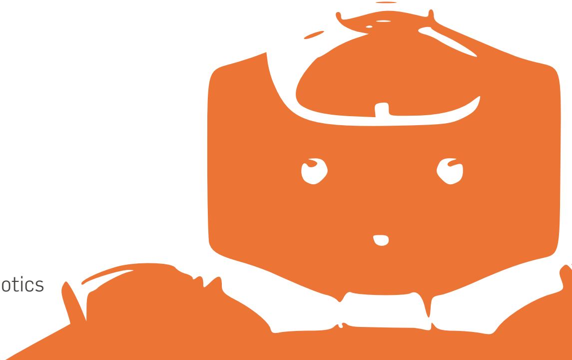
You can download the sources of this presentation here:
github.com/severin-lemaignan/module-mobile-and-humanoid-robots

ROBOTICS WITH PLYMOUTH UNIVERSITY

ROCO318
Mobile and Humanoid Robots
Sensors and Perception



Séverin Lemaignan

Centre for Neural Systems and Robotics
Plymouth University

PART 2 – SENSORS AND PERCEPTION

For further reading see Part C from (Siciliano and Khatib, 2008) or chapter 4 of (Siegwart and Nourbakhsh, 2004).

SENSOR CLASSIFICATION

SENSOR CLASSIFICATION

Proprioceptive sensors

- measure values internally to the system (robot),
- e.g. motor speed, wheel load, heading of the robot, battery status

Exteroceptive sensors

- information from the robots environment
- distances to objects, intensity of the ambient light, unique features.

Passive sensors

- energy coming from the environment

Active sensors

- emit their proper energy and measure the reaction
- better performance, but some influence on envrionment

EXAMPLES OF CLASSIFICATION (1/2)

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

PC: proprioceptive; EC: exteroceptive; A: active; P: passive; A/P: active/passive

EXAMPLES OF CLASSIFICATION (2/2)

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

CHARACTERIZING SENSOR PERFORMANCE

BASIC SENSOR RESPONSE RATINGS (1/2)

- **Dynamic range**: ratio between lower and upper limits, sometimes expressed in decibels (dB, power)

Multiplied by 10 to make the number a bit larger. That's why it's called *deci*Bel.

$$10 \cdot \log_{10} \frac{P_{upper}}{P_{lower}}$$

BASIC SENSOR RESPONSE RATINGS (1/2)

- **Dynamic range**: ratio between lower and upper limits, sometimes expressed in decibels (dB, power)

$$10 \cdot \log_{10} \frac{P_{upper}}{P_{lower}}$$

e.g. current measurement from 1 milliamp to 30 amps

$$20 \cdot \log_{10} \frac{I_{upper}}{I_{lower}} = 20 \cdot \log_{10} \frac{30A}{0.001A} = 90dB$$

20 instead of 10 because square of current or voltage is proportional to power.

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e.g. voltage measurement from 1 millivolt to 20 volts

$$20 \cdot \log_{10} \frac{I_{upper}}{I_{lower}} = 20 \cdot \log_{10} \frac{20V}{0.001V} = 86dB$$

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- **Range**

  upper and lower limits

BASIC SENSOR RESPONSE RATINGS (2/2)

- **Resolution**

  minimum difference between two values
  usually: lower limit of dynamic range = resolution
  for digital sensors it is usually the A/D resolution,
  e.g. $5V/255$ (8 bit)

- **Linearity**

  variation of output signal as function of the input signal
  linearity is less important when signal is after treated with a computer

- **Bandwidth or Frequency**

  the speed with which a sensor can provide a stream of readings
  usually there is an upper limit depending on the sensor and the sampling rate
  Lower limit is also possible, e.g. acceleration sensor

IN SITU SENSOR PERFORMANCE

Characteristics that are especially relevant for real world environments

- **Sensitivity**

  ratio of output change to input change
  in real world environments, the sensor often has a high sensitivity to other environmental changes, e.g. illumination

- **Cross-sensitivity**

  sensitivity to environmental parameters that are orthogonal to the target parameters

- **Error / Accuracy**

  difference between the sensor's output and the true value

$$accuracy = 1 - \underbrace{\frac{|m - v|}{v}}_{= \text{ error}}$$

m: measured value; v: true value

IN SITU SENSOR PERFORMANCE

Systematic error $\Rightarrow$**deterministic** errors

- caused by factors that can (in theory) be modeled $\rightarrow$prediction
- e.g. calibration of a laser sensor or of the distortion caused by the optics of a camera

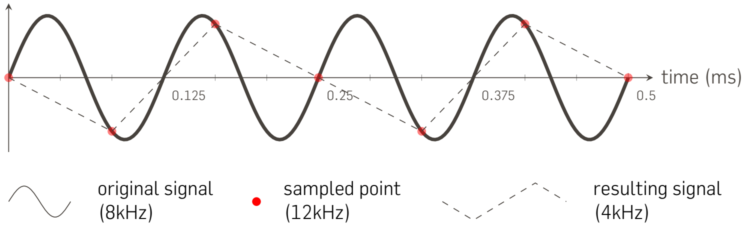
Random error $\Rightarrow$**non-deterministic**

- no prediction possible
- however, they can be described probabilistically
- e.g. hue instability of camera, black level noise of camera...

SAMPLING RATE

Nyquist theorem

- The sampling rate has to be at least **twice as high** as the fastest changes. If not, you are going to miss relevant information.



- e.g. if sound signal changes at 3kHz, you have to sample at at least 6kHz to not miss anything of the signal.

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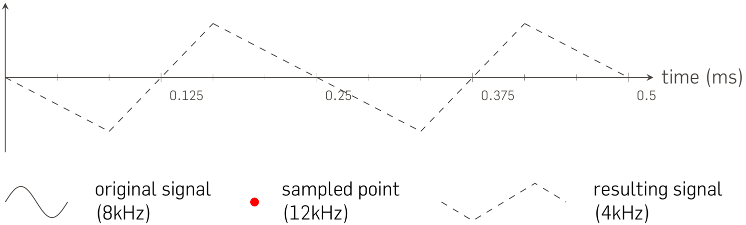

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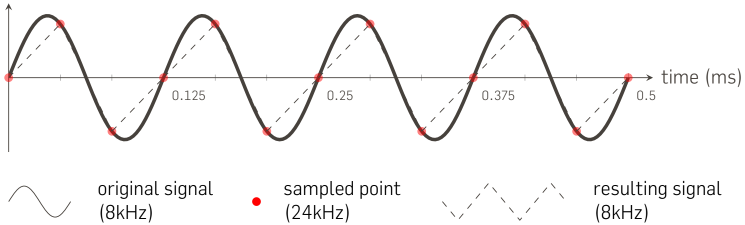

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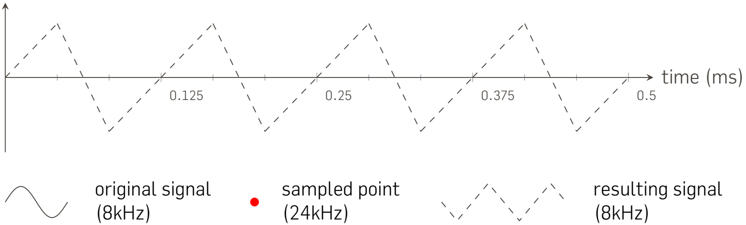

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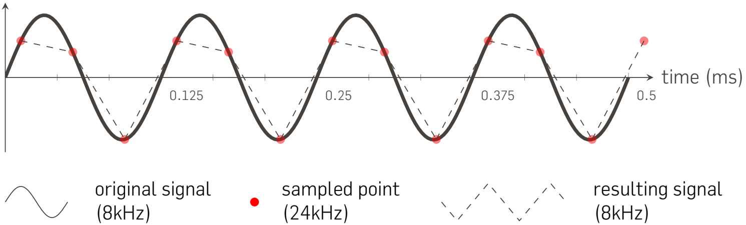

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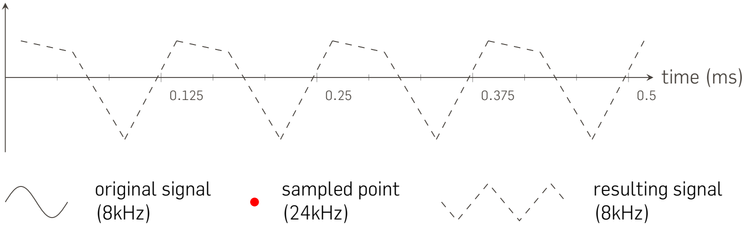

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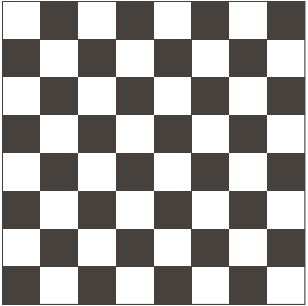
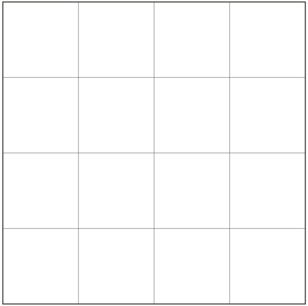
NYQUIST: EXAMPLE



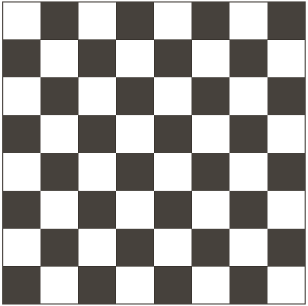
Original



Under sampled

Under sampling results in ***aliasing*** (in computer imaging this is tackled by anti-aliasing).

NYQUIST: EXAMPLE



Original

Under sampled

Under sampling results in ***aliasing*** (in computer imaging this is tackled by anti-aliasing).

CHARACTERIZING ERROR IN MOBILE ROBOTICS

- Mobile Robot has to perceive, analyze and interpret the state of the surrounding
- Measurements in real world environment are dynamically changing and error prone.
- Examples:

  changing illuminations
  specular reflections
  light or sound absorbing surfaces
  cross-sensitivity of robot sensor to robot pose and robot-environment dynamics

  - rarely possible to model $\longrightarrow$appear as random errors
  - systematic errors and random errors might be well defined in controlled environment.
    This is not the case for mobile robots !!

MULTI-MODAL ERROR DISTRIBUTIONS: THE CHALLENGES IN ...

Behavior of sensors modeled by probability distribution (random errors)

- usually very little knowledge about the causes of random errors
- often probability distribution is assumed to be symmetric or even Gaussian
- however, it is important to realize how wrong this can be!
- Examples:

  Sonar (ultrasonic) sensor might overestimate the distance in real environment and is therefore not symmetric. Thus the sonar sensor might be best modeled by two modes:

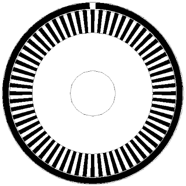
  - mode for the case that the signal returns directly
  - mode for the case that the signals returns after multi-path reflections.

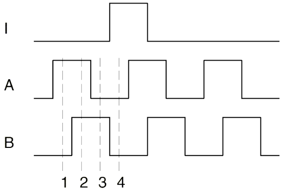
  Stereo vision system might correlate to images incorrectly, thus causing results that make no sense at all.

OVERVIEW OF SENSORS OFTEN USED ON MOBILE ROBOTS

WHEEL / MOTOR ENCODERS

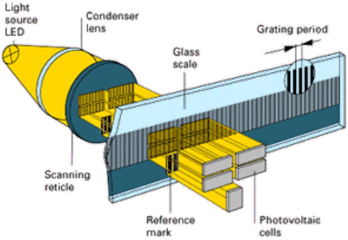
- Measures position or speed of the wheels or steering.
- Wheel movements can be **integrated** to get an estimate of the robots position →**odometry**
- Optical encoders are proprioceptive sensors
  - Due to errors (slippage etc.) the position estimate in relation to a fixed reference frame is only valuable for short movements
- Typical resolutions: 2000 increments per revolution
  - For high resolution: interpolation
- Quadrature encoder (two emittor/detector pairs)
  - Gives direction and 4 times higher resolution.

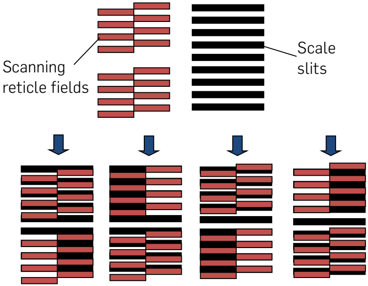




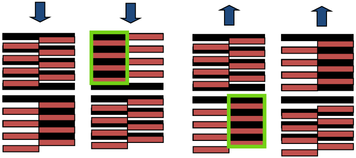
State	Ch A	Ch B
S_1	High	Low
S_2	High	High
S_3	Low	High
S_4	Low	Low

WHEEL / MOTOR ENCODERS





Notice what happens when the direction changes:



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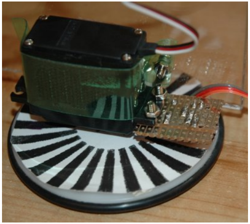
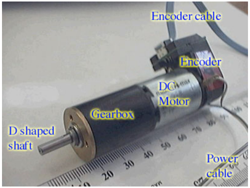


Home-made encoder



Commercial encoder

Absolute encoder disk

HEADING SENSORS

- Heading sensors can be proprioceptive (gyroscope, inclinometer) or exteroceptive (compass).
- Used to determine the robots orientation and inclination.
- Allow, together with an appropriate velocity information, to integrate the movement to an position estimate. This procedure is called **dead reckoning** (from ship navigation).

COMPASS

Since over 2000 B.C., when Chinese suspended a piece of naturally magnetite from a silk thread and used it to guide a chariot over land.

Magnetic field on earth: **absolute measure for orientation**

Large variety of solutions to measure the earth magnetic field:

- mechanical magnetic compass
- direct measure of the magnetic field (Hall-effect, magnetoresistive sensors)

Major drawbacks:

- weakness of the earth field
- easily disturbed by magnetic objects or other sources
- not feasible for indoor environments

COMPASS

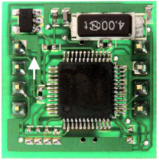
Solid state compass, e.g. Honeywell HMR3100:

Features

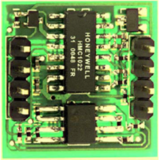
- 5° Heading Accuracy, 0.5° Resolution
- 2-axis Capability
- Small Size (19mm x 19mm x 4.5mm), Light Weight
- Advanced Hard Iron Calibration Routine for Stray Fields and Ferrous Objects
- 0° to 70°C Operating Temperature Range
- 2.6 to 5 volt DC Single Supply Operation

General Description

The Honeywell HMR3100 is a low cost, two-axis electronic compassing solution used to derive heading output. Honeywell's magnetoresistive sensors are utilized to provide the reliability and accuracy of these small, solid state compass designs. The HMR3100 communicates through binary data and ASCII characters at four selectable baud rates of 2400, 4800, 9600, or 19200. This compass solution is easily integrated into systems using a simple USART interface.



Top Side



Bottom Side

http://datasheet.digchip.com/197/197-01540-0-HMR3100.pdf

GYROSCOPE

Reports an acceleration of rotation to a **relative frame of reference**.

Unlike a compass! that keeps the orientation to a fixed frame: reference to an absolute frame of reference.

GYROSCOPE

Reports an acceleration of rotation to a **relative frame of reference**.

Unlike a compass! that keeps the orientation to a fixed frame: reference to an absolute frame of reference.

Two categories, the mechanical and the optical gyroscopes

Mechanical Gyroscopes

- Standard gyro
- Rated gyro

Optical Gyroscopes

- Rated gyro

MECHANICAL GYROSCOPES

Concept: inertial properties of a fast spinning rotor $\Rightarrow$ **gyroscopic precession**

Angular momentum associated with a spinning wheel keeps the axis of the gyroscope inertially stable.

Reactive torque τ (tracking stability) is proportional to the spinning speed ω, the precession speed Ω and the wheels inertia $\mathcal{I}$.

$\mathcal{I} = \int_W r^2 dm$

$$\tau = \mathcal{I} \cdot \omega \cdot \Omega$$

No torque can be transmitted from the outer pivot to the wheel axis: **spinning axis will therefore be space-stable**

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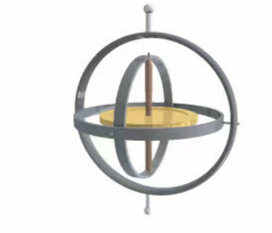
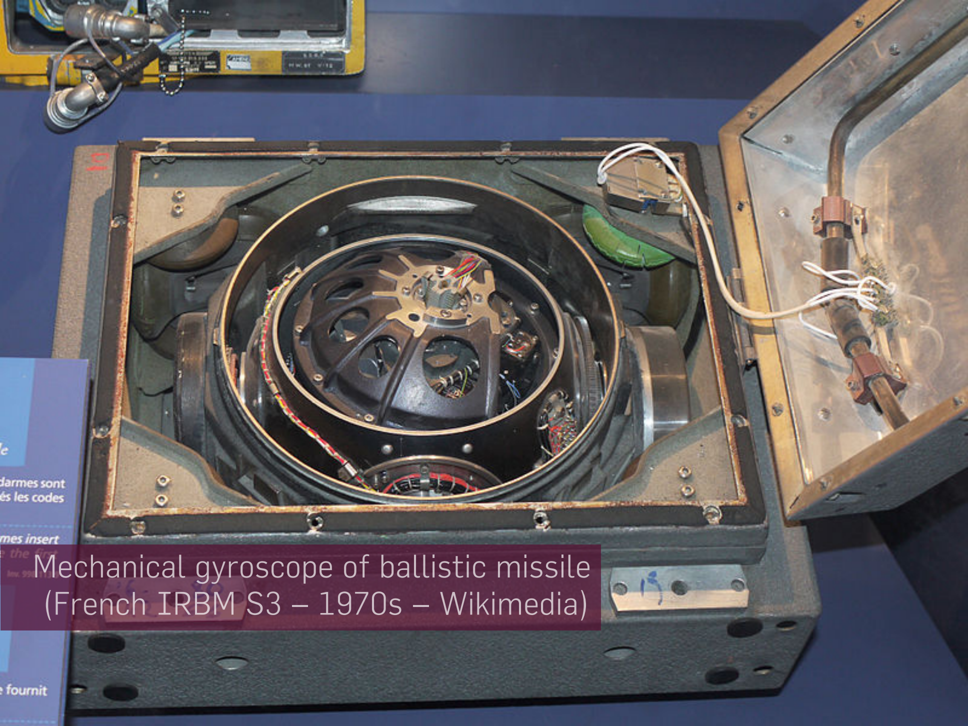


Quality: 0.1° over 6 hours

If the spinning axis is aligned with the north-south meridian, the earth's rotation has no effect on the gyro's horizontal axis

If it points east-west, the horizontal axis reads the earth rotation



Mechanical gyroscope of ballistic missile
(French IRBM S3 – 1970s – Wikimedia)

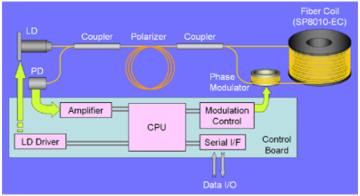
RATE GYROS

Same basic arrangement shown as regular mechanical gyros

But: gimble(s) are restrained by a torsional spring

enables to measure angular speeds instead of the orientation.

OPTICAL GYROSCOPES



Hitachi fibre optical gyroscope

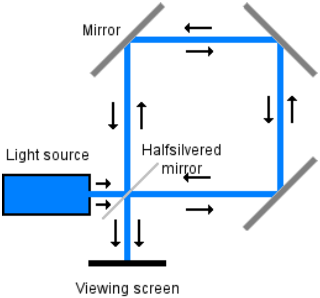
First commercial use started only in the early 1980 when they where first installed in airplanes.

Optical gyroscopes sensitive to only one plane. Report **angular speed** instead of absolute orientation.

OPTICAL GYROS: SAGNAC EFFECT

A beam of light is split, both beams follow a trajectory in opposite directions.

One is traveling in a fiber clockwise, the other counterclockwise around a cylinder (older setups use a ring of mirrors).

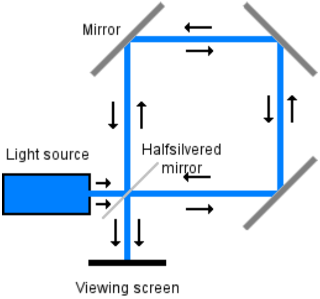


OPTICAL GYROS: SAGNAC EFFECT

Laser beam traveling in direction of rotation

- slightly shorter path →shows a higher frequency
- difference in frequency D_f of the two beams is proportional to the angular velocity ω of the cylinder

On return to the point of entry both beams form an **interference pattern**. Rotating the apparatus results in a **changing interference pattern**.



VIBRATING STRUCTURE GYROSCOPES

A small vibrating element replaces the spinning wheel.

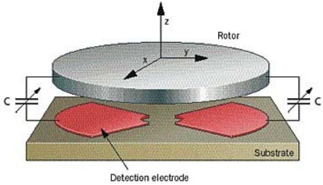
- **Measures angular acceleration** (= rate gyroscope)
- **Small** due to **MEMS** technology (*Micro Electro Mechanical System*): lithographic etching of mechanical structure of mm (or smaller) size.

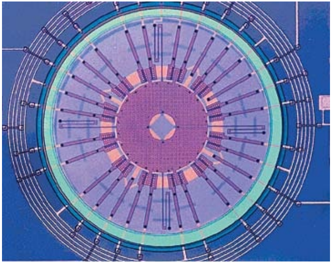
Many different ways of implementing this:

- Vibrating wheel gyroscope
- Piezoelectric element gyroscope
- Tuning forks manufactured using MEMS technology
- ...

VIBRATING WHEEL GYROSCOPE

Relies on gyroscopic effect, but executed in MEMS technology.



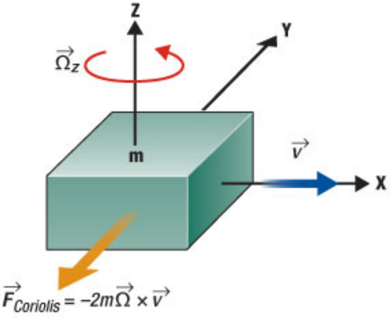


Source: *Quora*

Wheel vibrates (equivalent to rotating), tilt due to gyropscopic effect change detected by change in capacitance

TECHNOLOGY: CORIOLIS EFFECT

Mass m moving in one direction at speed $\vec{v}$, when rotated at speed $\vec{\Omega}$, experiences a **Coriolis** force $\vec{F}_{coriolis}$:



Source: STM

Displacement measured as ***change in capacitance***.

EXAMPLE

STMicroElectronics

- low-power three-axis angular rate sensor
- I2C, SPI
- 70 mdps sensitivity
- Datasheet

In depth information on gyroscopes see **http://ieee-sensors2013.org/sites/ieee-sensors2013.org/files/Serrano_Slides_Gyros2.pdf**

USE OF GYROSCOPES

Most gyroscopes return angular velocity: $\boldsymbol{rad} \cdot \boldsymbol{s}^{-1}$.

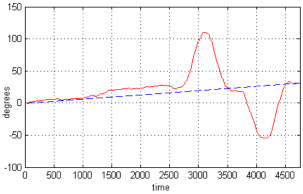
Angular velocity can be converted to angle $\boldsymbol{a}$ (***attitude*** of the gyro) through integrating reading $\dot{\boldsymbol{a}}$ over time:

$$a = \int_0^t \dot{a} dt$$

A variable with a dot on top is that variable at a particular point in time

While classic optical or mechanical gyroscopes do not suffer from drift, MEMS gyroscopes do.

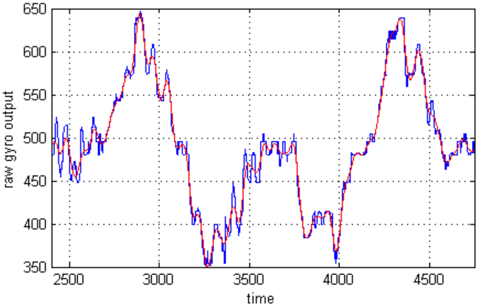
Example, 30° drift over 12 sec!



Source: Tom Pycke

USE OF GYROSCOPES

MEMS gyroscopes are very noisy:



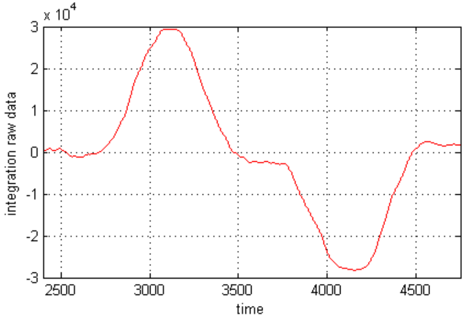
Gyro rotates 90° clockwise and then 90° counter clockwise and back. Blue line is raw output from gyro, red is low pass filtered.

Filtering needed to get rid of noise.

USE OF GYROSCOPES

Runge-Kutta filter, implements a “running average”, smoothing out the noise.

$$a_t = a_{t-1} + \frac{1}{6}(\dot{a}_{t-3} + 2\dot{a}_{t-2} + 2\dot{a}_{t-1} + \dot{a}_t)$$



Source: Tom Pycke

ACCELEROMETERS

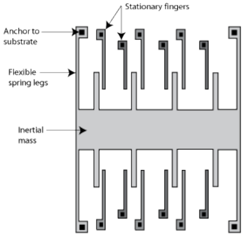
Accelerometers measure acceleration of the device

- Single axis: only measure a in one direction.
- Multi axis: measures in multiple direction, 3 axis is sufficient.
- Measured in $\frac{m}{s^2}$ or in $g = 9.81 \cdot \frac{m}{s^2}$.

Principle: damped mass on a spring; when mass accelerates, displacement is measured and translated to acceleration.

- Modern accelerometers are MEMS
- Displacement is often indirectly measured using capacitive, peizoelectric or piezo resistive sensors.

Crystalline material changes resistance when under pressure



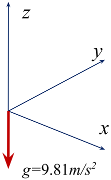
Source: *BYU*

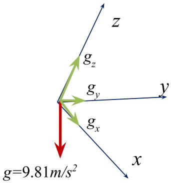
ACCELEROMETER AS TILT SENSOR

An accelerometer always senses the Earth's gravitational vector $\vec{g} = 9.81 \cdot \frac{m}{s^2}$.

As such an accelerometer can be used to **measure rotation**.

- Gravity vector will be sensed on all three axes as $\vec{g_x}, \vec{g_y}, \vec{g_z}$.
- The gravitation vector can be decomposed in three components, which need to vector sum to $\vec{g}$.
- However, it cannot measure rotation around the $\vec{z}$-axis, for that a gyroscope is still needed.

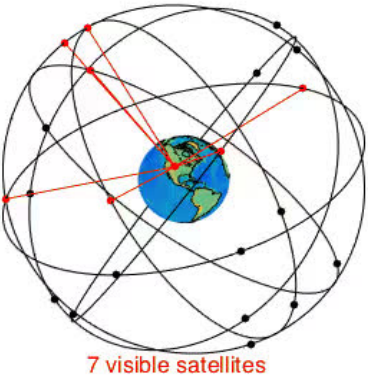




GLOBAL POSITIONING SYSTEM (GPS)

- Developed for military use (since 1978)
- Cost of maintenance estimated at $400M per year
- Recently it became accessible for commercial applications
- 24 satellites (excluding five spares) orbit the earth every 12 hours at a height of 20,190 km
- 4 satellites are located in each of six planes inclined 55° with respect to the plane of the earth's equators
- From any location on the planet at least **4 satellites can be seen**

GLOBAL POSITIONING SYSTEM (GPS)



Source: Wikipedia

GPS - SUMMARY

- Location of any GPS receiver is determined through a **time of flight measurement**
- Two forms of clock information: **Coarse/Acquisition** (C/A) code which is public and **Precise** code which is for military apps. The code also carries the identifier of the satellite.
- Satellites carry **high-precision atomic clocks**, while GPS receivers have low precision crystal oscillator clocks (updated by the atomic clocks)

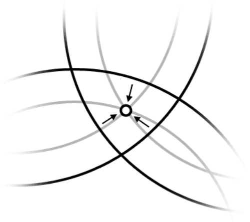
GPS – CALCULATING POSITION

- Suppose the time of flight to three satellites is known: t_1, t_2, t_3.
- The distance to each satellite is $r_i = v_{air} \cdot t_i$
- If the receivers position is (x, y, z), and the satellites position are (x_i, y_i, z_i), the following relations hold:

$$r_i = \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2}$$

GPS – CALCULATING POSITION

Three spheres, intersection results in two solutions for (x, y, z).
One is above the earth's surface, the other below.



GPS – CALCULATING POSITION

A deviation in the receivers clock results an error on the distance to the satellite.

For example, for a satellite at 25,000km from the receiver, ***a 0.1ms deviation between clocks results in an error of 30m in the distance to the satellite***.

GPS – CALCULATING POSITION

Assume the time difference between the atomic clocks and the receiver clock is Δ_t. The distance to the satellites is now erroneously estimated at $r_i = v_{air} \cdot (t_i + \Delta_t)$

Δ_t can be calculated by taking an extra satellite into account.

$$r_1 = \sqrt{(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2} + K \cdot \Delta_t$$

$$r_2 = \sqrt{(x - x_2)^2 + (y - y_2)^2 + (z - z_2)^2} + K \cdot \Delta_t$$

$$r_3 = \sqrt{(x - x_3)^2 + (y - y_3)^2 + (z - z_3)^2} + K \cdot \Delta_t$$

$$r_4 = \sqrt{(x - x_4)^2 + (y - y_4)^2 + (z - z_4)^2} + K \cdot \Delta_t$$

GPS – ACCURACY

With the C/A code, the time of flight can be measured to within 10ns, which is an error of $\approx$ 3m.

Sources of error on the distance to satellite estimate:

- Time of flight measure accuracy: $\pm$ 3m
- Satellite clock errors: $\pm$ 2m
- Ephemeris errors (position of satellites): $\pm$ 2.5m
- Ionospheric effects (signal dispersion): $\pm$ 5m
- Tropospheric effects (dispersion due to humidity): $\pm$ 0.5m
- Multipath distortion (reflections in environment): $\pm$ 1m
- Numerical errors $\pm$ 1m or less

$\Rightarrow$ **typical accuracy is 15m**, but this varies a lot

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GPS - IMPROVEMENTS

L1 and L2 frequency

Same time information is transmitted on two frequencies, these frequencies will experience noise in a different way. Can be used to cancel atmospheric noise.

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Differential GPS (DGPS)

Stationary receiver, with known position, read GPS position and calculate the error. This error is broadcast over an FM band to receiver in the neighbourhood. Accuracy is 1 to 3 meters.

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Satellite Based Augmentation System (SBAS)

Ground based receivers calculate ionospheric delays and clock drift, this is relayed to geosynchronous satellites which then broadcast it to all receivers in its view.

The American FAA has a system which works in the Western hemisphere, called Wide Area Augmentation System (WAAS).

GALILEO

Europe's response to GPS (or GLONASS, the Russian global positioning system).

- 30 spacecraft
- orbital altitude: 23,222 km
- 3 orbital planes, 56° inclination (9 operational satellites and one active spare per orbital plane)
- satellite lifetime: $>$12 years

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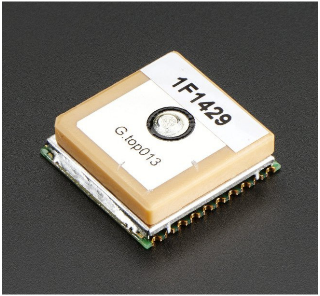
- Free access: 1m accuracy
- Subscription access: up to 10cm accuracy
- Better high altitude positioning

GPS - RECEIVERS

Adafruit GPS Module - MTK3339 chipset



Source: Adafruit

- -165 dBm sensitivity, 10 Hz updates, 66 channels
- Ultra low power usage: 20mA current draw while tracking
- 3.3V operation,
- 16mm x 16mm x 5mm and 4 grams
- ≈ £23

GPS - RECEIVERS

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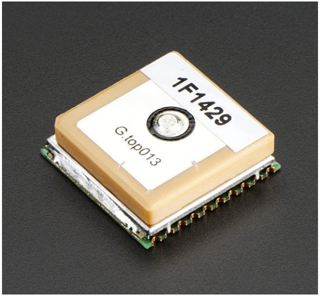

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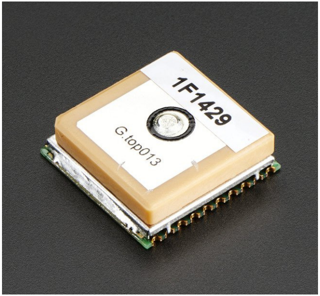
Why 66 channels when only max. 12 satellites are visible?

GPS - RECEIVERS

Adafruit GPS Module - MTK3339 chipset



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- 3.3V operation,
- 16mm x 16mm x 5mm and 4 grams
- $\approx$ £23

Improved correlation time $\rightarrow$ faster acquisition; lower power consumption

GPS – APPLICATIONS IN ROBOTICS

GPS only works **outdoors**

- Due to limited energy (–163 dBw or 5 x 10–17 watts) and high frequency (1.57542 GHz for L1 signal and 1.2276 GHz for L2 signal) of signal, GPS packets do not penetrate buildings.

Limited accuracy

- Accuracy several meters up to tens of meters. Autonomous vehicles will need to rely on other localisation methods.

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Accuracy can be dramatically improved using a local DGPS antenna.

GPS – EXAMPLES

Positioning of outdoor service robots

Source: www.robotera.eu

Agricultural robots

Sowing, weeding, harvesting with cm precision

OTHER RADIO LOCALISATION METHODS

Mainly used in mobile phones and mobile devices

GSM-based triangulation

- Uses strength of GSM signal of different GSM base stations to estimate position
- Works indoors, but accuracy limited to a radius of about 1km

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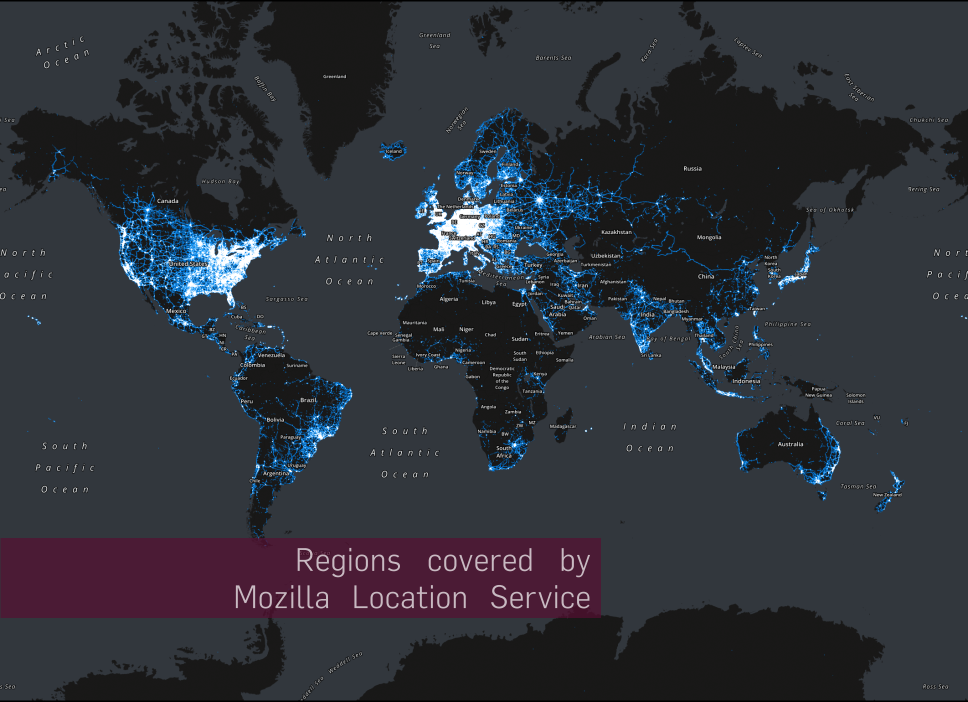
WiFi-based localisation

- Whenever a device connects to a WiFi router, it knows the IP of the router. Some Internet providers know at which address a router is and provide this (*geo-coding*)
- When available, more accurate as range of WiFi router is limited, radius of about 50m.
- Alternatively, positioning via databases that associate unique IDs (MAC addresses) of WiFi routers with their location. For example, Mozilla Location Service



Regions covered by Mozilla Location Service

RANGE SENSORS (TIME OF FLIGHT)

Large range distance measurement →**range sensors**

Range information: key element for **localisation** and **environment modeling**

Ultrasonic sensors as well as laser range sensors make use of propagation speed of sound or electromagnetic waves respectively. The traveled distance of a sound or electromagnetic wave is given by $d = c \cdot t$, where:

- d: distance traveled (usually round-trip)
- c: speed of wave propagation
- t: time of flight

RANGE SENSORS (TIME OF FLIGHT)

It is important to point out that:

- Propagation speed ν of sound: $0.3\frac{m}{ms}$
- Propagation speed ν of of electromagnetic signals: $0.3\frac{m}{ns}$
  $\Rightarrow$ one million times faster

3 meters is:

- 10 ms for an ultrasonic system
- only 10 ns for a laser range sensor

Measuring the time of flight t with electromagnetic signals is **not an easy task**; laser range sensors are expensive and delicate

RANGE SENSORS (TIME OF FLIGHT)

The quality of time of flight range sensors mainly depends on:

- Uncertainties about the exact time of arrival of the reflected signal, due to reflections, multiple echos, ...
- Internal sensor inaccuracies in the time of flight measure (laser range sensors)
- Opening angle of transmitted beam (ultrasonic range sensors)
- Interaction with the target (surface, specular reflections)
- Variation of propagation speed
- Speed of mobile robot and target (if not at standing still)

ULTRASONIC SENSOR (SONAR)

Transmit a packet of (ultrasonic) pressure waves.

The distance ***d*** of the echoing object can be calculated based on the propagation speed of sound ***c*** and the time of flight ***t***:

$$d = \frac{c_{gas} \cdot t}{2}$$

The speed of sound c_{gas} in a gas is given by:

$$c_{gas} = \sqrt{g \cdot R \cdot T}$$

where:

- g: adiabatic index, 1.40 for air
- R: gas constant, 287.053072 $\frac{J}{kg \cdot K}$ for air
- T: temperature in degree Kelvin

ULTRASONIC SENSOR (SONAR)

The speed of sound in air can be approximated by:

$$c_{air} = 331.3\sqrt{1 + \frac{J}{273.15}}$$

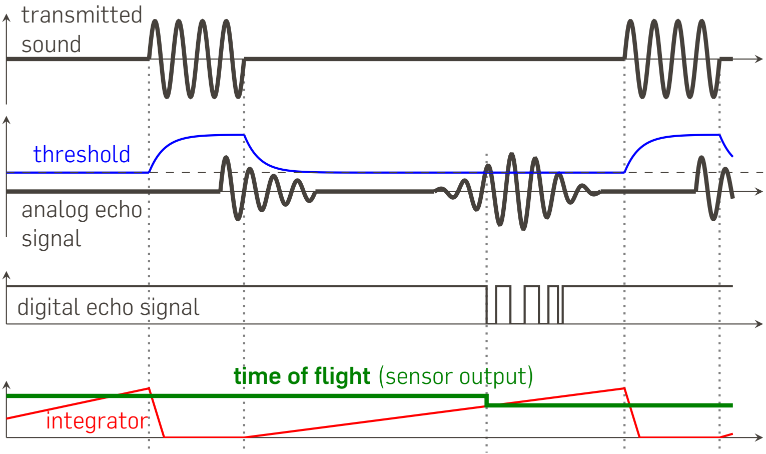
with J the air temperature in Celsius.

If no correction for temperature would be done, what would the error be?

Assume obstacle at 1m, and $T = 15°C$:

T ($°C$)	c	t	**Error (%)**
-10	325.2	0.00615	**4.6**
0	331.3	0.00604	**2.7**
15	340.3	0.00588	**0**
30	349.0	0.00573	**-2.5**

SONAR: SIGNALS



Source: *Autonomous Mobile Robots, p.127*

ULTRASONIC SENSOR PROPERTIES

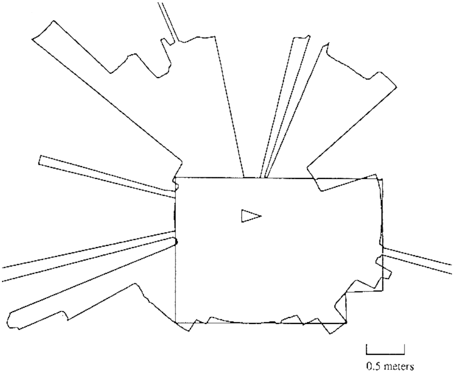
- Typical frequency: **40 – 180 kHz**
- Generation of sound wave: piezo transducer
- Transmitter and receiver: same unit or separate units (for reduced *blanking time*)

Sound beam propagates in a cone-like manner:

- opening angles around 20 to 40 degrees
- acquisition of ***regions of constant depth*** rather than depth points $\rightarrow$ segments of an arc (sphere for 3D)

PROBLEMS WITH REFLECTION

- Soft surfaces absorb most of the acoustic energy
- Surfaces that are far from being perpendicular to the direction of the sound: specular reflection



Source: Autonomous Mobile Robots, p.129

CYCLE TIME OF ULTRASONIC SENSORS

When emitter and receiver are one and the same piece of hardware, the sensor has a **blanking time**.

- Time after the ping in which the sensor is blind
- Close obstacles will be missed

Cycle time is rather low

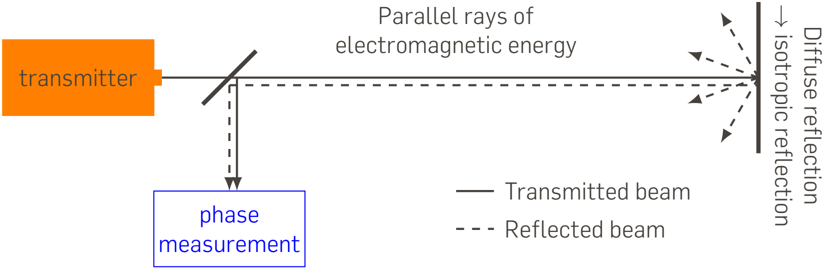
- In a moderately sized room where obstacles are 3m away, the time of flight is about 20ms. The sensor refresh rate is 50Hz.
- However, if a ring of sonar sensors is used, only one sensor at a time can be fired. For example, a 20 sensor ring will only operate at 2.5Hz.

SONAR SENSORS

LV-MaxSonar

- **http://www.maxbotix.com/**
- Detect 0 to 6.5m, range sensing 0.2 to 6.5m
- 42 kHz sonar ping.
- Serial out.
- Free run or triggered.
- $25 - $30

LASER RANGE SENSOR



- Transmitted and received beams coaxial
- Transmitter illuminates a target with a collimated beam
- Receiver detects the time needed for round-trip
- A mechanical mechanism with a mirror sweeps

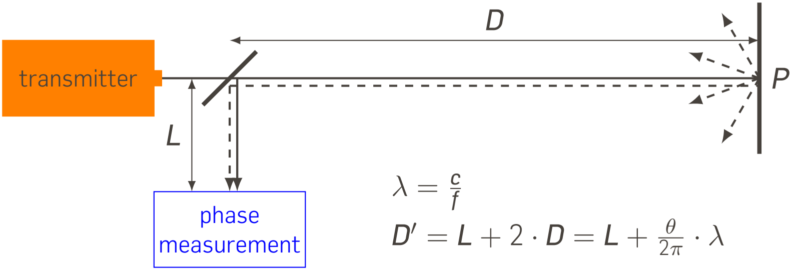
  2D or 3D measurement

MEASURING TIME OF FLIGHT: PHASE-SHIFT MEASUREMENT

- *Pulsed laser*: same principle as ultrasonic sonar
- measurement of elapsed time directly
- **need to resolve picoseconds!** $\rightarrow$expensive hardware.

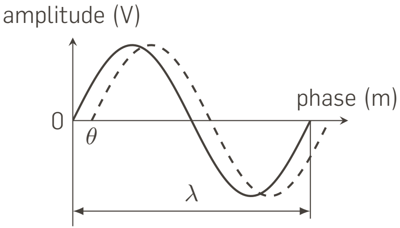
- *Indirect measure*: the time of flight measured using a **phase shift** measurement to produce range estimation.
- technically easier than the above two methods.

MEASURING TIME OF FLIGHT: PHASE-SHIFT MEASUREMENT



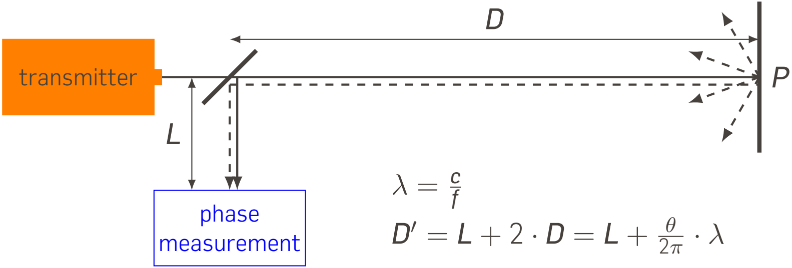
$$\lambda = \frac{c}{f}$$

$$D' = L + 2 \cdot D = L + \frac{\theta}{2\pi} \cdot \lambda$$



where c is the speed of light; f the modulating frequency; D' the total distance covered by the emitted light; θ the (measured) phase shift.

MEASURING TIME OF FLIGHT: PHASE-SHIFT MEASUREMENT



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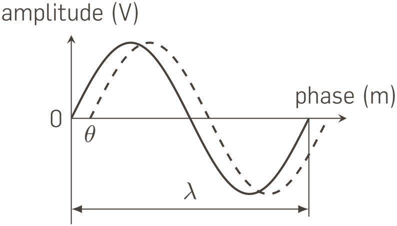
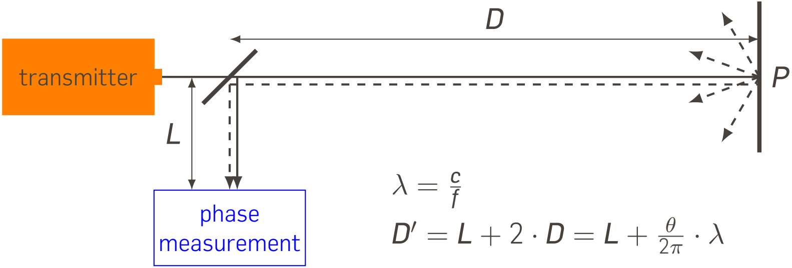


$$\Rightarrow D = \frac{\lambda}{4\pi}\theta$$

MEASURING TIME OF FLIGHT: PHASE-SHIFT MEASUREMENT



$$\lambda = \frac{c}{f}$$

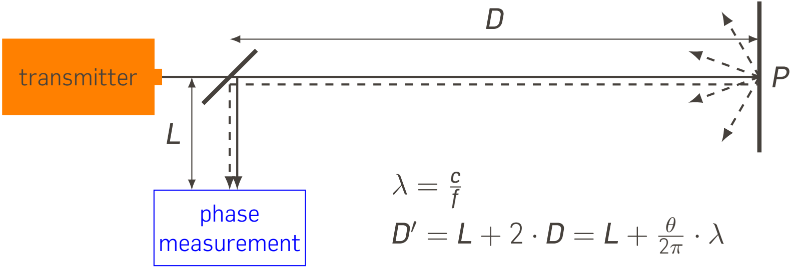
$$D' = L + 2 \cdot D = L + \frac{\theta}{2\pi} \cdot \lambda$$

For f = 5 Mhz, λ = 60 meters.

Theoretically, ***ambiguous range estimates*** are possible. For example if λ = 60m, a target at a range of 5m $\equiv$ target at 35m (same θ).

Usually not an issue as the range of the sensor is typically smaller than λ due to attenuation.

MEASURING TIME OF FLIGHT: PHASE-SHIFT MEASUREMENT



$$\lambda = \frac{c}{f}$$

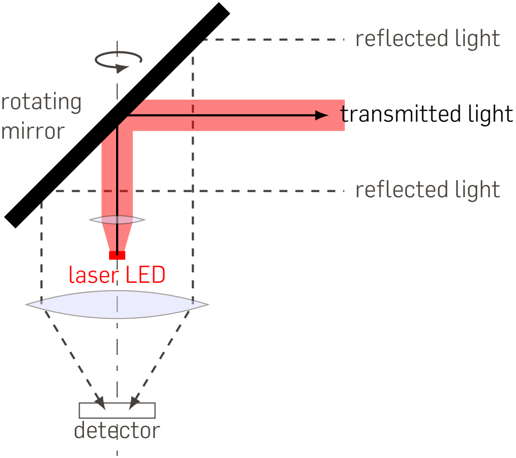
$$D' = L + 2 \cdot D = L + \frac{\theta}{2\pi} \cdot \lambda$$

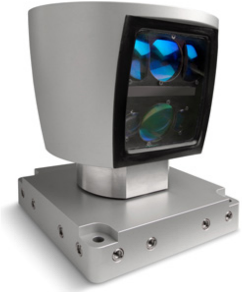
Confidence in the range (phase estimate) is *inversely proportional to the square of the received signal amplitude*.

Hence *dark, distant objects will not produce such good range estimates* as closer brighter objects ...

The sensors point down
to avoid ambiguities

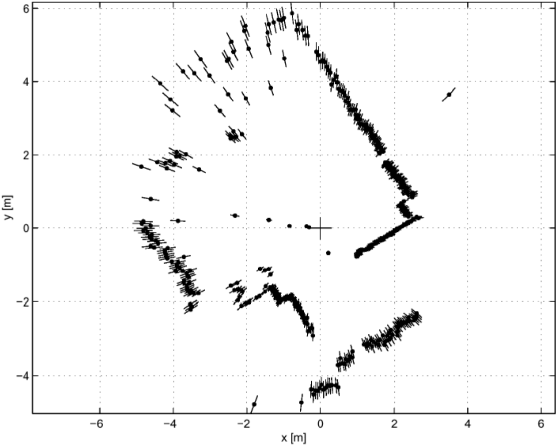
MECHANICAL IMPLEMENTATION





2D LASER SCAN

Typical range image of a 2D laser range sensor with a rotating mirror. The length of the lines through the measurement points indicate the uncertainties.



LASER RANGE FINDER

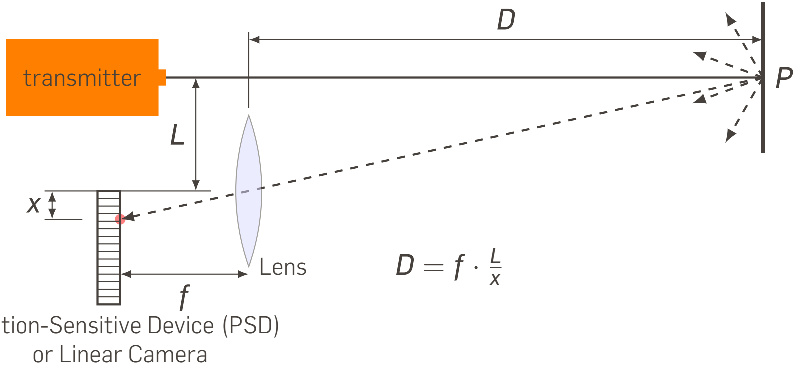
Hokuyo UST-10LX

- 270° field of view.
- 0.25° angular resolution.
- 40 Hz scan rate.
- Ethernet
- Range 20mm to 10m ± 40mm
- Dimensions: 50 x 50 x 70mm
- Power: 0.15A 24V
- $1775 in 2016

Source: acroname

TRIANGULATING DISTANCE SENSOR

Principle of 1D laser triangulation



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

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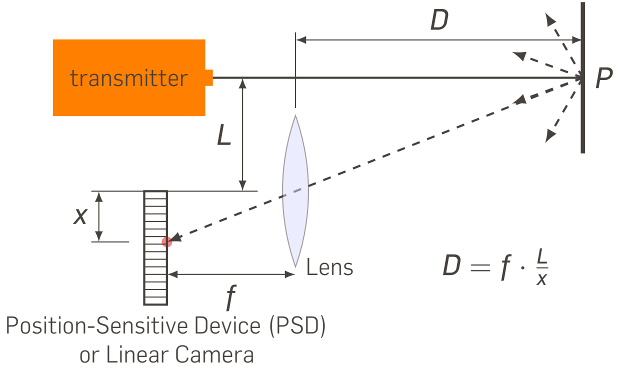


$$D = f \cdot \frac{L}{x}$$

Note that distance is proportional to $\frac{1}{x}$: **the closer, the more accurate**.

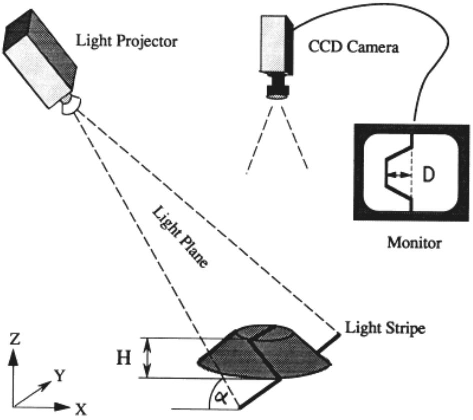
SHARP GP SERIES DISTANCE SENSORS

- Cheap (≈ £6)
- Distance measurement between 8 and 80cm (for GP2D12 model)
- Output: analogue voltage (3.1V at 10cm to 0.4V at 80cm)
- Less dependant on reflectivity of material than normal IR distance sensors
- Measurement every 40ms (25Hz)

STRUCTURED LIGHT (VISION, 2D, 3D)

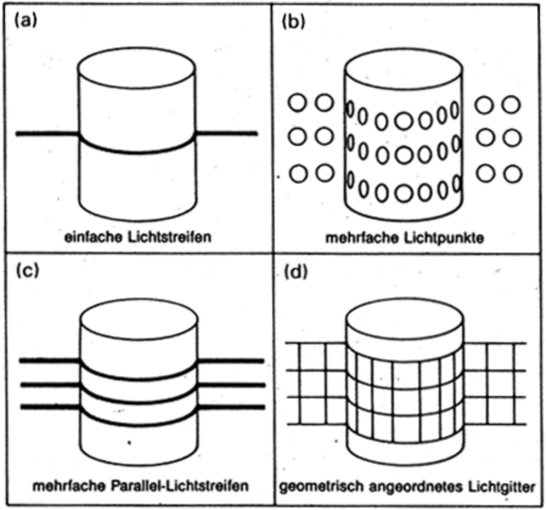
- Eliminate the correspondence problem of stereo vision by projecting structured light on the scene.
- Project slits of light or emits collimated light (e.g. laser) by means of a rotating mirror.
- Reflection sensed by camera.
- Range to an illuminated point can be determined from simple geometry.

STRUCTURED LIGHT (VISION, 2D, 3D)



$$H = D \cdot tan(\alpha)$$

STRUCTURED LIGHT (VISION, 2D, 3D)

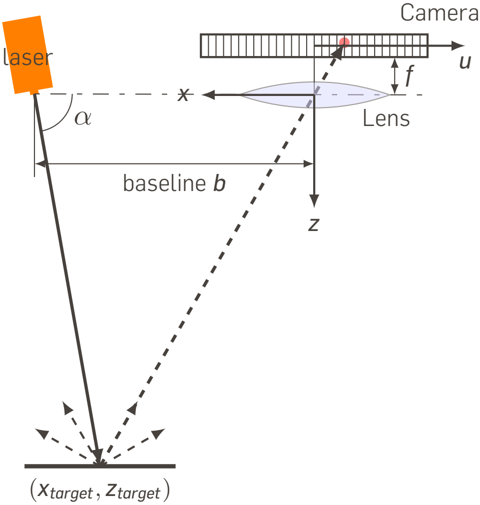


STRUCTURED LIGHT – PRINCIPLE

One dimensional schematic of the principle. From the figure, simple geometry shows that:

$$x_{target} = \frac{b \cdot u}{f \cdot cot(\alpha) + u}$$

$$z_{target} = \frac{b \cdot f}{f \cdot cot(\alpha) + u}$$



STRUCTURED LIGHT – PRINCIPLE

Range resolution is defined as the **triangulation gain** G_p:

$$\frac{\partial u}{\partial z} = G_p = \frac{b \cdot f}{z^2}$$

Baseline length b

- the smaller b, the more compact the sensor can be.
- the larger b, the better the range resolution is.

However, for large b, the chance that an illuminated point is not visible to the receiver increases!

STRUCTURED LIGHT – PRINCIPLE

Range resolution is defined as the **triangulation gain G_p**:

$$\frac{\partial u}{\partial z} = G_p = \frac{b \cdot f}{z^2}$$

Focal length f

A larger focal length f gives

- a smaller field of view
- an improved range resolution
- less lens distortion
- a larger sensor head

CAMERA

Hardware

- Two technologies: CCD or CMOS
- Monochrome or colour
- Resolution between 1 x 64 pixels and 4000 x 4000 pixels
- Small, low-power and cheap
- Prices anything between 40p and £3000

Cameras have dropped significantly in price, and are the cheapest high-tech sensor around

CAMERA OUTPUT

Most cameras provide digital output:

- USB1.0, USB1.1, USB2.0, USB3.0, Firewire (aka IEEE 1394 – mostly replaced by USB3.0), Ethernet, or any hardware bus or proprietary bus (like on the Raspberry Pi).

Some –mostly older– camera designs do not, and provide an analog (RGB or composite) signal instead.

$\rightarrow$ a **frame grabber** is needed to digitise the signal. Matrox is the leading manufacturer of frame grabbers.

CAMERA PARAMETERS

Shutter speed

Rate at which an image is refreshed, e.g. 25ms, 1/400 s.

Iris position (aka **aperture**)

Size of the lens opening, mechanically operated. Allows more or less light in.

Camera gain

Amplification of the camera signal. *Noise is amplified as well.*

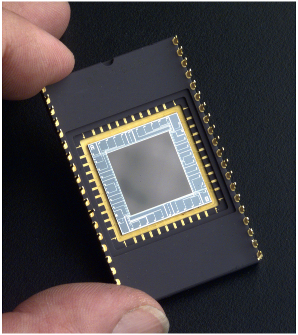
White balance (aka color temperature)

Mixture of blue, red and green components that define white. Often needed to cancel out influences of illumination.

CCD TECHNOLOGY

Charge-coupled device (*CCD*)

- Each pixel has a photodiode and a capacitor, the capacitor is charged or discharged as photons hit the light-sensitive silicon.
- The charge in the capacitor is proportional to the light intensity.
- The charge is read out at the corner of the chip's surface.
- Charge is transferred over the chip' surface to that corner, like a "bucket brigade".



Source: Wikipedia

More details on CCD sensors

CCD TECHNOLOGY

Some sort of shutter is needed to prevent smear in the camera image.

- *Mechanical shutter*: expensive and high power consumption.
- *Frame transfer CCD*: one half of the chip’s surface is opaque, charge is transferred there and then read out.
- *Interline architecture*: every other line is opaque, faster shutter speeds possible. Less sensitive to light.

CCD TECHNOLOGY

Available sensors can function from far infrared (100μm) to X-rays (1nm).

Common sensors in the range 400nm – 1000nm $\Rightarrow$ Human visual spectrum from 380nm to 780nm, so ***less sensitive to blue light*** and ***oversensitive to red and infrared***.

CCD TECHNOLOGY

CCD – advantages

- high quality, relatively low noise images
- high quantum efficiency

  70 to 80% of photons are converted into a charge, ideal for low light conditions.
- *integrating function* of pixels.

  can be used to measure for prolonged times in very dim settings.

CCD TECHNOLOGY

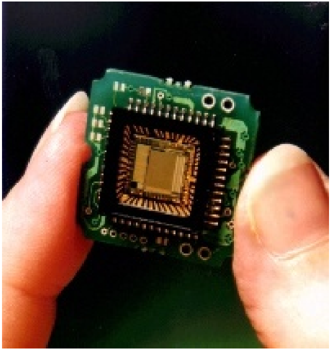
CCD – disadvantages

- integrating light measurement
  - in bright light, capacitors can **saturate**
  - saturation leads to charge leaks from one pixel to the other: causes **blooming** the image
- large silicon size due to circuitry to read out pixels
- interfacing between CCD and CMOS technology is not straight-forward
  - hinders cheap hardware
- complex clocking issues on chip
- large dissipation

CMOS TECHNOLOGY

Complementary Metal Oxide Semiconductor (*CMOS*)

- Photodiode with circuitry that reads out light intensity.
- **No** integrating measurement, but a **proportional** measurement instead.
- Pixel values are read out much like in RAM memory.



CMOS TECHNOLOGY

CMOS – advantages

- CMOS technology is mature and simple

  Production costs are a fraction of that of CCD.
- No complex clocking in chip.
- Low power consumption.
- Proportional measurement

  $\rightarrow$ no saturation of pixels.
- Smaller silicon size.
- Random access to pixels (just like RAM).
- Easy interfacing to CMOS technology.

  CMOS circuitry, e.g. for bus, can be integrated on the same silicon area.

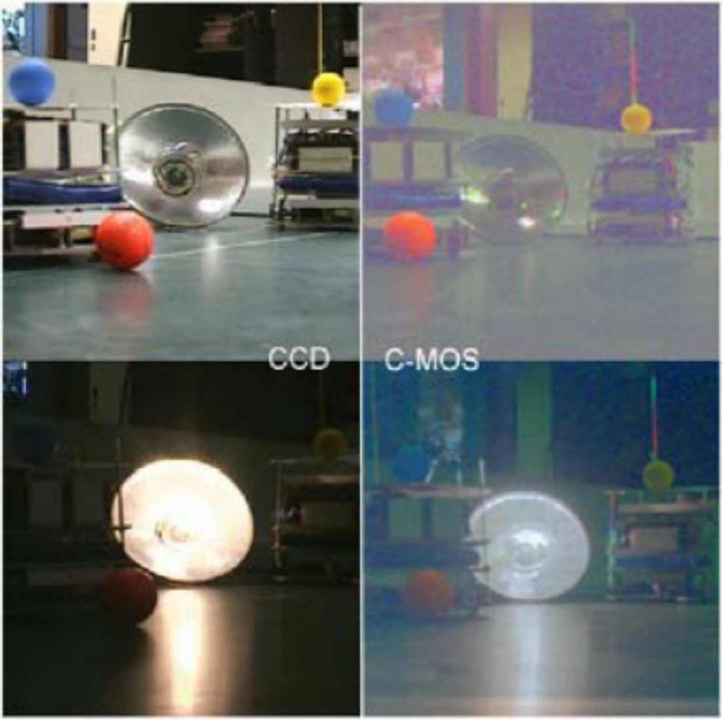
CMOS TECHNOLOGY

CMOS – disadvantages

- Each photodiode has CMOS circuitry which takes up silicon real estate, but is not sensitive to incoming light

  CMOS camera is less sensitive than CCD.
- CMOS has a larger pixel mismatch and is typically more noisy than CCD.

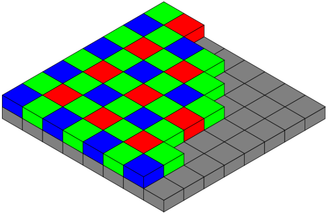
  This has improved considerably over the years, see CMOS in high-end ## digital cameras.


CCD
C-MOS

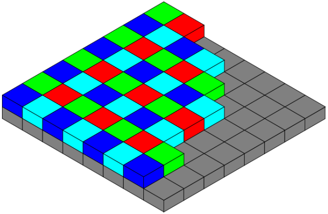
COLOUR CAMERAS

With one CCD or CMOS sensor, a filter is placed in front of the sensor surface.

- Resolution, relative to monochrome camera, is reduced by 75%
- Bayer (GRGB) or RGBE (E = Emerald) filter



Bayer filter



RGBE filter

COLOUR CAMERAS

Three sensor cameras.

- In expensive and professional colour cameras, the images is optically split in three.
- Each copy is sent to a separate sensor, each sensor has a R, G, or B filter.

$\Rightarrow$ No resolution loss due to Bayer or RGBE filter

$\Rightarrow$ No problem of misalignment of filter

OMNIDIRECTIONAL CAMERA

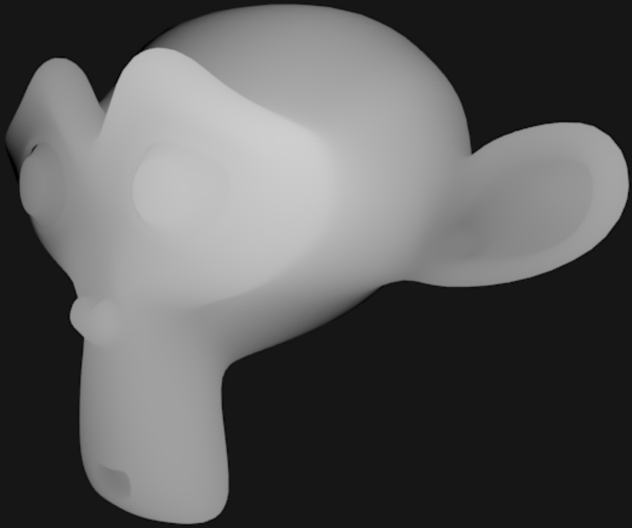
Most robots need 360° vision, this can be provided by a **omnidirectional camera**.

IMAGE PROCESSING AND COMPUTER VISION

- See Phil Culverhouse's lectures.
- Take an MSc Robotics next year.

RGB-D CAMERAS: MANY TECHNOLOGIES

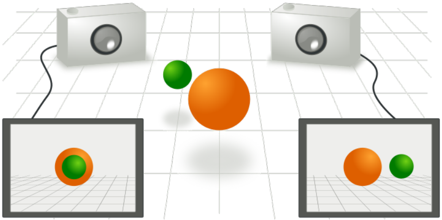
- Stereo-vision
- Structured light
- Speckle decorrelation
- Time-of-Flight
- (...several other like coded-aperture)




Elphel NC353L
/* source inside */
hama

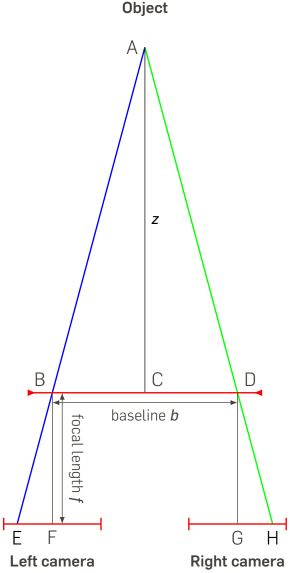
STEREOVISION

- A camera typically forms a 2D mapping of a 3D environment.
- Reconstructing depth from a 2D image is in most cases impossible.
- A solution to this is using a **stereo camera** which can calculate the depth (i.e. *z* axis) of pixels.
- Using two slightly different views from the same scene and a precise knowledge of camera parameters.



Source: Wikipedia

STEREOVISION



$$
\begin{aligned}
d &= EF + GH && (1)\\
&= BF\left(\frac{EF}{BF} + \frac{GH}{BF}\right) && (2)\\
&= BF\left(\frac{EF}{BF} + \frac{GH}{DG}\right) && (3)\\
&= BF\left(\frac{BC + CD}{AC}\right) && (4)\\
&= BF\frac{BD}{AC} = \frac{k}{z}, \text{ where} && (5)
\end{aligned}
$$

$k = BD \times BF = b \cdot f$

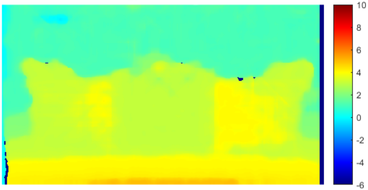
$z = AC$

$d = \frac{b \cdot f}{z}$ is the **disparity**

STEREOVISION

Disparity map

Pixel disparity: for each **pixel patch** on the left, by how many pixel the same patch is **shifted** on the right?



STEREOVISION

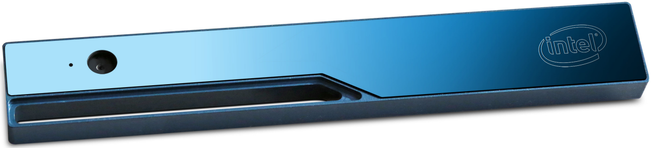
Advantages

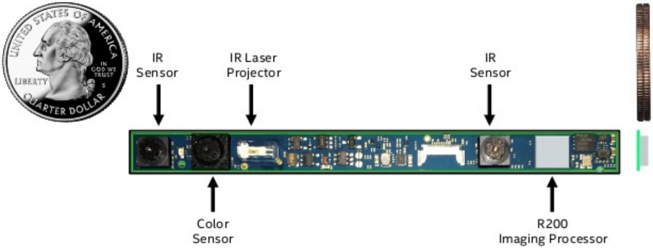
- Simple technology
- Works great outdoors

Disadvantages

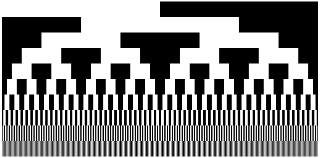
- Two calibrated cameras needed
- Multiple computationally intensive steps
- Depends on illumination and scene texture
- Requires texture $\Rightarrow$ active stereovision

ACTIVE STEREO-VISION

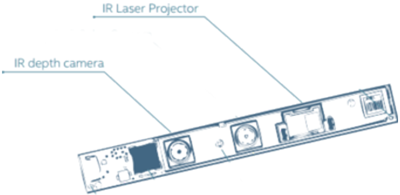




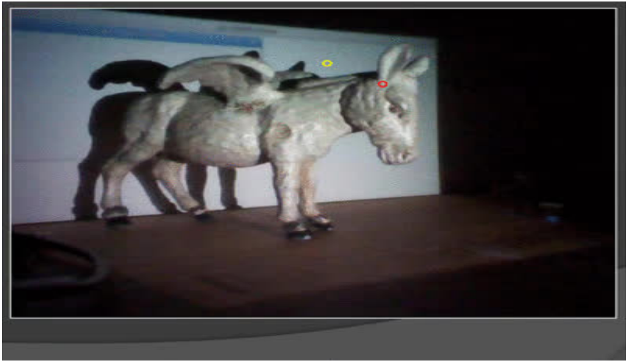
STRUCTURED LIGHT



Gray code

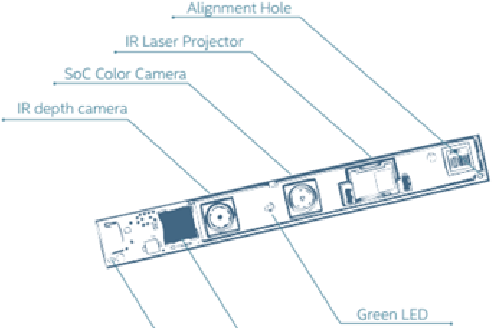


STRUCTURED LIGHT

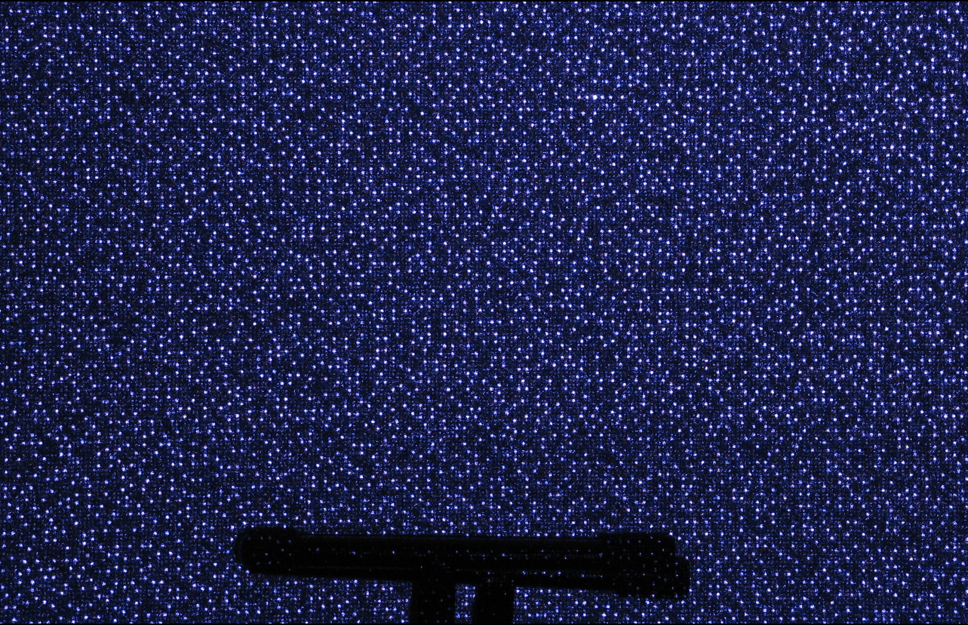


	Yellow	Red
Gray code	110100111	010000111
Projector col.	314	250
Camera col.	335	392
Disparity	335-314=21	392-250=142

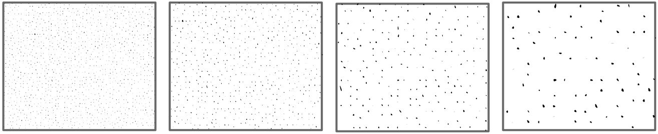
STRUCTURED LIGHT CAMERAS

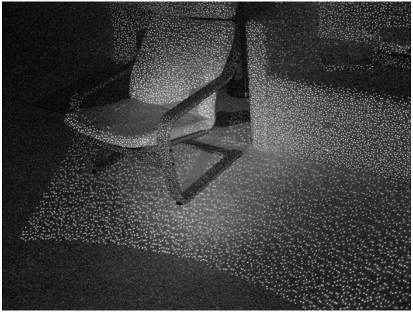


SPECKLE DECORRELATION



MULTISCALE PATTERN





KINECT 360 - PRIMESENSE 3D CAMERA

Infrared laser light pattern projected onto scene and filmed with CMOS camera.

- Class 1 laser device: safe for eyes.
- 1cm depth resolution, 3mm height and width.
- 320x240 16-bit depth @ 30 frames/sec, 640x480 32-bit colour@ 30 frames/sec, 16-bit audio @ 16 kHz
- Stronger light than Swissranger 3D cam: laser dots vs LED light.

KINECT 360 - PRIMESENSE 3D CAMERA

The hardware is only one aspect of the sensor.

The software is equally important.

- Matching a cloud of points in 3D space to 2 body models is a very hard problem in artificial intelligence.
- Machine learning used to let the software learn mapping between 3D points and body models (see IEEE article)

KINECT 360 - PRIMESENSE 3D CAMERA

Principles

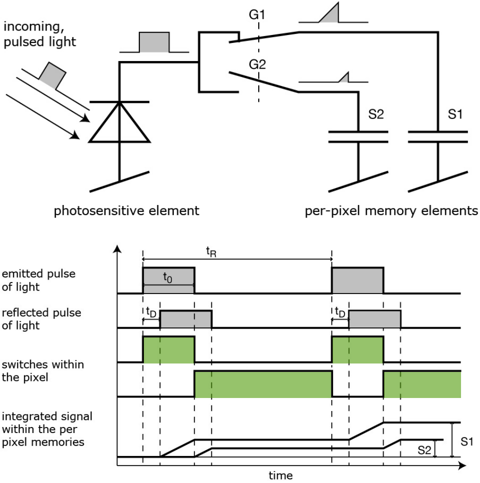
- Dot pattern (speckles) is projected in near IR light.
- CMOS IR camera records image.
- Pattern is known by sensor. Calibration is done at time of manufacturing: a set of calibration images is stored in the device.
- Each dot pattern encodes a coordinate

From US Patent

More at TUM

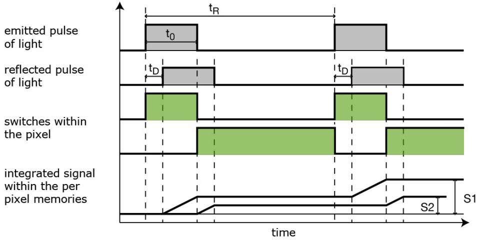
TIME-OF-FLIGHT CAMERAS

TIME-OF-FLIGHT CAMERAS



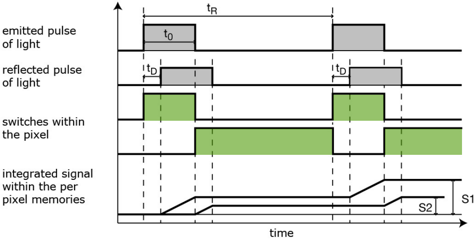
Source: *Wikipedia*

TIME-OF-FLIGHT CAMERAS



$$t_D = 2 \cdot \frac{D}{c} = 2 \cdot \frac{2.5m}{300000000\frac{m}{s}} = 0.00000001666s = 16.66ns$$

TIME-OF-FLIGHT CAMERAS



$$t_D = 2 \cdot \frac{D}{c} = 2 \cdot \frac{2.5m}{300000000\frac{m}{s}} = 0.00000001666s = 16.66ns$$

$$D = \frac{1}{2} \cdot c \cdot t_0 \cdot \frac{S2}{S1+S2}$$

COMPARISON OF (SOME) RGB-D CAMERAS

	Kinect 360 (v1)	Kinect One (v2)
Range	0.6m – >5m	1.37m – 8m?
Price (new)	£230	£118
Depth resolution	640x480px, 11bits	512x424px, 13bits
Libraries	libfreenect/OpenNI1	libfreenect2
horizontal FoV	57	70
vertical FoV	43	60
Microphones?	4	4

	Intel RealSense SR300	Intel RealSense R200
Range	0.2m – 1.6m	0.6m – 3.5m (10m outdoors)
Price (new)	£66	£66
Depth resolution	640x480	640x480
Libraries	librealsense	librealsense
horizontal FoV	77	77
vertical FoV	43	47
Microphones?	2	0

HOW DO WE USE IT?

2 main options:

- 1. Microsoft SDK
- 2. OpenNI

Microsoft SDK needs specific versions of Visual Studio

Microsoft SDK is best complemented with the Developer Tools (which has lots of great example applications)

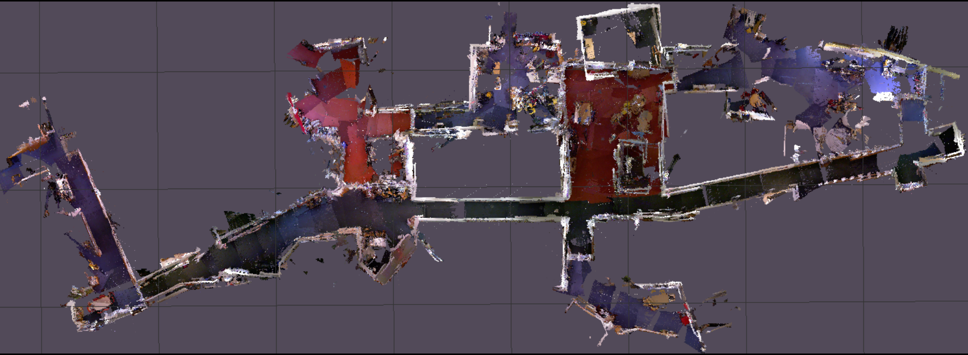
APPLICATIONS IN ROBOTICS

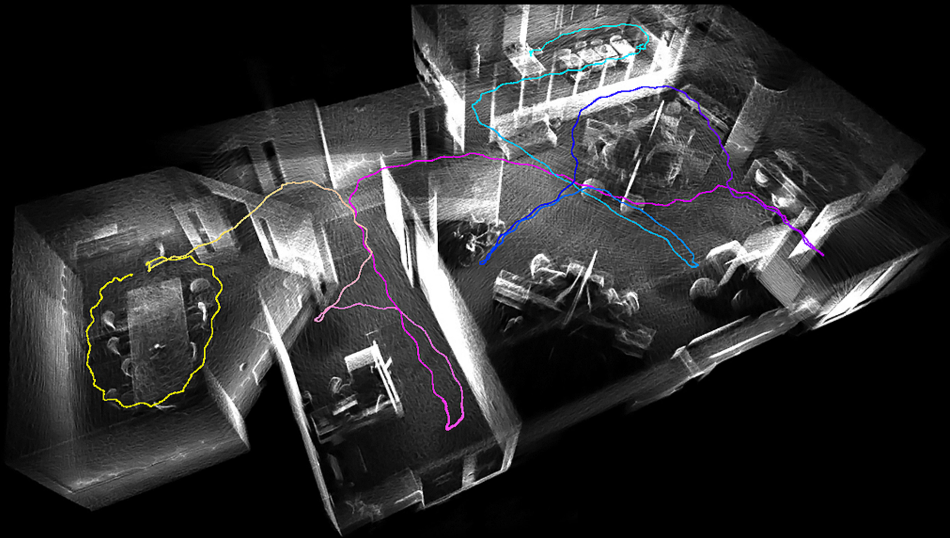
APPLICATIONS IN ROBOTICS

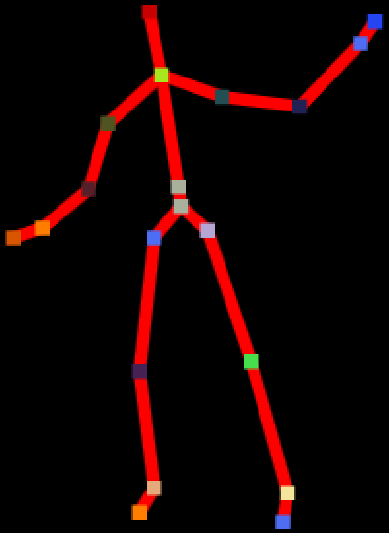
Two brief examples:

- 3D SLAM
- Skeleton tracking

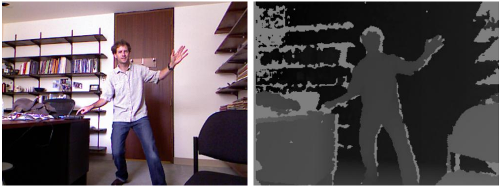
3D SLAM: SIMULTANEOUS LOCALIZATION AND MAPPING







SKELETON TRACKING



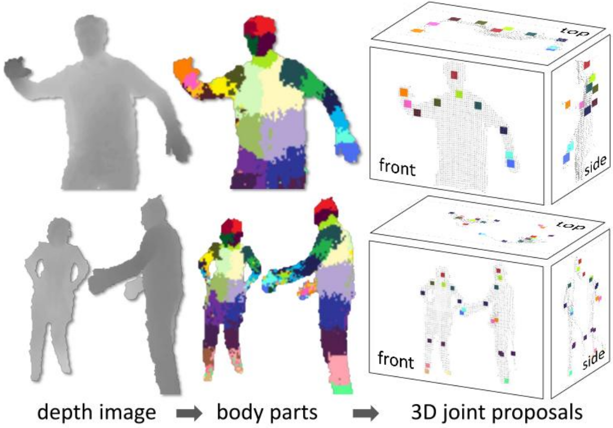
[Source: John MacCormick, Shotton et al., CVPR 2011]

SKELETON TRACKING

[Source: John MacCormick, Shotton et al., CVPR 2011]

SKELETON ESTIMATION

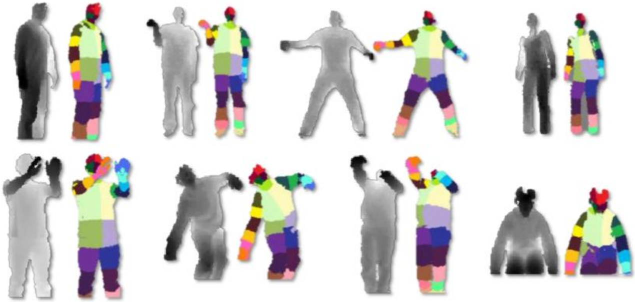
1. Estimate body parts using a randomized decision forest
2. Estimate the skeleton



[Source: John MacCormick, Shotton et al., CVPR 2011]

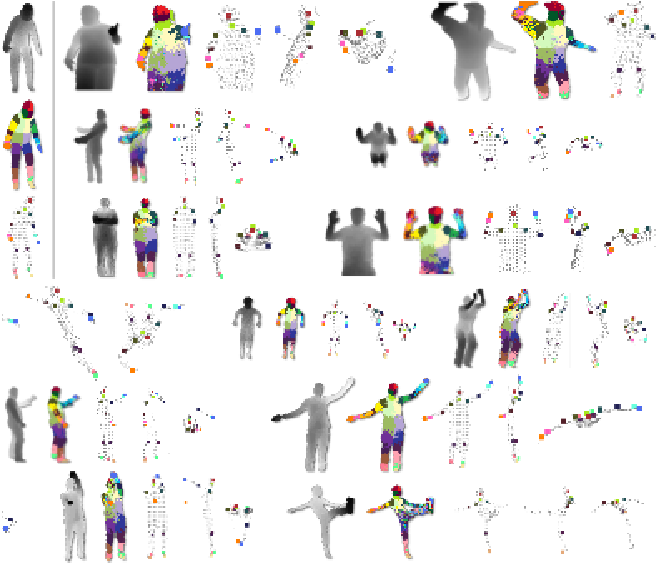
BODY PARTS

Train a decision tree from ≈1M samples, computer-generated from ≈100K acquired pairs (depth image, motion capture). This allow **tagging** of body parts in the depth image.



[Source: John MacCormick, Shotton et al., CVPR 2011]

SKELETON



IN ROBOTICS APPLICATIONS

Tele-operation:

- Plymouth: **https://www.youtube.com/watch?v=wf4waMhPHmc**
- Plymouth Baxter: **https://www.youtube.com/watch?v=XKRIOhcInqE**
- NASA: **https://www.youtube.com/watch?v=pqNC72fgetc**
- Full body: **https://www.youtube.com/watch?v=7vq-1TiXi3g**
- 2 arms: **https://www.youtube.com/watch?v=kECNyr7vOkM**

Autonomous navigation:
https://www.youtube.com/watch?v=eWmVrfjDCyw

Cutting bananas?:
https://www.youtube.com/watch?v=TmTW61MLm68#t=356

That's all, folks!

Questions:

Portland Square B316 or **severin.lemaignan@plymouth.ac.uk**

Slides:

github.com/severin-lemaignan/module-mobile-and-humanoid-robots