions

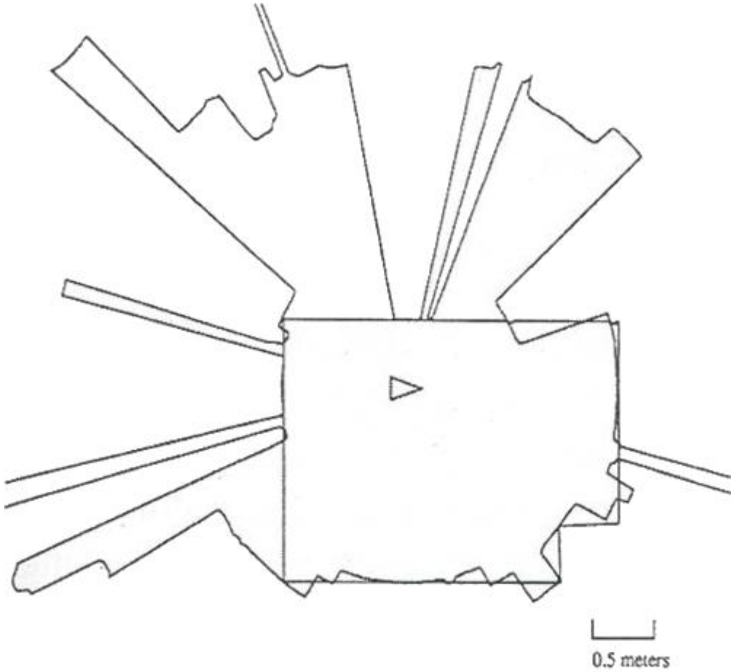
- Alike total reflexion, the sound waves are not directly reflected back to the sensor
- Through reflexions on several walls the wave finally returns to the sensor
- Obstacles appear to be farther away than they are



Occurrence of errors caused by multiple reflexions

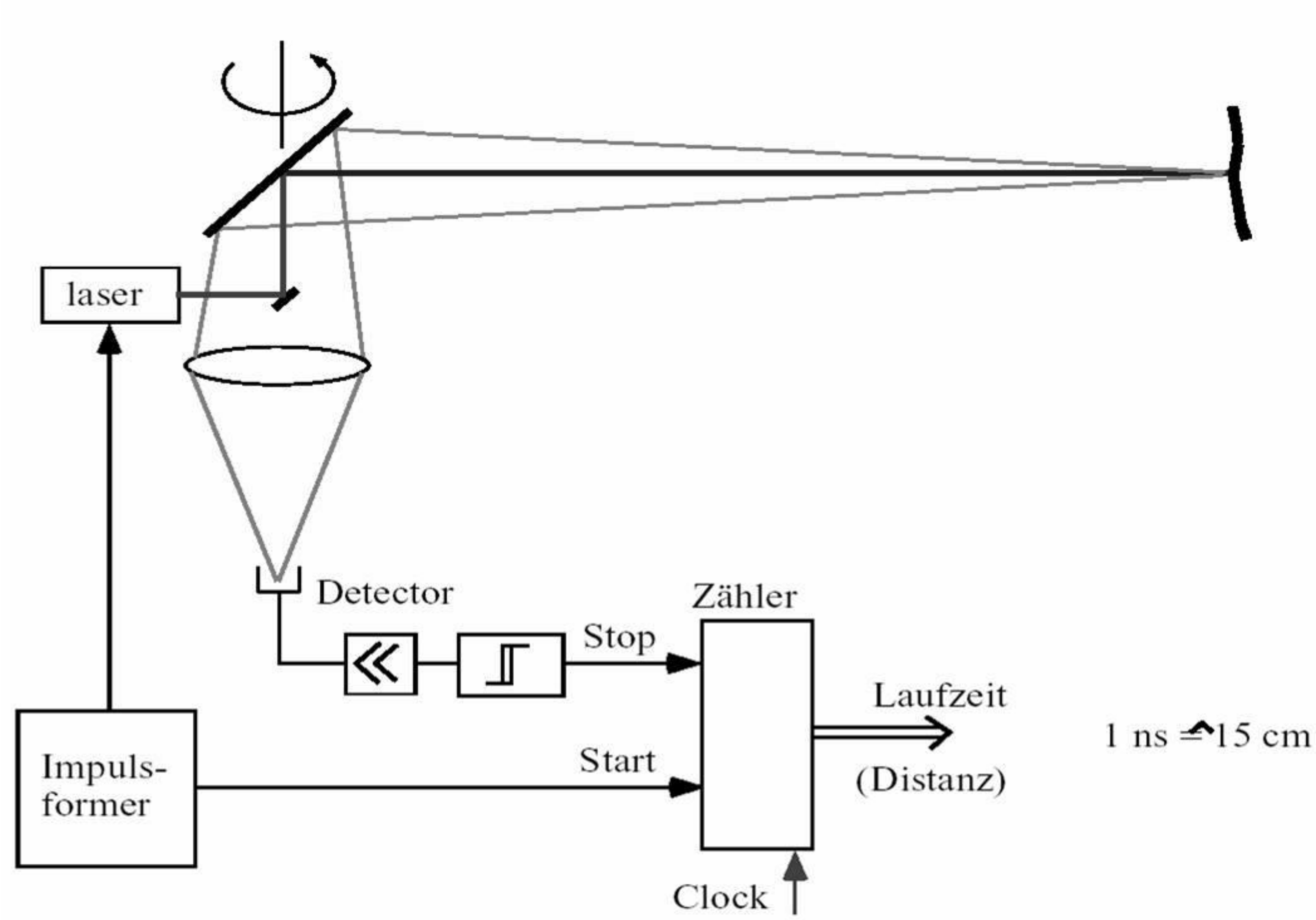
Ultrasonic Snapshot of a Room

- Typical measurement of a room with ultrasound sensors
- Serious problems at the corners
- No point measurement — cone measurement



Recorded sensor data in comparison to real room dimensions

Laser Distance Detection



Principle of active distance measurement employing a laser

Example: SICK Laser Scanner

- Impulse length: $\approx 1\text{ns}$
- Impulse power: 10 W
- Rate: $18000/\text{s}$
- Scan angle: $180\,°$ in 20 ms
- Angular resolution: $0.5\,°$
- Detector clock: 3 GHz
- Range: $0\text{–}4\text{–}12\text{ m}$
- Distance increment: 5 cm
- Distance error: $\pm 2.5\text{ cm}$
- Detectable objects: $1.8\,\%$ reflection at 4 m

SICK Laser Scanner

Example: SICK S3000 Sicherheitslaser

- Wave length: 905nm
- Scan angle: $190\,°$ in $20\ \mathrm{ms}$
- Angular resolution: $0.25\,°$
- Max. Distance: 49m
- 2 Safety zones: 15 m
- Nr. of field sets:16 and 32
- Resolution: $30\ \mathrm{mm}\ - 150\ \mathrm{mm}$

Sick S3000 Anticollision

Solid-State LiDAR

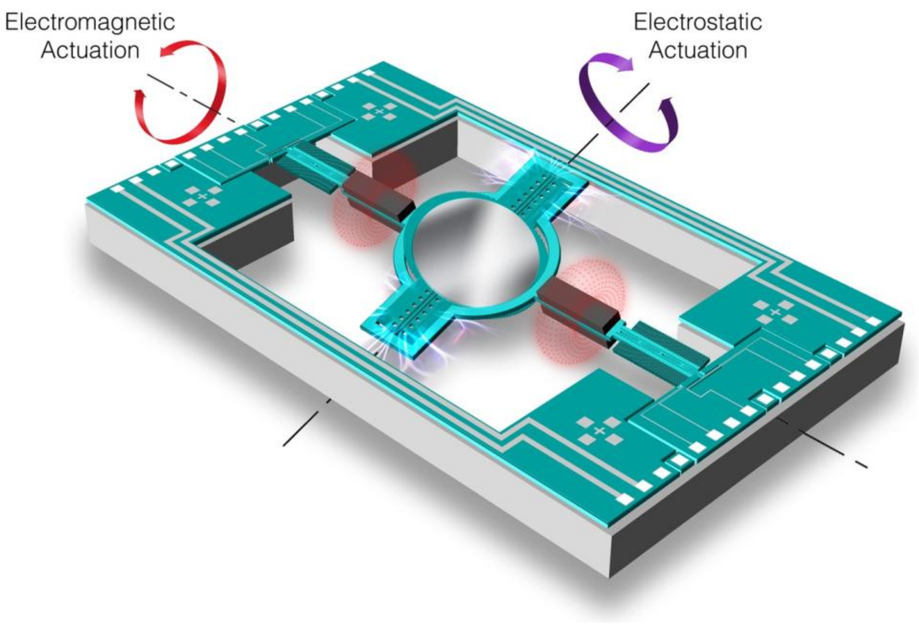
- Solid-state := no large rotating mirror for beam steering
- Smaller, as no actuation is necessary
- Can be produced in large scale (MEMS chips)
- Field of view is restricted (no 360°)

Velodyne HDL-32E

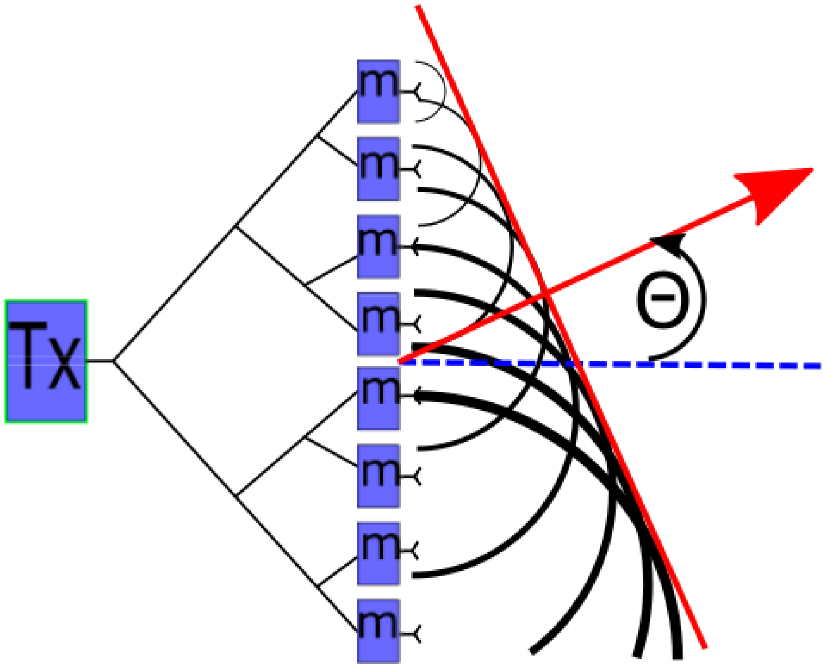
Innoviz Pro

Alternative Steering Technologies

- MEMS
  - Micro-mirror on small chip (1x1cm) → mass production
  - Mirror is moved electro-mechanical
  - Fast, sine-shaped trajectories
- OPA (Optical Phased Array)
  - Principle known from antennas
  - Interference of light waves
  - Steering via phase shift
  - Low energy consumption, as light beam is not pulsed.
  - No mechanical parts at all


Electromagnetic Actuation
Electrostatic Actuation

MEMS

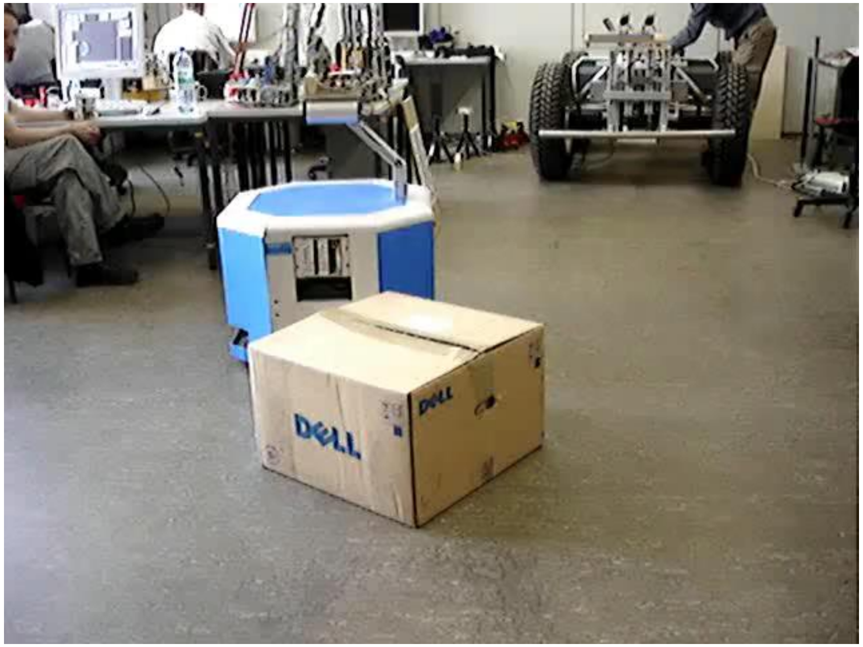

Tx
m
m
m
m
m
m
m
m
Θ

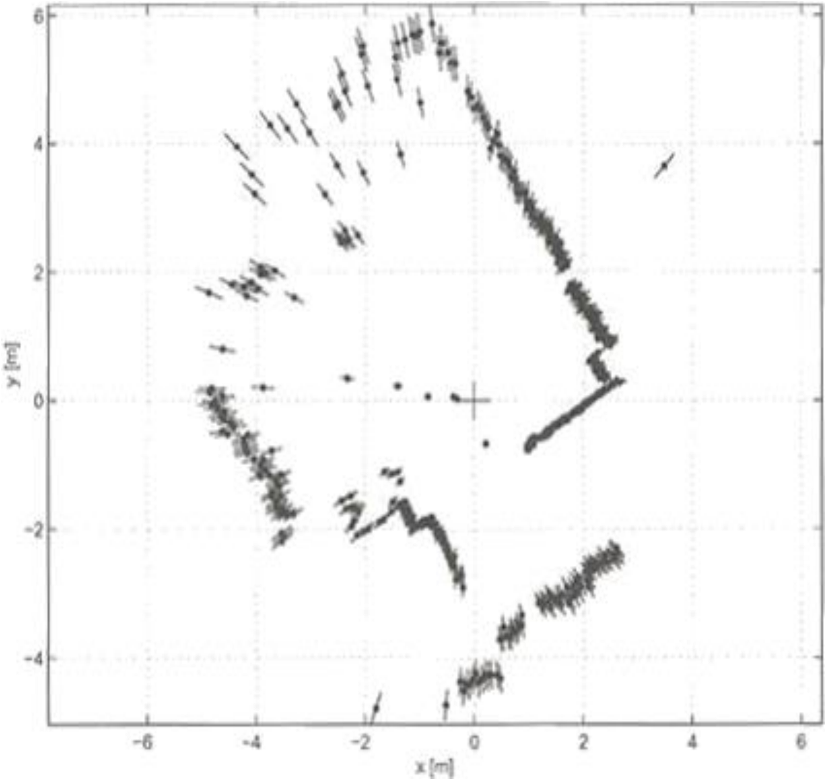
OPA

Innoviz Pro: MEMS-based LiDAR (2020)

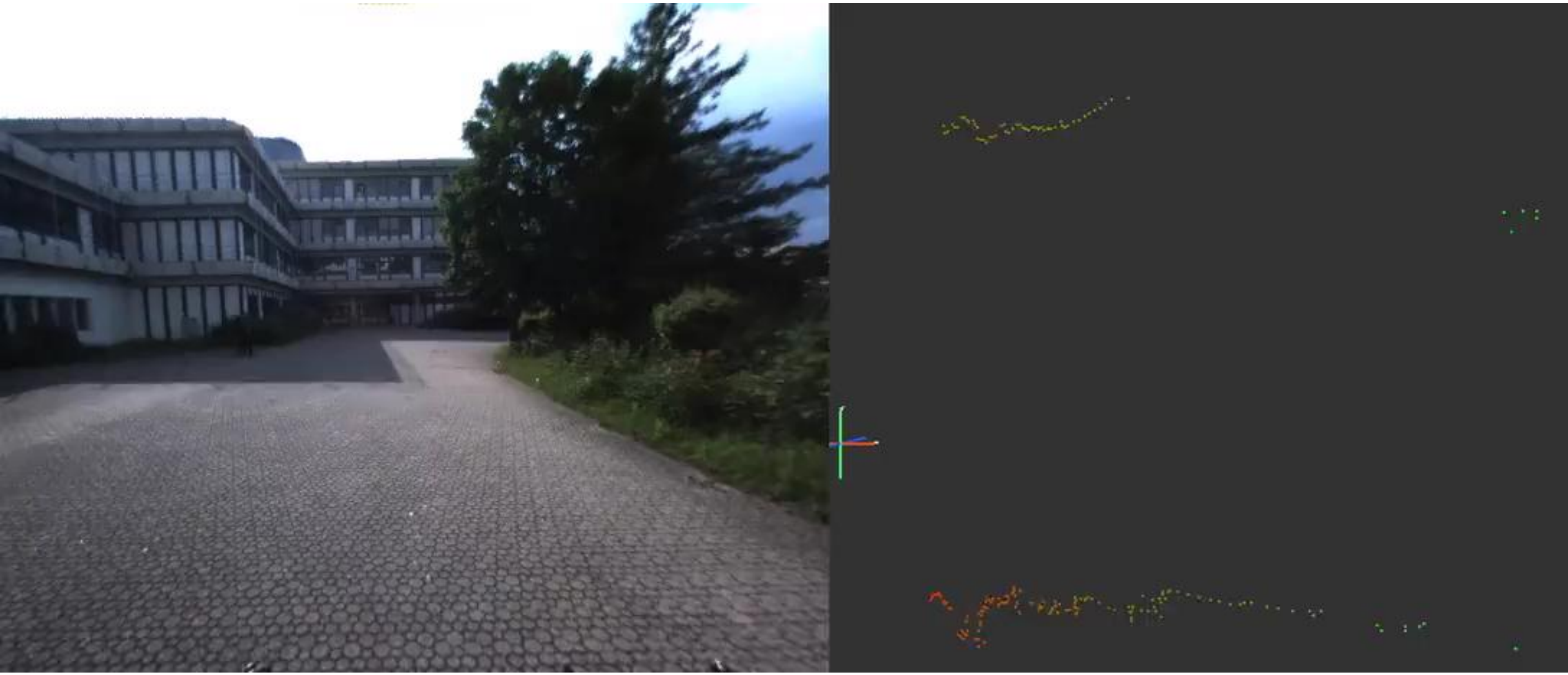
- Field of View: 72° Hx18.5° V
- Angular resolution: 0.18° Hx0.4° V
- Frame rate: 16Hz
- Range: 105m
- Dimension: 73x66x165mm
- Wavelength: 905nm
- Range Accuracy: 5cm
- Minimum range: 2.1m

Wall Detection with a SICK Laser Scanner

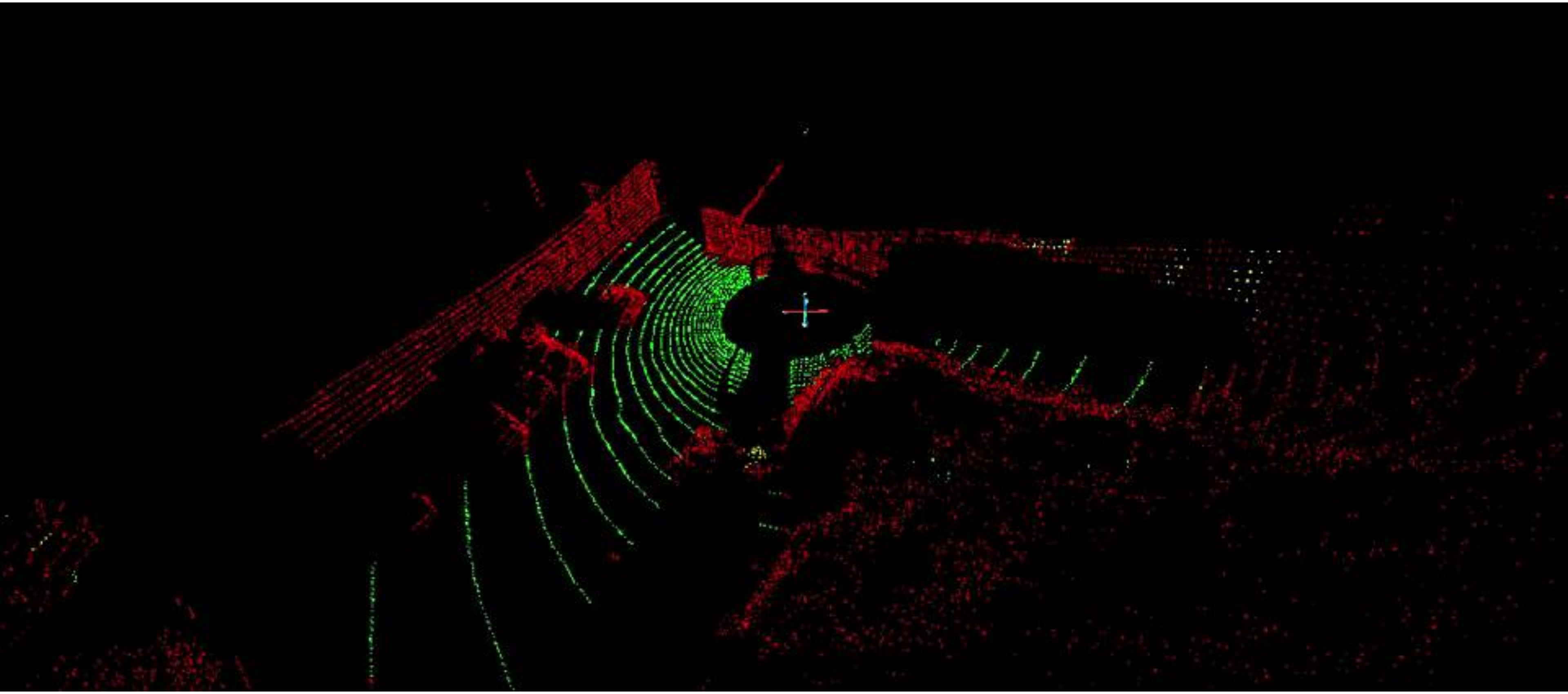




2D Laser Range Finder (SICK LMS151)

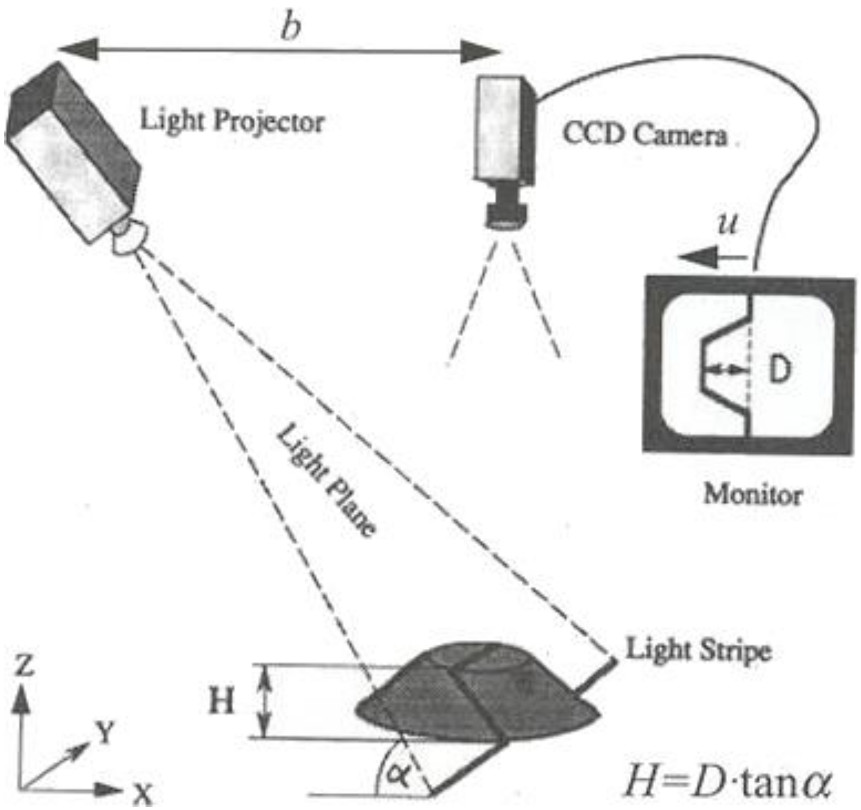


3D Laser Range Finder (Velodyne HDL-32)



Active Triangulation

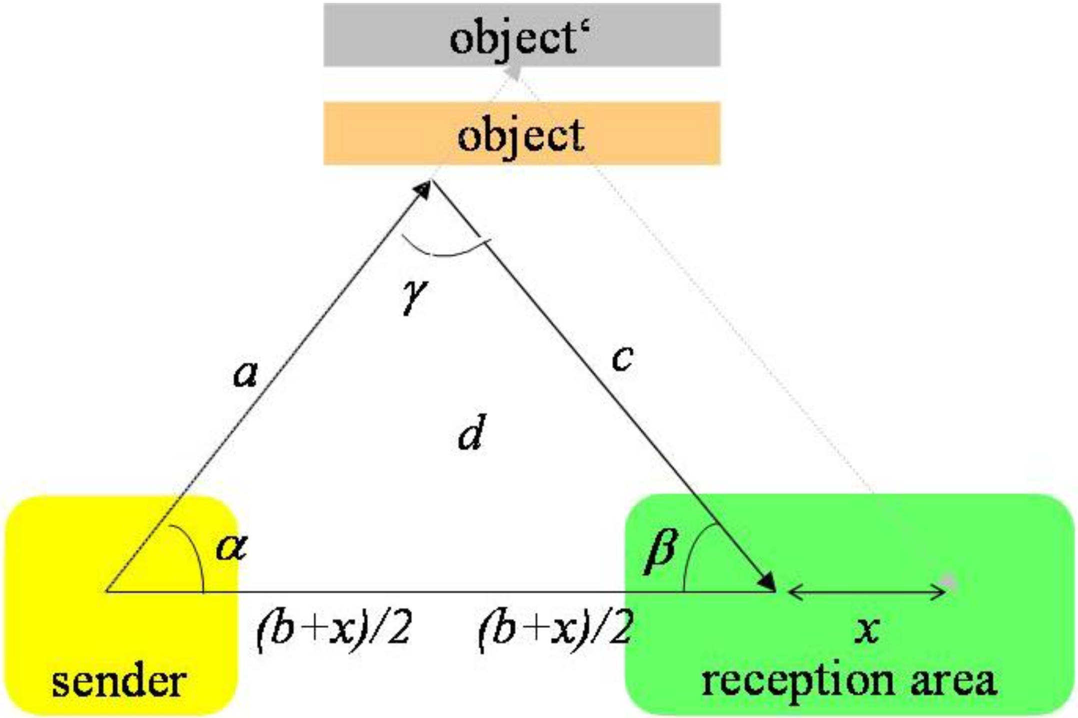
- Sender and receiver with known distance
- Sender emits beam (e. g. laser) onto the object
- Receiver (e. g. CCD-cam, PSD) measures displacement x indirectly



Setup for active triangulation

Active Triangulation

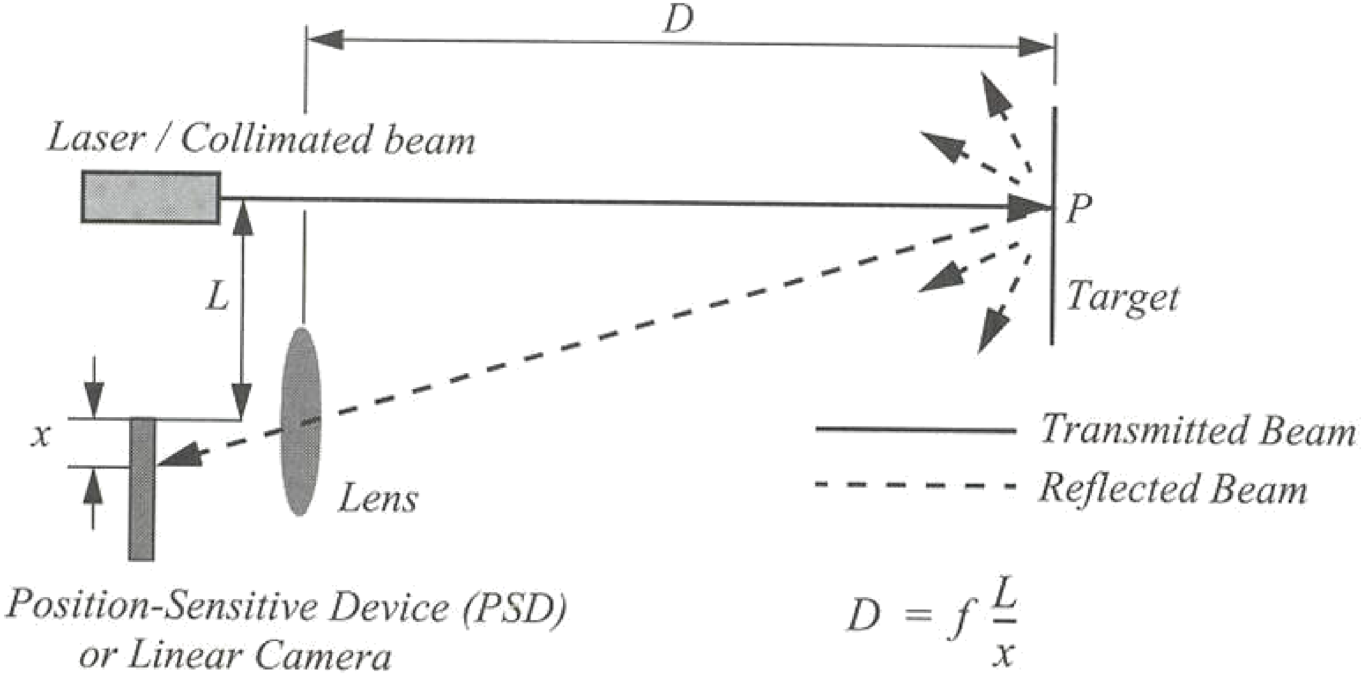
- Assumption: symmetric setup (i.e. $a = c$, $\alpha = \beta$)
- Distance to object: $d = \frac{1}{2}(b + x) \cdot \tan\alpha$
- With increasing distance the resolution degrades (approaching pole of $\tan\alpha$ at $90\,°$)



Distance computation

1D Distance Measuring

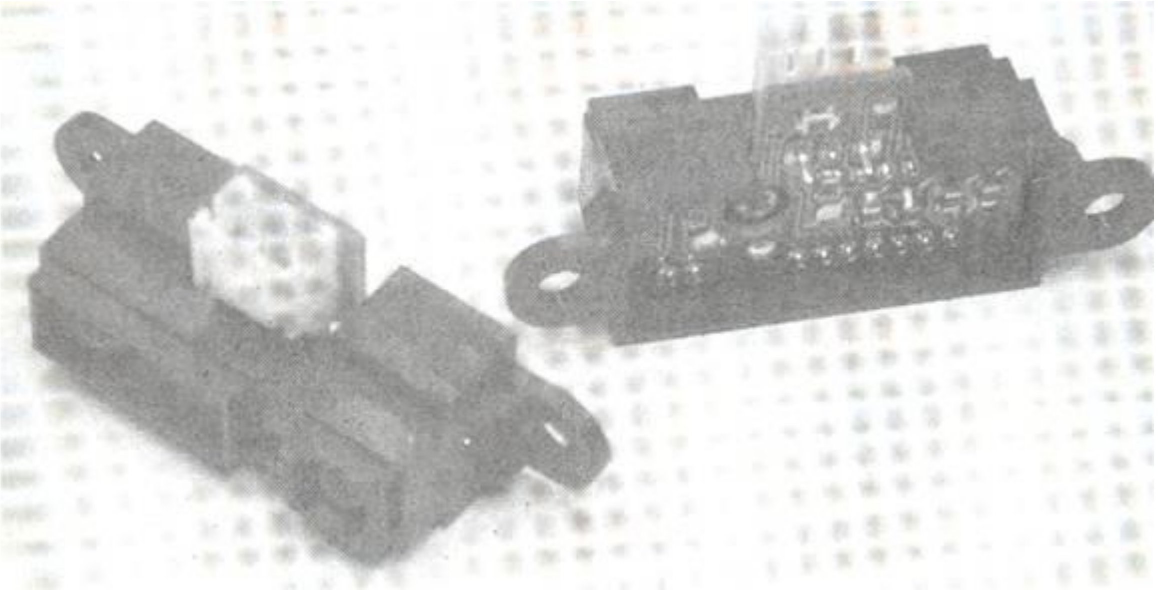
- Triangulation to determine position
- Close-up range ($8 - 80\ \mathrm{cm}$)
- High precision and resolution



$$D = f\,\frac{L}{x}$$

1D Distance Measuring

- Reflected light is absorbed by PSD or 1D CCD-camera
- Distance is proportional to $1/x$
- f = focal length

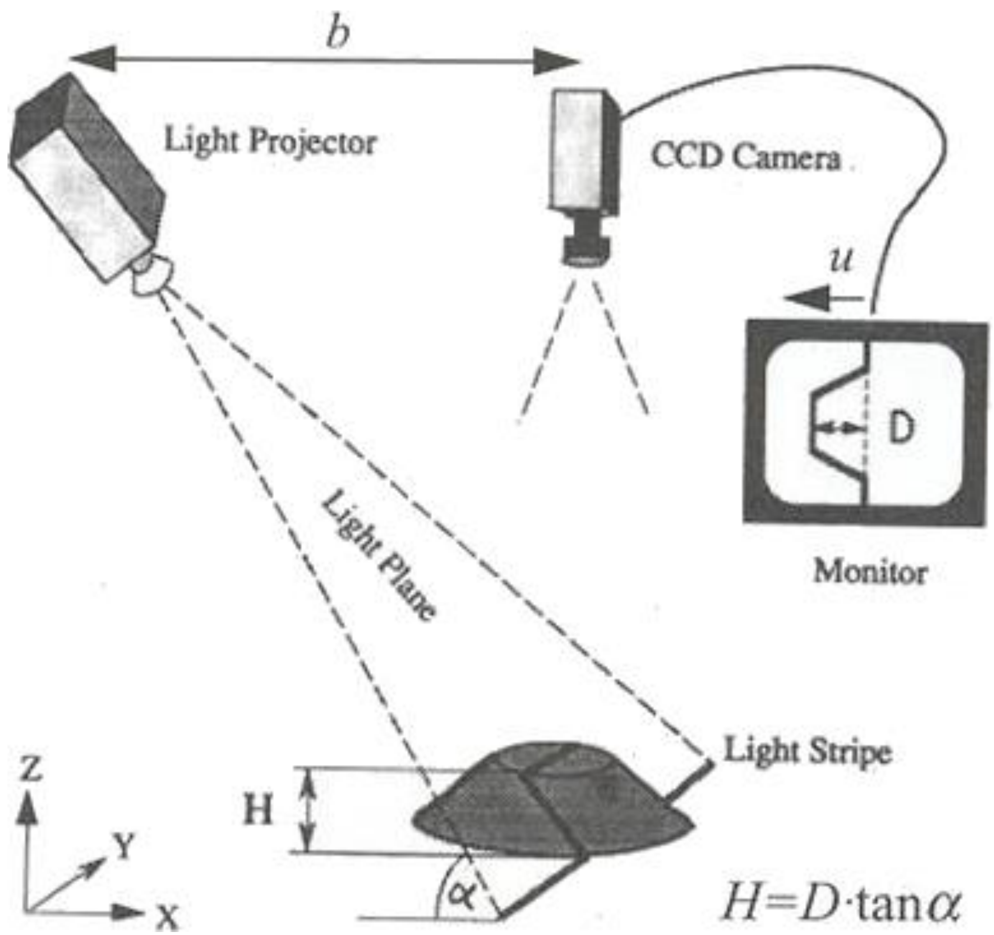


Sharp infrared sensor

Structured Light

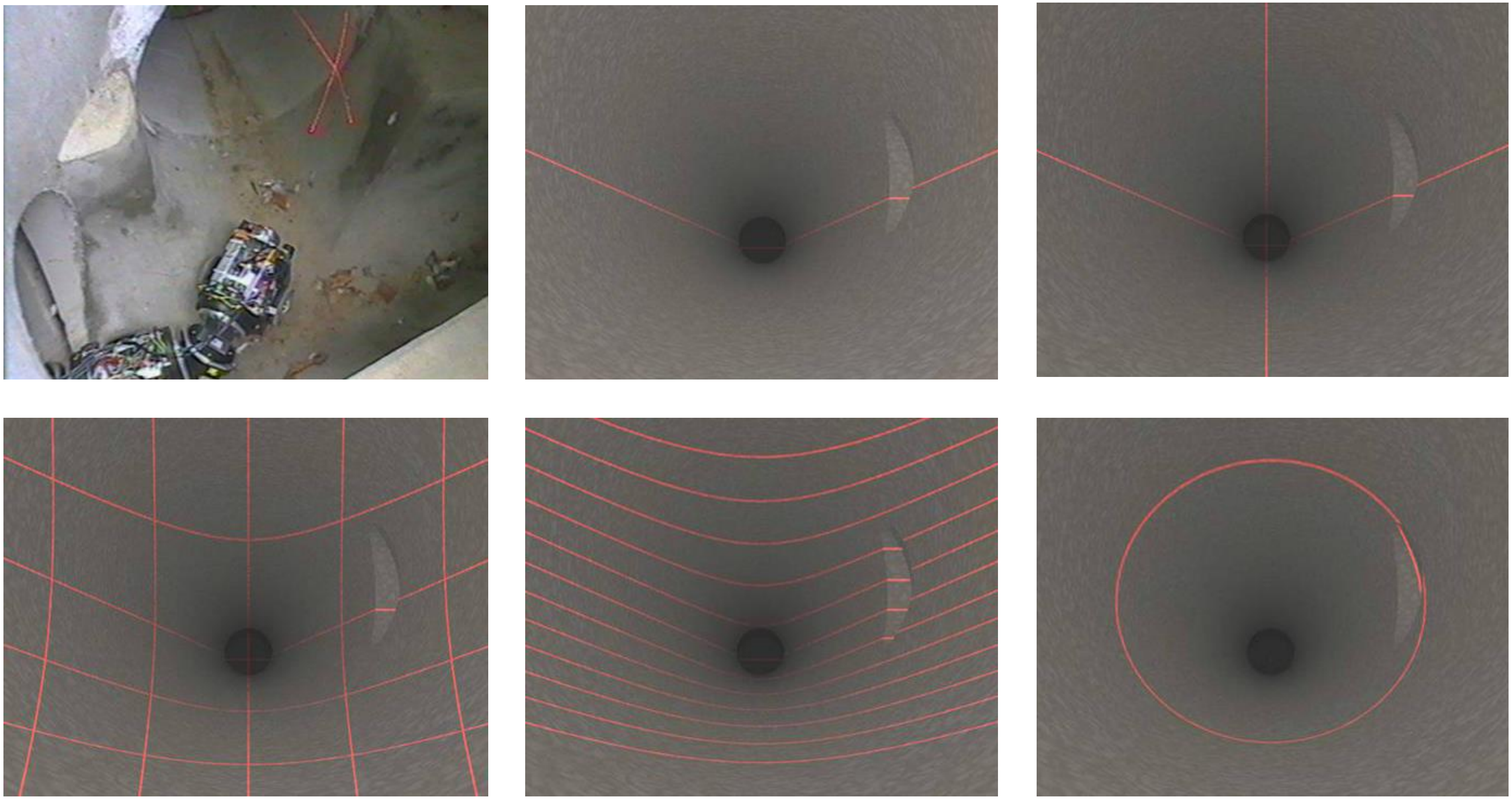
$$x = \frac{bu}{f \cdot \cot\alpha - u}$$

$$y = \frac{bf}{f \cdot \cot\alpha - u}$$



Basic setup to use structured light as surface sensor

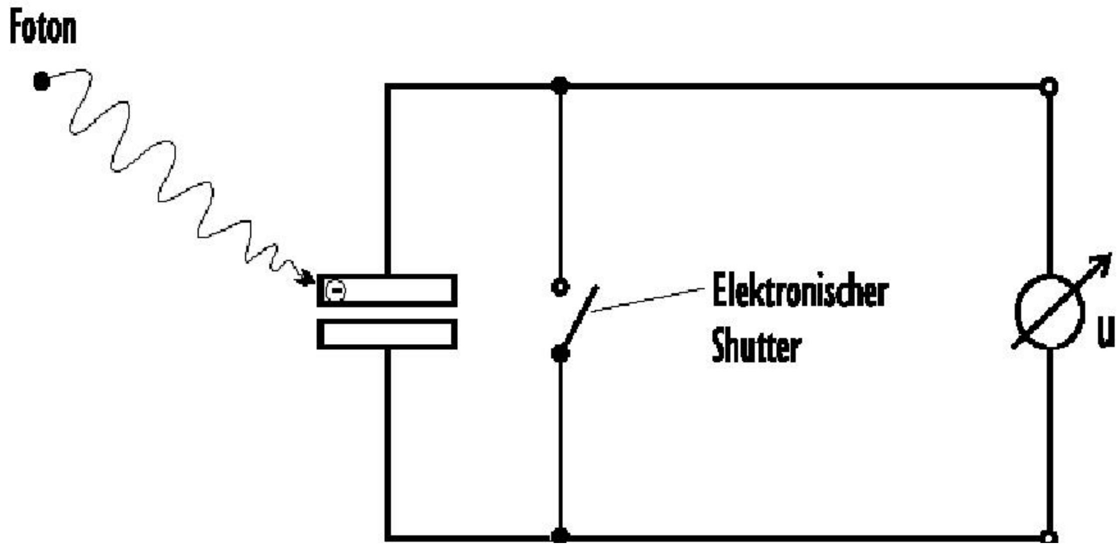
Structured Light for Sewer Inspection



Vision Sensors

CCD Cameras

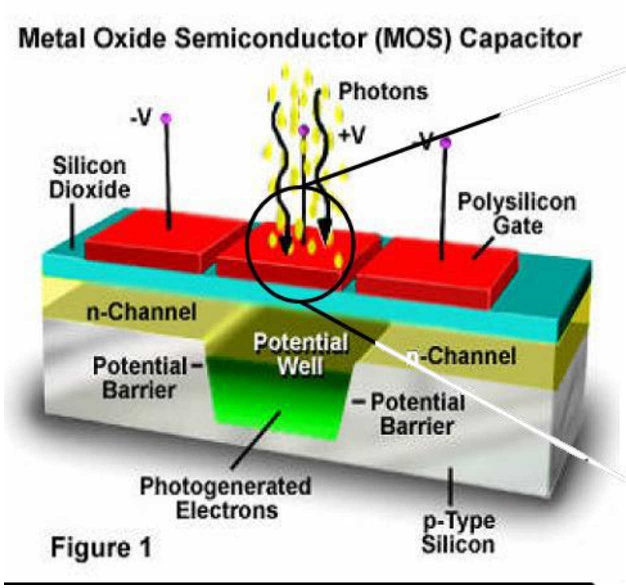
- Photon beam induce charge, that is collected over a fixed period of time
- Electric Shutter exposure time
- Low noise level

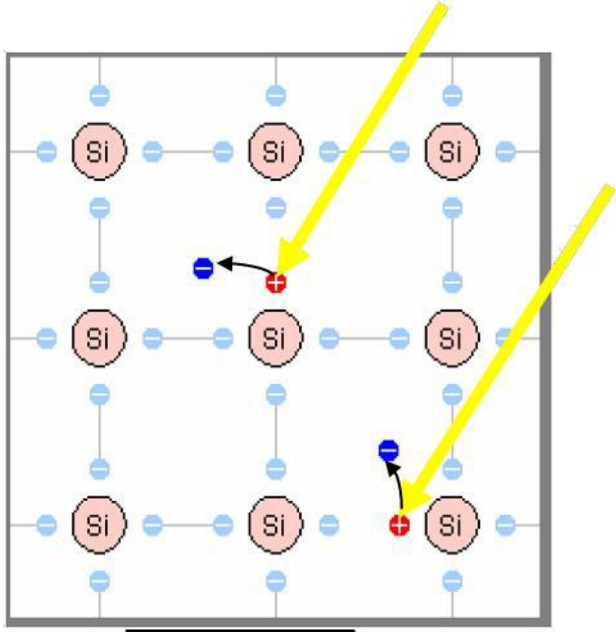


Working principle of CCD camera

Working Principle of CCD Cameras

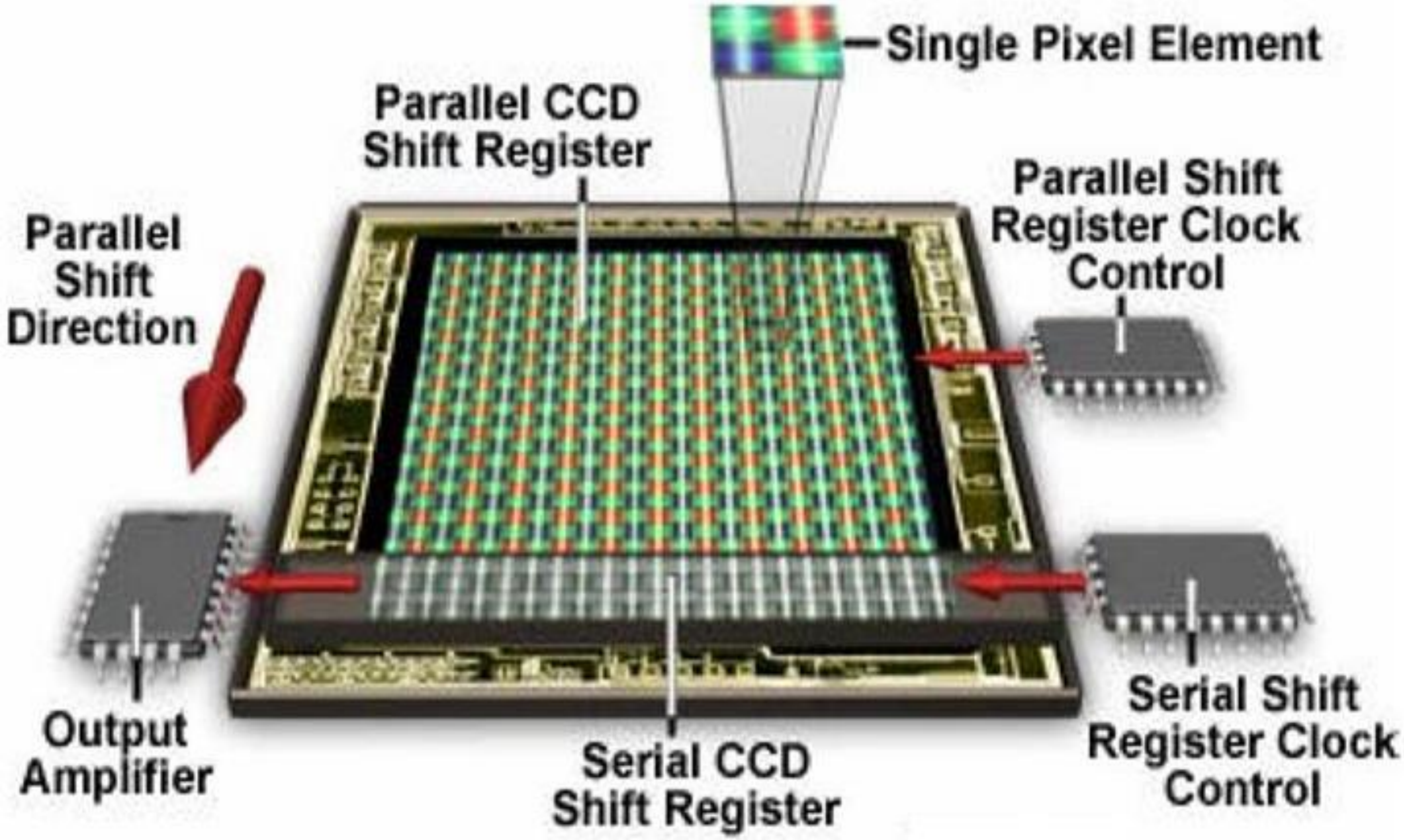
- Basis of semiconductor cameras: “inner photoelectric effect”
- Through stimulation (light) electrons are lifted from the valence band (bound) to the conduction band (free charge carriers)
- Free electrons are gathered in a charge pool





Working principle of CCD cameras

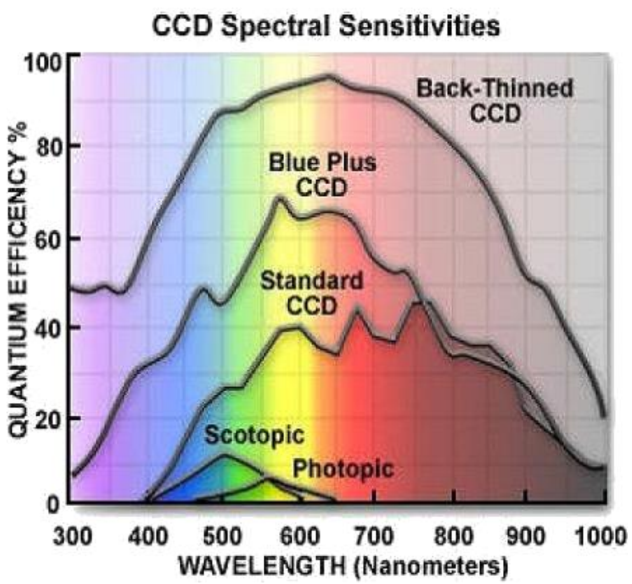
Readout of CCD Chips

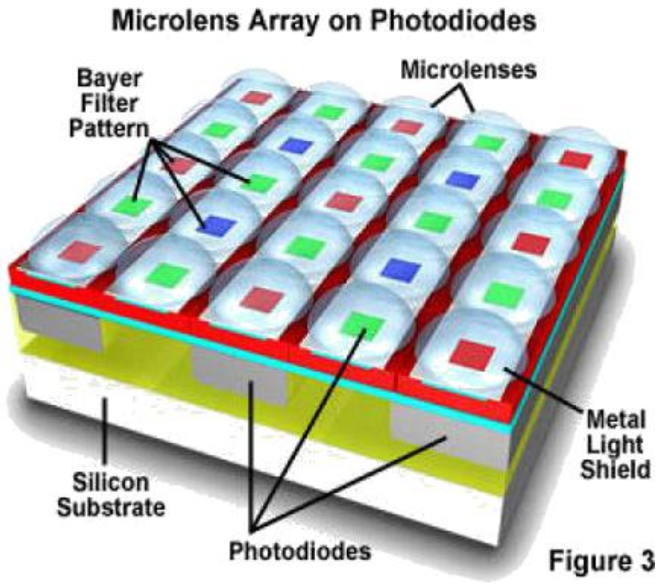


CCD Sensor

Color

- CCD Chips are sensitive to the complete visible spectrum, but especially to red light
- Color images through application of RGB-filters and following combination of 4 photo diodes for 1 pixel
- Micro lenses increase light efficiency

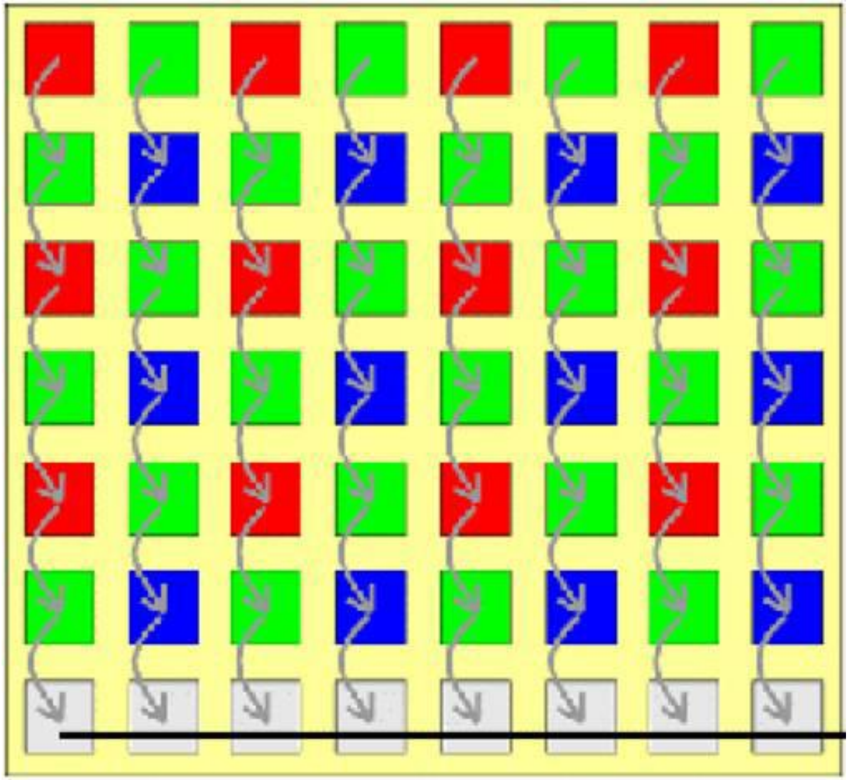




Color capturing basics

Color

- Photo diodes just store charge
- Evaluation is performed by a output amplifier per column
- Charge is transported there by “shifts”
- Pixels not individually addressable
- Single amplifier, compact design



Schematics of CCD chip surface

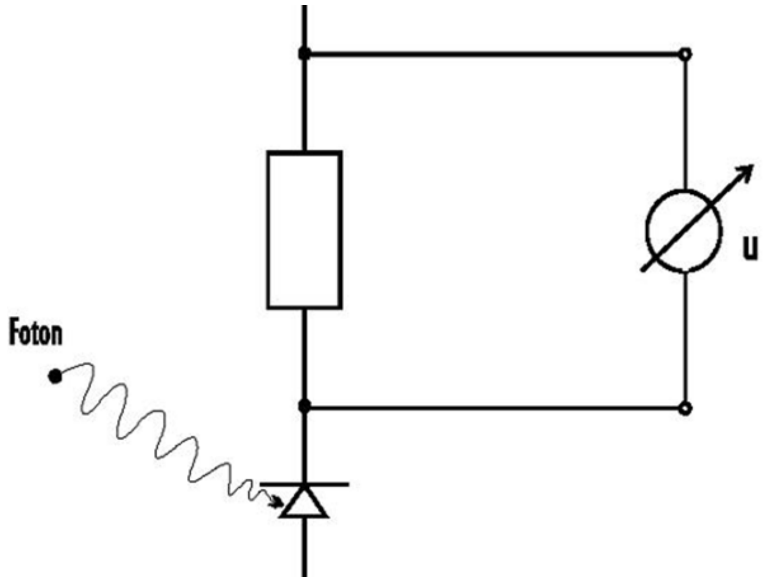
Blooming

- During integration of charge the charge pool may be flooded ⇒ "blooming"
- Effects nearby pixels
- Effects diodes in current column
- Avoidance of Blooming
- "drain canals" on the chip
- Reduction of exposure time
- Reduction of shutter opening

Examples of blooming effects

CMOS Cameras

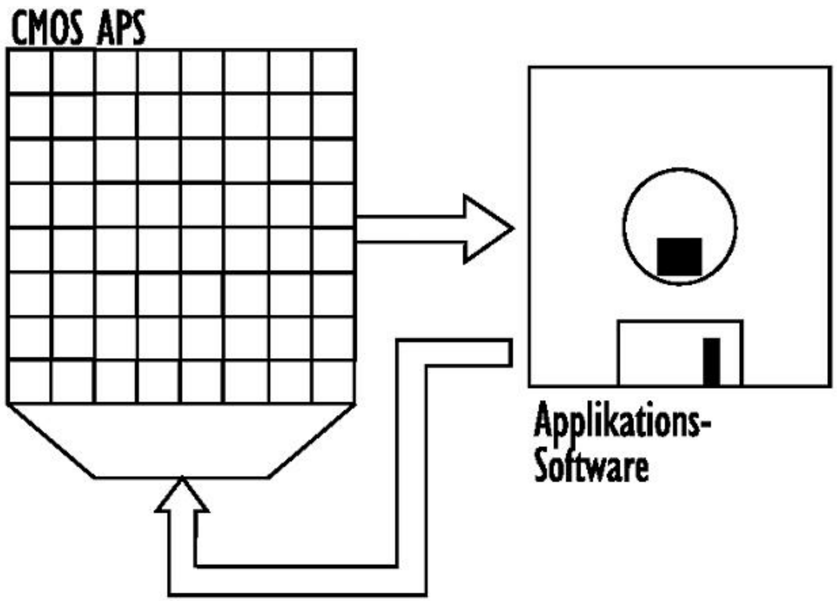
- Photo diode serial to resistor
- Continuous conversion of the photon beam into output voltage
- Severe noise



Measuring principle of a CMOS camera

CMOS Cameras

- Direct access to single pixel with $5\ \mathrm{MHz}$
- Example: $500\ \mathrm{pictures/sec}$ at 100×100 pixel resolution



Data flow of a CMOS camera

Comparison of CCD and CMOS

- Competing technology to CCD: CMOS
- Separate amplifier at each photo element
- No Integration of charge, but continuous transformation

Pros of both technologies in direct comparison:

CMOS

- Small size
- No blooming
- Bigger dynamics

CCD

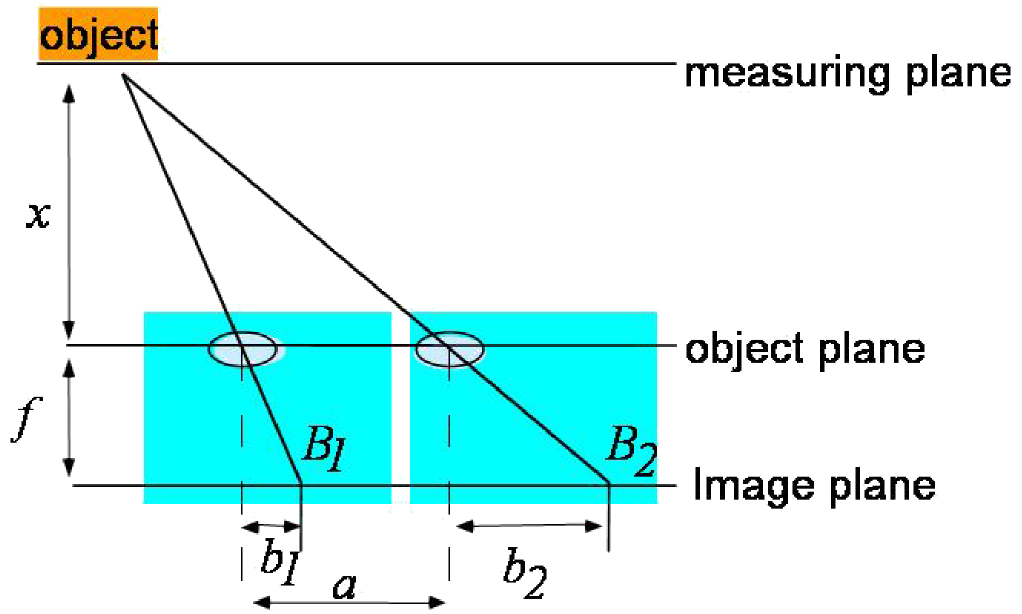
- Higher photo sensitivity
- Higher uniformity
- Less noise

Passive Triangulation

- Object is projected onto the image plane at different coordinates
- Theorem of intersecting lines

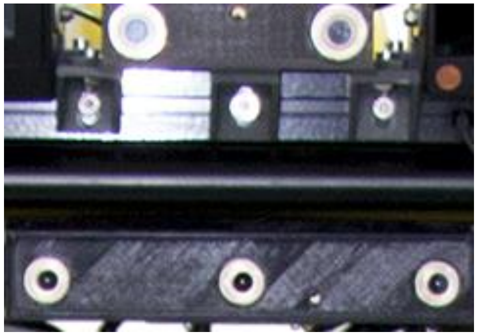
$$x = \frac{a \cdot f}{b_2 - b_1} = \frac{a \cdot f}{\beta}$$

- Focal length f
- Stereoscopic displacement β
- Binocular or trinocular systems



Principle of passive triangulation

Passive Triangulation - Example

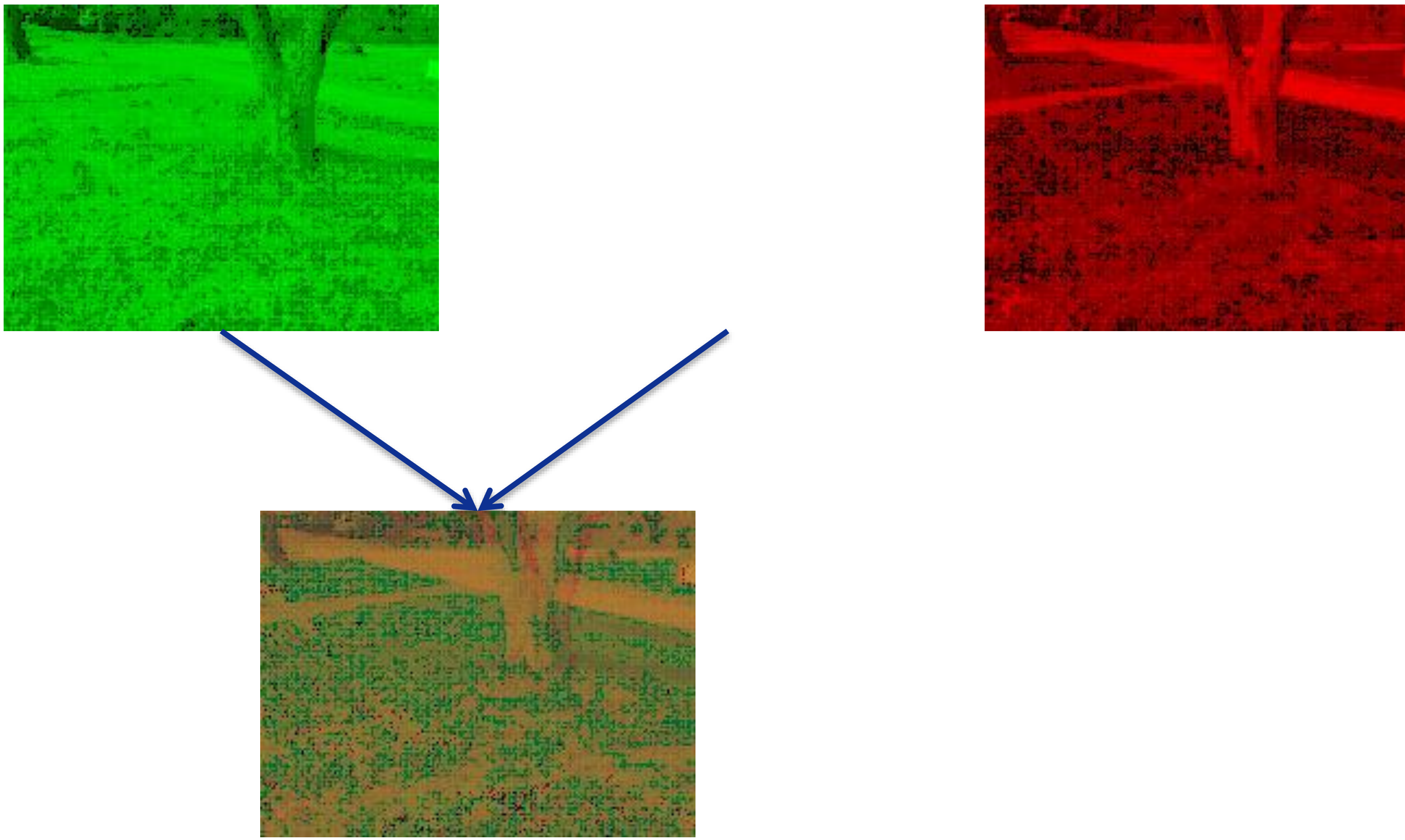


Stereo Camera Bumblebee 2 und 3

Measurement Problems:

- Correspondence: What are the corresponding points in the image plane that characterize the same point?
- Resolution degrades with increasing distance

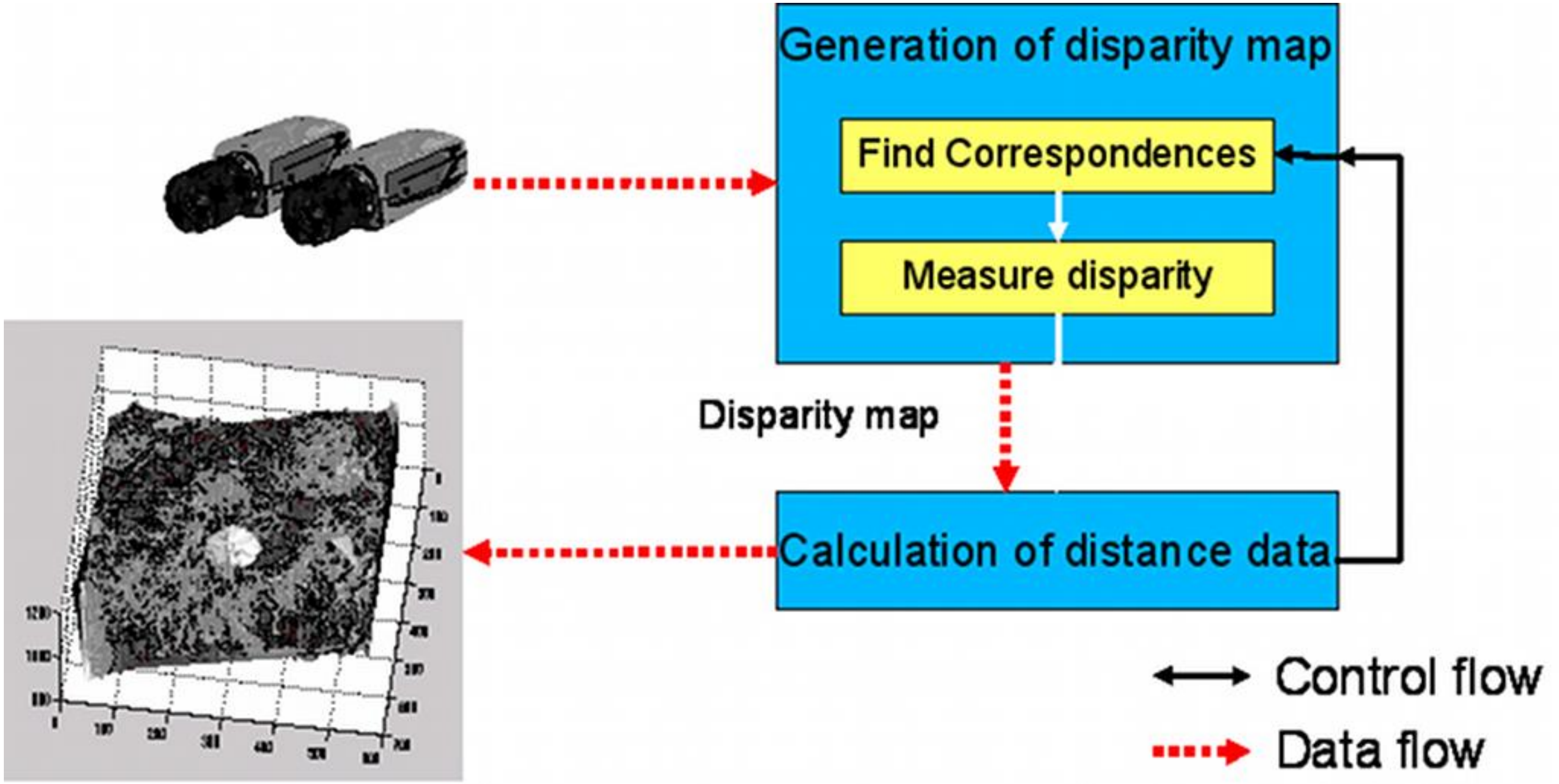
Fundamentals of Stereo Image Processing



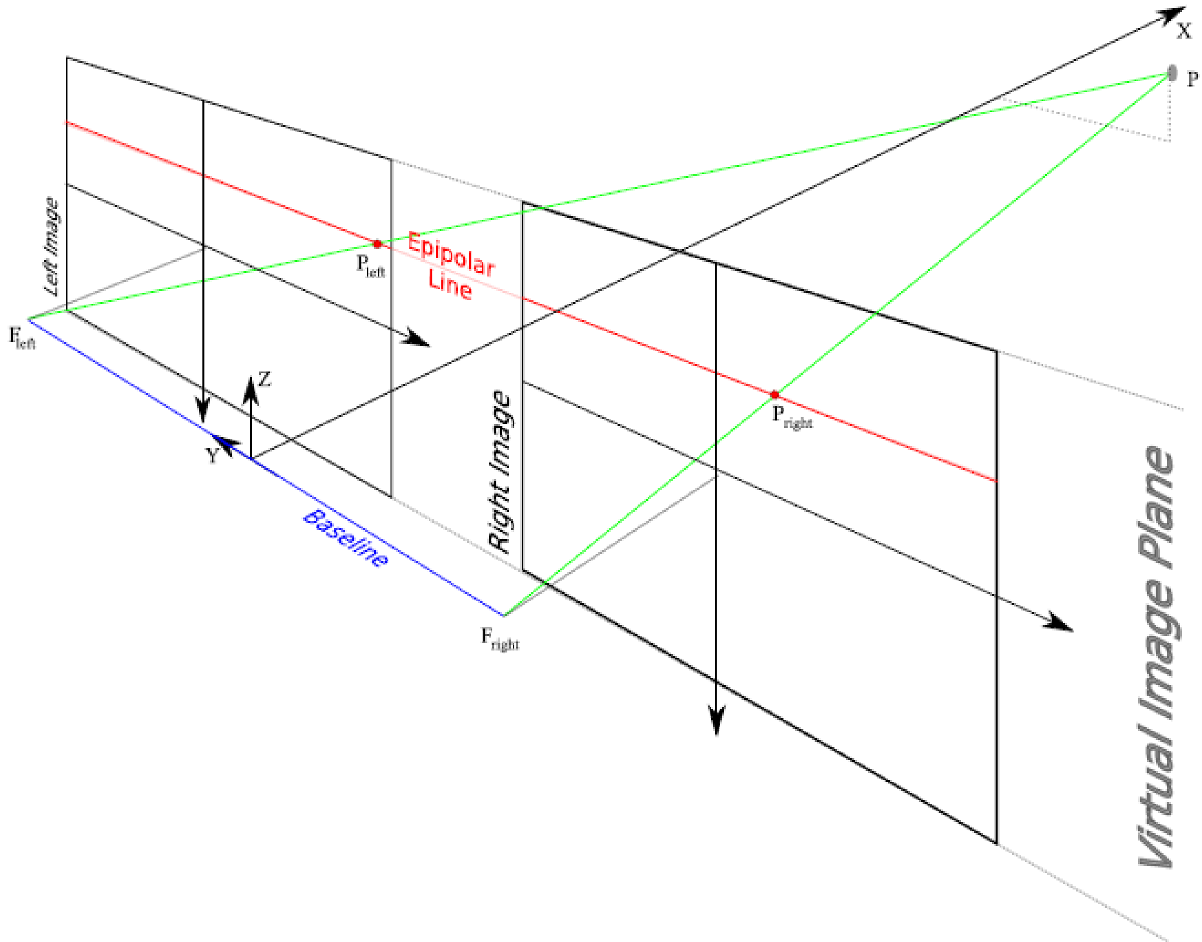
Fundamentals of Stereo Image Processing

- Objects appear in the left image more to the right than in the right picture ⇒ Disparity between pixels representing the same object
- Processing of disparity data allows it to calculate distance
- The closer the object, the bigger the disparity
- 3D reconstruction
  - Geometry must be given
  - Calculation through triangulation

General Approach



Canonical Stereo Geometry



Binocular stereo vision setup

Canonical Stereo Geometry

Definitions

- Baseline: Line connecting the lens centers
- Optical Axis: Line connecting the focal points of a lens system
- Point of origin: Origin of stereo camera coordinates system

Geometry

- The optical axis are parallel to each other
- Baseline is perpendicular to both optical axes
- Monotony of disparity
- Disparity of objects closer to the camera is bigger
- Disparity of objects away from the camera is smaller

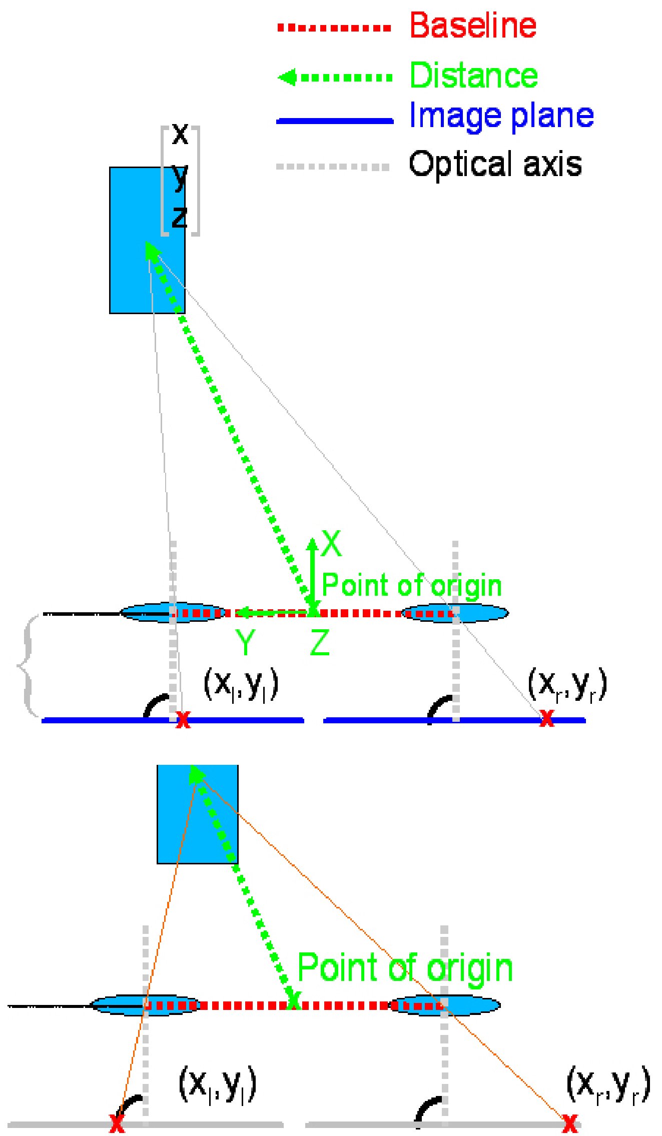
Calculation of Distance Values

- Input: disparity map
- Parameter
  - Focal length f in pixels
  - Length of baseline b
- Formulas

$$x = \frac{b \cdot f}{x_r - x_l}$$

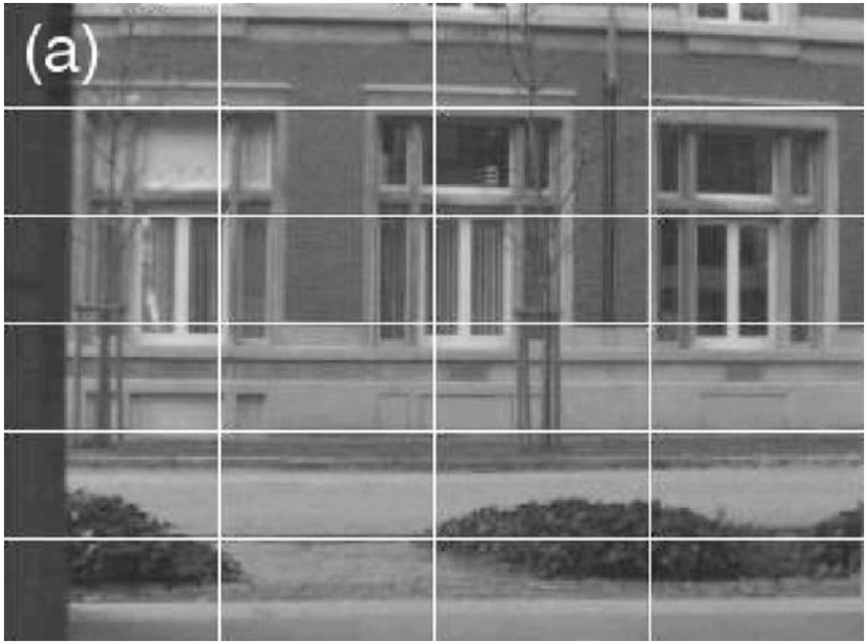
$$y = \frac{b}{2}\frac{(x_l + x_r)}{x_r - x_l}$$

$$z = \frac{b \cdot y_l}{x_r - x_l}$$

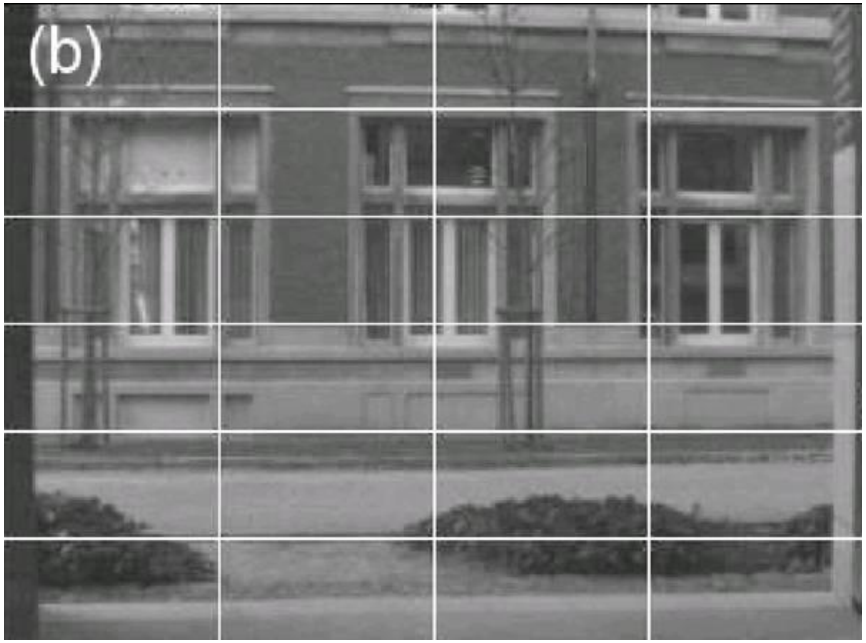


Far and near objects

Epipolar Constraint



Left stereo image



Right stereo image

Epipolar Constraint

- Features of an object in different image planes are located at specific locations
- Canonical case: Epipolar lines (horizontal)
- This assumption reduces the search area tremendously
- In this context disparity is the distance in x-direction of the pixels
- More complex camera constellations imply more complex epipolar structures

Problems: Camera and Stereo Geometry

- Camera distortion (intrinsic and extrinsic)
- Inaccuracies in stereo geometry

Distorted image

Rectified image

Disparity Map Generating Algorithms

Two classes of algorithms for dense disparity

- Window-based approach
- Line-based approach

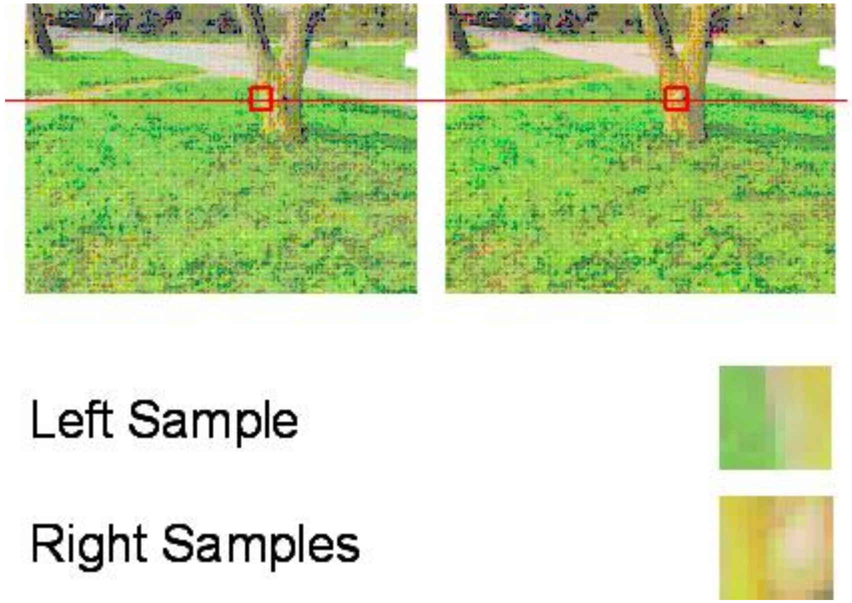
Sparse disparity vs. dense disparity

- Not all pixels are corresponded
- Example: line segment extraction
  ⇒ line segments are corresponded

=> Only dense disparity will be discussed further

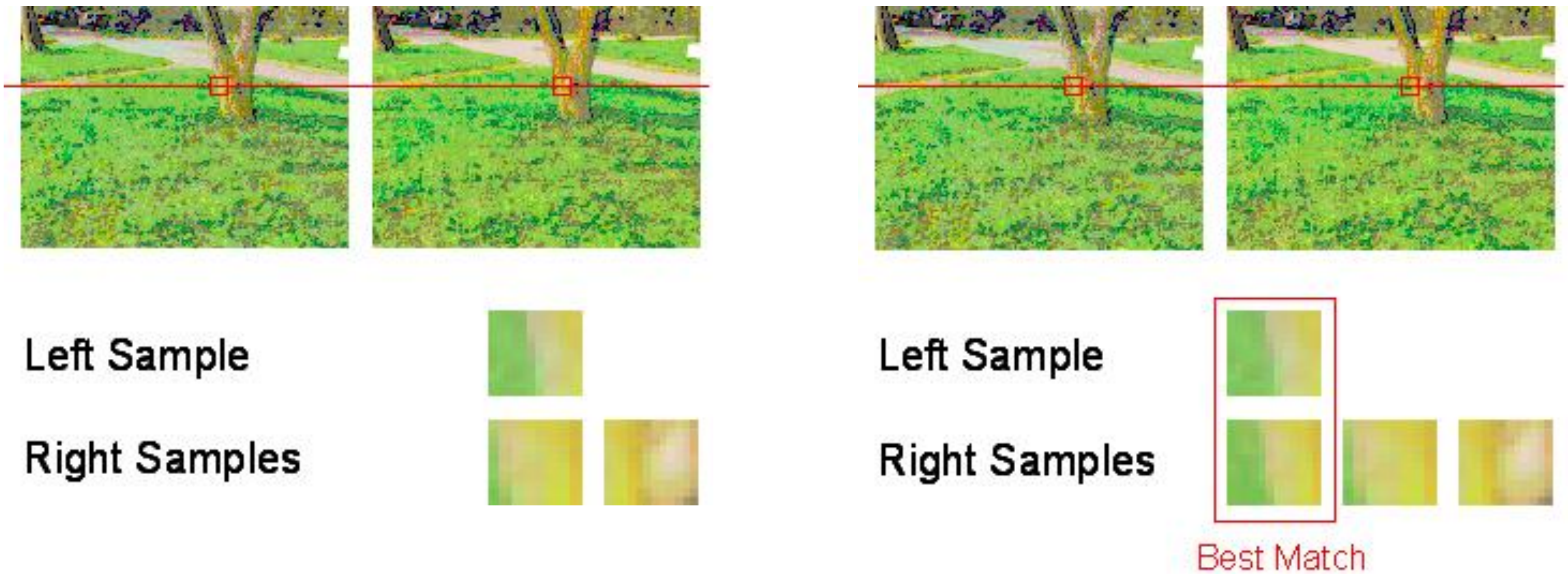
Window-based Approach

- Window is shifted along the epipolar line
- Max. disparity is limited (in general $30 - 50$ px)
- Patches are compared
- Best matches result in disparity values → map
- Variability: degree of similarity (e. g.: Sum of abs. diff.)
- Attempt to find local optimum



Window based approach

Window-based Approach



Window-based Approach

ComputeDisparity $(x, y, \mathrm{left\_img}, \mathrm{right\_img})$

- Search pixel in $\mathrm{right\_img}$ that corresponds with $\mathrm{left\_img(x, y)}$
- The window is slid over the right image from (x, y) to $(x - \mathrm{max\_disp}, y)$
- Best match concerning a suited similarity measure is returned

Common similarity measures

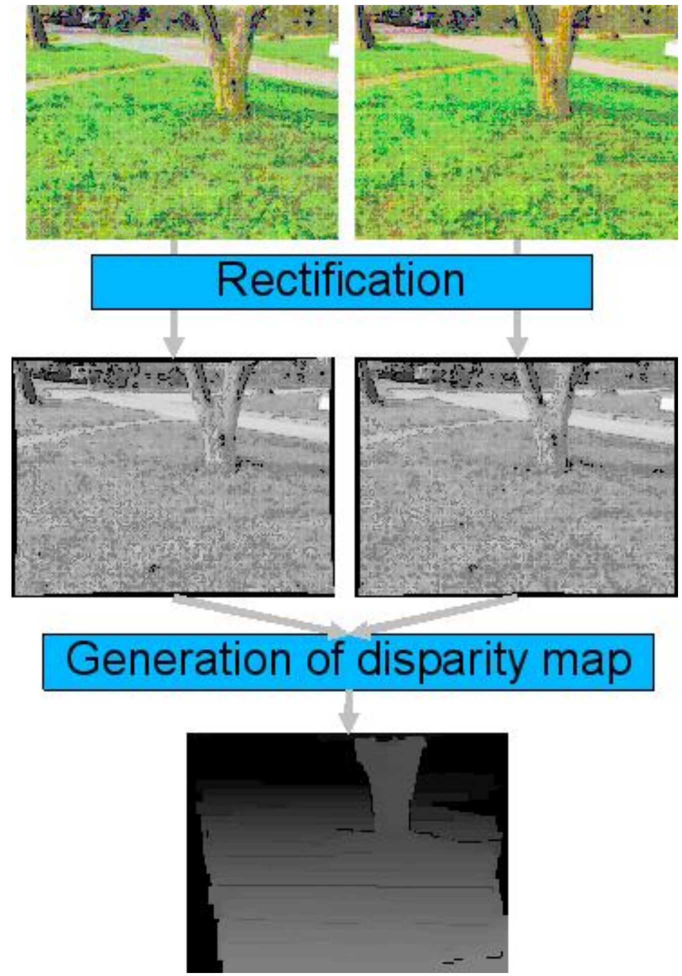
- Sum of absolute differences
- Sum of squared differences
- Correlation

Line-based Approach

- Analysis of paired horizontal (epipolar) scan lines
- Match Sequence: set of pixel pairs
- Scores are computed for several match sequences
  → Possible combinations are limited by max. disparity
- Global optimization attempt (for entire line)

Examplary Generation of Disparity Maps

- Source images
  - Light intensity calibrated
- Rectified images
  - Eliminate distortion effects
  - Compensate inaccuracies of the stereo geometry
- Disparity map
  - Disparity for each Pixel is 8 Bit coded → 0 to 255
  - Bright spots are closer, dark spots farther away



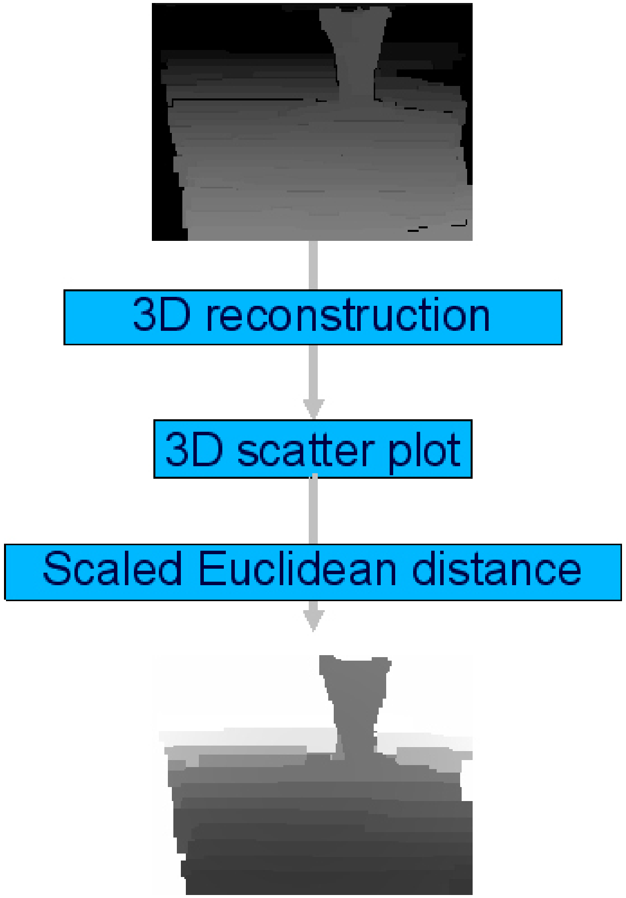
Disparity map generation

Calculation of Distance Values

- 3D reconstruction result in 3D scatter plot
- Calculation of Euclidean distance for each pixel

$$dist = \sqrt{x^2 + y^2 + z^2}$$

- Depth map (intuitive visualization)
  - Distance values are scaled into 8 Bits → 0 to 255
  - Dark spots are closer, bright spots far away from the camera system

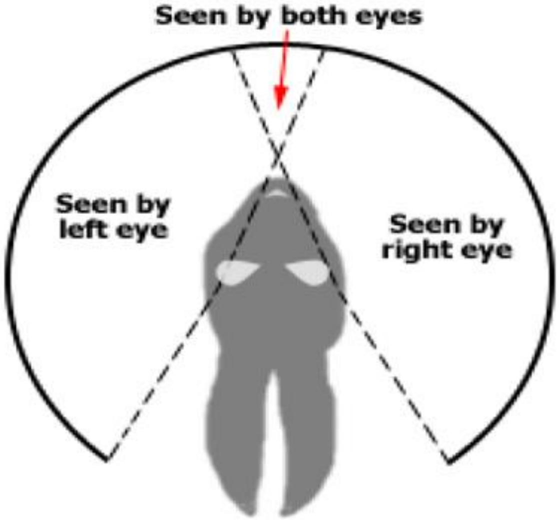


Depth map

Stereo Camera (Point Grey Bumblebee2)

Omnivision

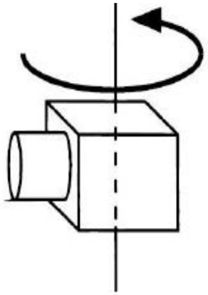
Painting by M.C. Escher



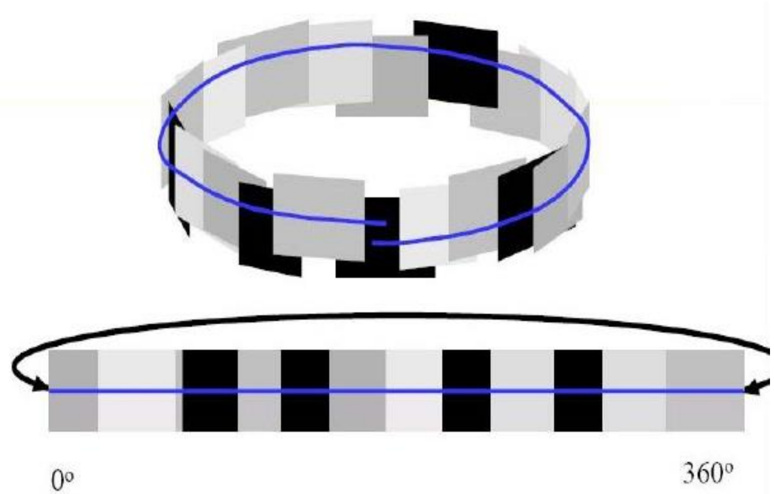
Field of vision in nature

Rotating Camera

- High resolution image
- Single center of projection possible
- Time consuming image processing



Multicamera Systems



Stitched Images

Rotating Camera

Stitched panorama view

Fisheye Lens

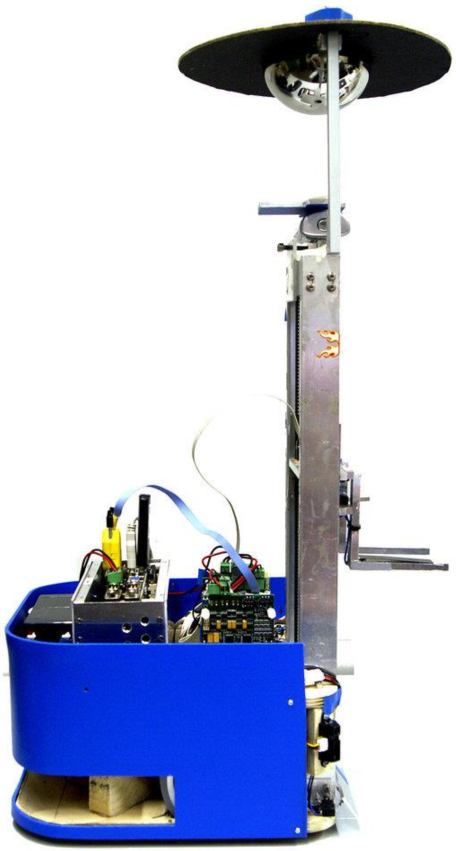
- Hemispherical view
- No single center of projection
- Good resolution in the center
- Poor resolution in the peripheral region

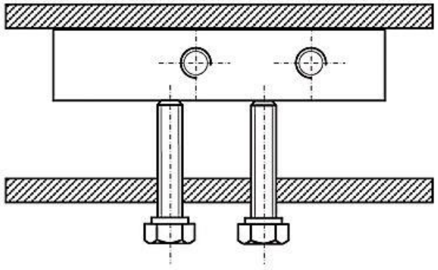
Fisheye lens

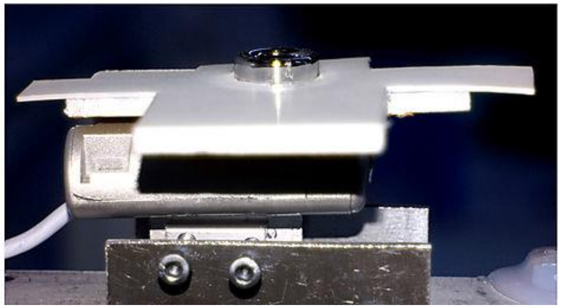
Fisheye Lens

Image taken with a fisheye lens

Applications of Omnivision



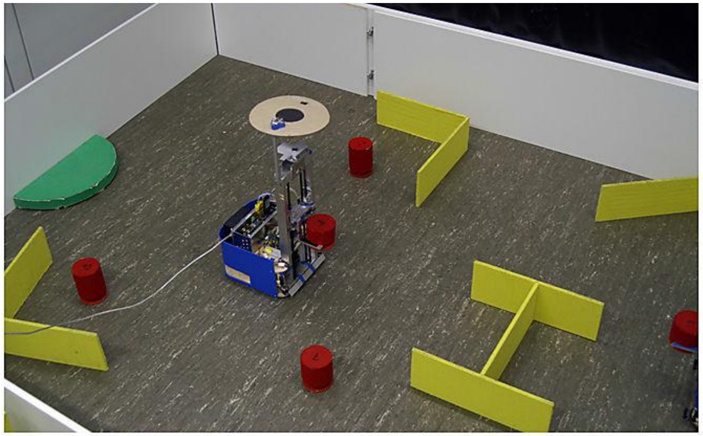


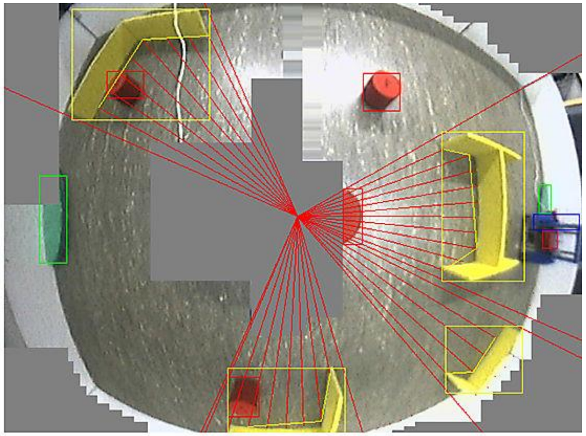


P.R.O.F.I labclass winter term 2006

Forklift robot equipped with Omnivision system

Applications of Omnivision





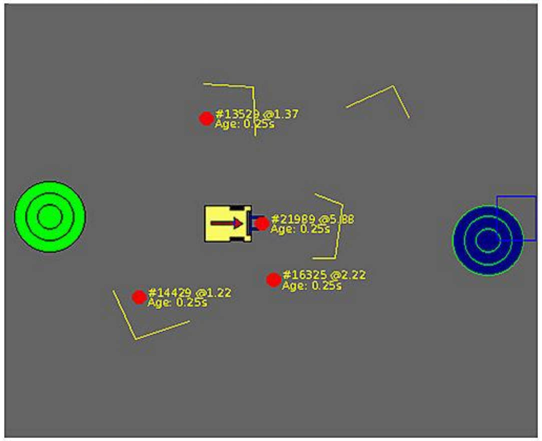


Image processing and object recognition

Coming Next

Modeling